HANDBOOK FOR ELECTRICITY METERING

10TH EDITION

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PREFACE
TO THE TENTH EDITION

The first edition of the *Electrical Meterman's Handbook*, now the *Handbook for Electricity Metering*, was first published in 1912. Nine revisions have since been published; the ninth edition appeared in 1992. As in the previous editions, the emphasis has been on fulfilling the needs of the metering practitioner.

In the tenth edition each chapter includes updated text and new graphics. The following major updates have been made to the 10th edition: new examples on complex numbers; addition of current measurement technology from basic to advance meters; expansion of information on optical voltage and current sensors; inclusion of new meter diagrams; current metering testing practices; updates on standard metering laboratory and related standards; and new electronic data collection information. To make the *Handbook* convenient either as a reference or textbook, a great deal of duplications has been permitted.

In the preparations of this *Handbook,* the Advisory Teams wish to make grateful acknowledgment for all the help received. Above all, credit must be given to the editors and committees responsible for previous editions of the *Handbook.* Although the tenth edition has been rewritten and rearranged, the ninth edition provided most of the material that made this rewriting possible.

The contribution made by the manufacturers has been outstanding for the chapters concerning their products and they have freely provided illustrations, assisted in editing chapters and provided text.

It is hoped that future editions will be prepared as new developments make them necessary. If users of this *Handbook* have any suggestions which they believe would make future editions more useful, such suggestions, comments, or criticisms are welcomed. They should be sent to the Edison Electric Institute, 701 Pennsylvania Avenue, N.W., Washington, D.C. 20004-2696.

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CHAPTER 1

INTRODUCTION TO THE METER DEPARTMENT

THE ELECTRIC UTILITY AND THE COMMUNITY

THE ELECTRIC COMPANY and the community which it serves are permanently interdependent. An electric company, by the nature of its business, cannot pick up its generating plant, transmission, or distribution system and move to some other community. It is firmly rooted where it is located. Its progress depends to a large extent upon the progress of the area it serves; also, it depends upon the respect and active support of its customers. It makes good sense for the electric company to work cordially and cooperatively with its customers toward the improvement of economic and civic conditions. Because of this, the meter reader or meter technician must be aware that they represent the "Company" when calling on a customer's home or business.

What the electric company sells and/or delivers has become essential to the point that loss of electric power causes more than inconvenience; it can mean real hardship, even tragedy. In addition, large quantities of electricity cannot be produced and stored and so must be immediately available in sufficient quantities upon demand. What this means is that we sell and/or deliver not only the commodity of electric energy but a very valuable service as well.

The service performed by the electric company and its employees should be so well done that every member of the company and the community can be proud of it.

THE DUTIES OF THE METER DEPARTMENT

The primary function of the meter department is to maintain revenue metering installations at the high level of accuracy and reliability as specified by company and regulatory requirements. This usually involves the installation, testing, operation, and maintenance of meters and metering systems.

Additional functions, which vary with individual companies, may include: appliance repair, connection of services, testing of rubber protective equipment, stocking and tracking metering equipment, operation of standards laboratories, manual meter reading, automated meter reading, interval data retrieval and processing, installation and maintenance of advanced meter options, acceptance testing of material and equipment, instrument calibration and repair, investigation of customer complaints, revenue protection and metering security, installation and maintenance of load survey and load management equipment, relay testing and high-voltage testing. Although possibly quite removed from metering, these and many similar functions may become the responsibility of the meter department predominantly for two reasons: first, the direct association of the work with metering, as in the case of meter reading, and, second, the characteristic ability of meter personnel to translate their knowledge and techniques to other fields requiring detailed electrical knowledge and specialized skills, as in the case of operation of standards laboratories, and instrument repair.

The electric meter, since it generally serves as the basis for customer billing, must be installed, maintained, tested, and calibrated to assure accuracy of registration. To accomplish this, the accuracy of all test equipment must be traceable through suitable intermediate standards to the basic and legal standards of electrical measurement maintained by the National Institute of Standards and Technology (NIST). Quality of workmanship and adherence to procedures must be consistently maintained at a level which will achieve this desired accuracy. Poor workmanship or deviation from procedures can have a serious effect on both the customer and the company. Standards, procedures, and instructions are essential to insure uniformity of operations, to prevent errors, and for overall safety and economy.

CUSTOMER CONTACTS

Because of the electric company's place in the community, and because members of the meter department may frequently meet customers face-to-face, it is important that all meter personnel exemplify those qualities of integrity and courtesy which generate confidence in the company. Day-to-day contacts with customers provide these employees with exceptional opportunities to serve as good-will ambassadors and may earn public appreciation for the services they and their company perform. To achieve this appreciation, employees must demonstrate a sincere desire to be helpful, as well as high ethical standards in the performance of their work.

In many companies the increase in outdoor meters as well as the implementation of automated meter reading systems, has resulted in a decrease in the meetings between customers and company employees. Therefore, every effort should be made to take advantage of those opportunities for building good will that do present themselves in areas other than meter reading.

First impressions are often lasting impressions. It is desirable that meter personnel look their best so that a good image of the company they represent will be left in the customer's mind. Neatness and cleanliness are of utmost importance. The little things which customers notice may have considerable influence on the company's reputation.

Visits to a customer's premises for meter reading, testing, or for other reasons, afford opportunities for personnel to demonstrate the company's interest in the customer's welfare. Courteous consideration of every request will create satisfaction and appreciation of the efforts made by the company to render good service.

However, customers should be referred to the appropriate department or person for answers to all questions on rates, billing, or any other matter which is outside the meter employee's area of expertise. Promises requiring action beyond the employee's own capability should be avoided. In practically all cases, assurance that any request will be conveyed to the proper party will satisfy the customer.

Upon entering a customer's premises, meter personnel should make their presence and business known and should cheerfully present identification card, badge, or other credentials when requested. All work done on customers' premises should be planned carefully and carried out promptly. While on customers' premises, conversations between company personnel should be about the work at hand and should not be argumentative.

If utility personnel notice any unusual conditions on the customer's premises or in the immediate vicinity which might affect safety, the company's system, or the customer's electric service, they should report them promptly to their immediate supervisors.

Telephone conversations with customers, like premise visits, can go a long way toward expressing the company's interest in the customer if they are conducted with intelligence and understanding. Sometimes considerable patience may be required, but even then, as at all times, a courteous tone of voice will prove most helpful.

KNOWLEDGE REQUIRED IN METERING

The theory of metering is highly technical. To understand their jobs, meter personnel must have a working knowledge of instruments and meters, elementary electricity, elementary mathematics, and certain practical aspects of electric services. A good understanding of electronics and personal computers (PCs) has become a requirement for work on electronic metering equipment, such as programmable electronic meters and interval data recorders. Today's meter technician should be competent in the following subjects:

- Math: fractions and decimals necessary to calculate meter constants, register ratios and pulse values.
- Electrical circuits: AC and DC circuits with particular reference to Ohm's Law and Kirchhoff's Law.
- Inductance, capacitance, power factor, and vector analysis.
- Electronic components and circuits.
- PCs, in particular, for communicating with and programming electronic meters.
- The current-carrying capacity of wire, the relationship between electricity and heat, and the causes and effects of voltage drops.
- The principles of indicating instruments.
- The principles of operation for both electromechanical and electronic watthour meters, and a good understanding of how to test and calibrate those meters.
- Single and polyphase circuits and how to meter them correctly.
- Blondel's Theorem and it's application.
- Principles of power, current, and voltage transformers and how to interconnect them.
- The correct methods of bonding, grounding, and shielding for both safety and the protection of electronic equipment.

- The application of fuses or circuit breakers.
- Basic telecommunication principles and practices.

Various books on metering which can be studied to attain technical knowledge are generally made available within the company. There are also many excellent instructional books and pamphlets issued by the manufacturers.

Besides the technical subjects mentioned before, effective meter personnel must be familiar with company policies, procedures, standards, and work practices that relate to metering. They should attain such additional knowledge of electrical engineering, self improvement, and the utility business in general, as opportunities provide. Above all, they must be willing to study and to learn.

METER SECURITY

As the cost of electricity rises to become a significant portion of the cost of living, the temptation to violate the security of metering equipment for the purpose of energy theft becomes irresistible for some. In addition, the possibility of an organized effort to tamper with metering equipment increases with the increased cost of energy. Therefore, the meter employee must be aware of the various techniques of energy theft and be constantly on the lookout for such violations. Since meter security systems vary throughout the industry, it becomes necessary for meter employees to completely familiarize themselves with their company's policy for securing meters and associated devices, and to keep constant vigil for violations. Incidents of tampering should be reported immediately in accordance with company instructions, taking care to preserve all evidence and to submit complete, well documented, and brief reports.

It is imperative to bear in mind that circumstantial evidence of tampering should not be interpreted as guilt until all evidence has been examined by those designated to do so. Therefore, courtesy toward all customers, even in strained circumstances, will speak well for you, your department, and your company.

Meter security begins with the seal that secures the glass cover to the base of the meter. This seal is applied without a tool and offers no interference when installing the meter. After the meter is installed, a seal must be applied to secure the meter mounting device whether it is the ring-type or ringless. Ring-type sockets are secured by sealing the ring that holds the meter in place. Ringless sockets are secured by installing the socket cover after the meter is in place, then sealing the cover hasp.

The demand reset mechanism is another area which needs to be secured with a seal to prevent undetected tampering. It should be sealed each time the demand is reset. If a different color seal is used each reading cycle, there is assurance that the demand was reset at the end of the last cycle.

To be sure your company's sealing program maintains its integrity, seals should be treated as security items. Only authorized personnel should have access to seals, and they should not be left where unauthorized people would come in contact with them.

The most important part of the sealing procedure is the follow-up. Every time the meter is read, the seal should be inspected, not just visually but physically. This seal should be tugged on and visually inspected to make sure there was no tampering and it is the proper seal for that meter. Evidence of tampering should be reported immediately.

There is a wide variety of seals available for all of these applications. Some require tools for installation, some do not. Some are all metal, some all plastic, and some a combination of both. Whatever seal is used, however, it should offer the following benefits:

- Be unique to your company and readily identifiable.
- Be impossible to remove without leaving visible signs of tampering.
- Be numbered so that particular seals can be identified with the location or installer.

Electronic meters may require software security, i.e., password protection. Most manufacturers provide for at least two level password protection. These levels are particularly useful to allow "read only" access to the meter by another department or company. In this case, one password will allow for reading or retrieving data from the meter and the other password will allow for both reading and writing or programming from/to the meter. It is important to maintain strict security on all metering passwords in accordance with company policy.

SAFETY

Safety is a full-time business and requires the hard work and full cooperation of every meter employee. Safety procedures are measures which, if followed, will enable personnel to work without injury to themselves or others and without damage to property.

Simply issuing safety procedures or rules does not guarantee safe work practices or produce good safety records. Meter employees must learn the safety rules of their company, apply them daily, and become safety-minded.

Meter personnel owe it to themselves, their families, and their company to do each step of every job the safe way. Careful planning of every job is essential. Nothing should be taken for granted. The meter employee must take responsibility for his/her own safety. Constant awareness of safety, coupled with training, experience, and knowledge of what to do and how to do it, will prevent most accidents.

Every meter employee's attention is directed to the following general suggestions, which are almost without exception incorporated in company safety rules:

- Horseplay and practical jokes are dangerous. Work safely, consider each act, and do nothing to cause an accident.
- Knowledge of safe practices and methods, first aid, and CPR is a must for meter personnel.
- Beware of your surroundings and alert to unsafe conditions.
- Report unsafe conditions or defective equipment to your immediate supervisor without delay.
- Have injuries treated immediately.
- Report all accidents as prescribed by company safety rules.
- Do a job hazard analysis when appropriate before beginning a job. Re-assess when something unexpected happens during the job.
- Exercise general care and orderliness in performance of work.
- The right way is the safe way. Do not take short cuts.
- Study the job! Plan ahead! Prevent accidents!
- Select the right tools for the job and use them properly.
- Keep tools in good working order.

- Use personal protective equipment when appropriate.
- Exercise good housekeeping at all times.
- Handle material with care. Lift and carry properly.
- Respect secondary voltage. It can be fatal.
- Never substitute assumptions for facts.
- The importance of working safely cannot be over-emphasized. Safety pays dividends in happiness to meter personnel and their families.
- **Remember, there is no job so important that it cannot be done in a safe manner.**

CHAPTER 2

COMMON TERMS USED IN METERING

THE FOLLOWING DEFINITIONS are to be considered as practical, common understandings. In order to keep the explanations as clear and simple as possible, occasional departures from exact definitions have been permitted. The explanations given are intended to be useful for meter personnel rather than for scientists. For additional definitions see the current version of ANSI C12.1 *Code for Electricity Metering*—Definitions Section, and ANSI/IEEE 100-1988 *Standard Dictionary of Electrical and Electronics Terms.*

A-Base—See Bottom-Connected Meter.

Accuracy—The extent to which a given measurement agrees with the defined value.

Ammeter—An instrument to measure current flow, usually indicating amperes. Where indication is in milliamperes, the instrument may be called a milliammeter.

Ampere—The practical unit of electric current. One ampere is the current caused to flow through a resistance of 1 ohm by 1 volt.

Ampere-Hour—The average quantity of electric current flowing in a circuit for one hour.

Ampere-Turn—A unit of magnetomotive force equal to that produced by one ampere flowing in a single turn of wire.

Annunciator—A label that is displayed to identify a particular quantity being shown.

Automatic Meter Reading (AMR)—The reading of meters from a location remote from where the meter is installed. Telephone, radio, and electric power lines are used to communicate meter readings to remote locations.

Autotransformer—A transformer in which a part of the winding is common to both the input and output circuits. Thus, there is no electrical insulation between input and output as in the usual transformer. Because of this interconnection, care must be exercised in using autotransformers.

Balanced Load—The term balanced load is used to indicate equal currents in all phases and relatively equal voltages between phases and between each phase and neutral (if one exists), with approximately equal watts in each phase of the load.

Base Load—The normal minimum load of a utility system; the load which is carried 24 hours a day. Plants supplying this load and operating day and night, are spoken of as "base-load plants."

Basic Impulse Insulation Level (BIL)—A specific insulation level expressed in kilovolts of the crest value of a standard lightning impulse (1.2 × 50 microsecond wave).

Blondel's Theorem—In a system of N conductors, N-l meter elements, properly connected, will measure the power or energy taken. The connection must be such that all voltage coils have a common tie to the conductor in which there is no current coil.

Bottom-Connected Meter—A meter having a bottom connection terminal assembly. Also referred to as an A-base electricity meter.

Bridge, Kelvin—An arrangement of six resistors, electromotive force, and a galvanometer for measuring low values of resistance. In this bridge a large current is passed through the unknown resistance and a known low resistance. The galvanometer compares the voltage drops across these two resistors in a high-resistance double ratio circuit made up of the other four resistors. Hence, the bridge is often called a "double bridge."

Bridge, Wheatstone—An arrangement of four resistances, one of which may be unknown and one generally adjustable, to which is applied an electromotive force. A galvanometer is used for continually comparing the voltage drops, thereby indicating the resistance values.

British Thermal Unit (BTU)—A unit of heat. One kilowatthour is equivalent to 3,413 BTUs.

Burden—The load, usually expressed in voltamperes at a specified power factor, placed on instrument transformer secondaries by the associated meter coils, leads, and other connected devices.

Calibration—Comparison of the indication of the instrument under test, or registration of meter under test, with an appropriate standard.

Capacitance—That property of an electric circuit which allows storage of energy and exists whenever two conductors are in close proximity but separated by an insulator or dielectric material. When direct voltage is impressed on the conductors, a current flows momentarily while energy is being stored in the dielectric material, but stops when electrical equilibrium is reached. With an alternating voltage between the conductors, the capacitive energy is transferred to and from the dielectric materials, resulting in an alternating current flow in the circuit.

Capacitive Reactance—Reactance due to capacitance. This is expressed in ohms. The capacitive reactance varies indirectly with frequency.

Central Station—Control equipment, typically a computer system, which can communicate with metering and load control devices. The equipment may also interpret and process data, accept input from other sources, and prepare reports.

Circuit, Three-Wire—A metallic circuit formed by three conductors insulated from each other. See Three-Wire System.

Circuit, Two-Wire—A metallic circuit formed by two adjacent conductors insulated from each other. When serving domestic loads one of these wires is usually grounded.

Circuit Breaker—A device, other than a fuse, designed to open a circuit when an overload or short circuit occurs. The circuit breaker may be reset after the conditions which caused the breaker to open have been corrected.

Circular Mil—The area of a circle whose diameter is one mil (1/1000 in). It is a unit of area equal to $\pi/4$ or 0.7854 square mil. The area of a circle in circular mils is, therefore, equal to the square of its diameter in mils.

Class Designation—The maximum of the watthour meter load range in amperes.

Clearance—Shortest distance measured in air between conductive parts.

Clockwise Rotation—Motion in the same direction as that of the hands of a clock, front view.

Conductance—The ability of a substance or body to pass an electric current. Conductance is the reciprocal of resistance.

Conductor Losses—The watts consumed in the wires or conductors of an electric circuit. Such power only heats the wires, doing no useful work, so it is a loss. It may be calculated from I^2R where I is the conductor current and R is the circuit resistance.

Connected Load—The sum of the continuous ratings of the connected load-consuming apparatus.

Constant—A quantity used in an equation, the value of which remains the same regardless of the values of other quantities used in the equation.

Constant, KYZ Output (K_e)—Pulse constant for the KYZ outputs of a solid-state meter, programmable in unit-hours per pulse.

Constant, Mass Memory (K_m)—The value, in unit quantities, of one increment (pulse period) of stored serial data. Example: K_m = 2.500 watthours/pulse.

Constant, Watthour—

(a) For an electromechanical meter (K_h): The number of watthours represented by one revolution of the disk, determined by the design of the meter and not normally changed. Also called Disk Constant.

(b) For a solid-state meter (K_h or K_t): The number of watthours represented by one increment (pulse period) of serial data. Example: K_h or K_t = 1.8 watthours/pulse.

Constant Kilowatthour of a Meter (Register Constant, Dial Constant)—The multiplier applied to the register reading to obtain kilowatthours.

Core Losses—Core losses usually refer to a transformer and are the watts required in the excitation circuit to supply the heating in the core. Core heating is caused by magnetic hysteresis, a condition which occurs when iron is magnetized by alternating current, and by the eddy currents flowing in the iron. Core losses are often called iron losses.

Creep—For mechanical meters, a continuous motion of the rotor of a meter with normal operating voltage applied and the load terminals open-circuited. For electronic meters, a continuous accumulation of data in a consumption register when no power is being consumed.

Creepage Distance—Shortest distance measured over the surface of insulation between conductive parts.

Current Circuit—Internal connections of the meter and part of the measuring element through which flows the current of the circuit to which the meter is connected.

Current Coil—The coil of a watthour meter through which a magnetic field is produced that is proportional to the amount of current being drawn by the customer.

Current Transformer—An instrument transformer designed for the measurement or control of current. Its primary winding, which may be a single turn or bus bar, is connected in series with the load. It is normally used to reduce primary current by a known ratio to within the range of a connected measuring device.

Current Transformer, Continuous Thermal Current Rating Factor—The factor by which the rated primary current is multiplied to obtain the maximum allowable primary current based on the maximum permissible temperature rise on a continuous basis.

Current Transformer Phase Angle—The angle between the current leaving the identified secondary terminal and the current entering the identified primary terminal. This angle is considered positive when the secondary current leads the primary current.

Cutout—A means of disconnecting an electric circuit. The cutout generally consists of a fuse block and latching device or switch.

Cycle—One complete set of positive and negative values of an alternating current or voltage. These values repeat themselves at regular intervals (See Hertz).

Damping of an Instrument—The term applied to its performance to denote the manner in which the pointer settles to its steady indication after a change in the value of the measured quantity. Two general classes of damped motion are distinguished as follows:

(a) **Under-Damped**—When a meter pointer oscillates about the final position before coming to rest.

(b) **Over-Damped**—When the pointer comes to rest without overshooting the rest position.

The point of change between under-damped and over-damped is called critical damping and occurs when the degree of pointer overshoot does not exceed an amount equal to one half the rated accuracy of the instrument.

Dead-Front—Equipment which, under normal operating conditions, has no live parts exposed, is called dead-front.

Demand—The average value of power or related quantity over a specified interval of time. Demand is expressed in kilowatts, kilovoltamperes, kiloVARs, or other suitable units. An interval may be 1, 5, 10, 15, 30, or 60 minutes.

Demand, Continuous Cumulative—The sum of the previous billing period maximum demands and the present period maximum demand.

Demand, Cumulative—The sum of the previous billing period maximum demand readings. At the time of billing period reset, the maximum demand for the most recent billing period is added to the previously accumulated total of all maximum demands.

Demand, Maximum—The highest demand measured over a selected period of time such as one month. Also called Peak Demand.

Demand, Rolling Interval—A method of measuring power or other quantity by taking measurements within fixed intervals of the demand period. This method can be used to determine total demand, average demand, maximum demand, and average maximum demand during the full interval.

Demand, Sliding Window—See Demand, Rolling Interval.

Demand, Threshold Alert—An output to indicate that a programmed value of demand has been exceeded.

Demand Constant (Pulse Receiver)—The value of the measured quantity for each received pulse, divided by the demand interval, expressed in kilowatts per pulse, kiloVARs per pulse, or other suitable units. The demand interval must be expressed in parts of an hour such as $^1/_4$ for a 15 minute interval or $^1/_{12}$ for a 5 minute interval.

Demand Delay—The programmable amount of time before demand calculations are restarted after a power outage. Also called Cold Load Pickup and Demand Forgiveness.

Demand Deviation—The difference between the indicated or recorded demand and the true demand, expressed as a percentage of the fullscale value of the demand meter or demand register.

Demand Factor—The ratio of the maximum demand to the connected load.

Demand Interval (Block-Interval Demand Meter)—The specified interval of time on which a demand measurement is based. Intervals such as 10, 15, or 60 minutes are commonly specified.

Demand Interval Synchronization—Physical linking of meters to synchronize the demand intervals of all meters. Also called Demand Timing Pulse.

Demand Meter—A metering device that indicates or records the demand, maximum demand, or both. Since demand involves both an electrical factor and a time factor, mechanisms responsive to each of these factors are required as well as an indicating or recording mechanism. These mechanisms may be separate or structurally combined with one another.

Demand Meter, Indicating—A demand meter equipped with a readout that indicates demand, maximum demand, or both.

Demand Meter, Integrating (Block-Interval)—A meter that integrates power or a related quantity over a fixed time interval and indicates or records the average.

Demand Meter, Lagged—A meter that indicates demand by means of thermal or mechanical devices having an approximately exponential response.

Demand Meter, Time Characteristic (Lagged-Demand Meter)—The nominal time required for 90% of the final indication, with constant load suddenly applied. The time characteristic of lagged-demand meters describes the exponential response of the meter to the applied load. The response of the lagged-demand meter to the load is continuous and independent of selected discrete time intervals.

Demand Meter, Timing Deviation—The difference between the elapsed time indicated by the timing element and the true elapsed time, expressed as a percent of the true elapsed time.

Demand Register—A mechanism for use with an integrating electricity meter that indicates maximum demand and also registers energy (or other integrated quantity).

Demand-Interval Deviation—The difference between the measured demand interval and the specified demand interval, expressed as a percentage of the specified demand interval.

Detent—A device installed in a meter to prevent reverse rotation (or meter registration).

Dial-Out Capability—Ability of a meter to initiate communications with a central station.

Disk Constant—See Constant, Watthour (a).

Disk Position Indicator, or "Caterpillar"—An indicator on the display of a solid-state register that simulates rotation of a disk at a rate proportional to power.

Display—A means of visually identifying and presenting measured or calculated quantities and other information. (Definition from ANSI C12.1.)

Diversity—A result of variation in time of use of connected electrical equipment so that the total maximum demand is less than the sum of the maximum demands of the individual units.

Eddy Currents—Those currents resulting from voltages which are introduced in a conducting material by a variation of magnetic flux through the material.

Effective Resistance—Effective resistance is equal to watts divided by the square of the effective value of current.

Effective Value (Root-Mean-Square Value)—The effective value of a periodic quantity is the square root of the average of the squares of the instantaneous value of the quantity taken throughout one period. This value is also called the root-mean-square value and is the value normally reported by alternating current instruments.

Electrical Degree—The 360th part of one complete alternating current cycle.

Electricity Meter—A device that measures and records the summation of an electrical quantity over a period of time.

Electromagnet—A magnet in which the magnetic field is produced by an electric current. A common form of electromagnet is a coil of wire wound on a laminated iron core, such as the voltage coil of a watthour meter stator.

Electromechanical Meter—A meter in which currents in fixed coils react with the currents induced in the conducting moving element, generally a disk(s), which causes their movement proportional to the energy to be measured. Also called induction watthour meter.

Electromotive Force (EMF)—The force which tends to produce an electric current in a circuit. The common unit of electromotive force is the volt.

Element—A combination of a voltage-sensing unit and a current-sensing unit which provides an output proportional to the quantities measured.

Embedded Coil—A coil in close proximity to, and nested within, a current circuit loop of a meter used to measure the strength of a magnetic field and develop a voltage proportional to the flow of current.

Embedded System—A microcomputer system including microprocessor, memory, power supply, and supporting input and output devices, usually designed for a dedicated application.

Energy—The integral of active power with respect to time.

Farad—The practical unit of capacitance. The common unit of capacitance is the microfarad.

Field, Magnetic—A region of magnetic influence surrounding a magnet or a conductor carrying electric current.

Field, Stray—Usually a disturbing magnetic field produced by sources external or foreign to any given apparatus.

Firmware—Computer programs used by embedded systems and typically stored in read-only memories. See Memory.

Full Load—A current level for testing the accuracy of a watthour meter, typically indicated on a meter by the abbreviation "TA", for test amps.

Galvanometer—An instrument for indicating a small electric current.

Gear Ratio—The number of revolutions of the rotating element of a meter compared to one revolution of the first dial pointer.

Ground—A conducting connection, whether intentional or accidental, between an electric circuit or equipment and earth.

Ground Return Circuit—A current in which the earth is utilized to complete the circuit.

Grounding Conductor—A conductor used to connect any equipment device or wiring system with a grounding electrode or electrodes.

Grounding Electrode—A conductor embedded in the earth which has conductors connected to it to (1) maintain a ground potential and (2) to dissipate current into the earth.

Henry—The practical unit of inductance. The millihenry is commonly encountered. The common unit of inductance is the millihenry.

Hertz (Cycles per Second)—The practical unit of frequency of an alternating current or voltage. It is the number of cycles, sets of positive and negative values, occurring in one second.

Horsepower—A commercial unit of power equal to the average rate of doing work when 33,000 pounds are raised one foot in one minute. One horsepower is approximately equal to 746 watts.

Hot-Wire Instrument—An electrothermic instrument whose operation depends on the expansion by heat of a wire carrying the current which produces the heat.

Hybrid Meter—A watthour meter with electromechanical and solid-state components.

Hysteresis Loss—The energy lost in a magnetic core due to the variation of magnetic flux within the core.

Impedance—The total opposing effect to the flow of current in an alternating current circuit. It may be determined in ohms from the effective value of the total circuit voltage divided by the effective value of total circuit current. Impedance may consist of resistance or resistance and reactance.

Induced Current—A current flow resulting from an electromotive force induced in a conductor by changing the number of lines of magnetic force linking the conductor.

Inductance—That property of an electric circuit which opposes any change of current through the circuit. In a direct current circuit, where current does not change, there is no inductive effect except at the instant of turn-on and turn-off. However, in alternating current circuits the current is constantly changing, so the inductive effect is appreciable. Changing current produces changing flux which, in turn, produces induced voltage. The induced voltage opposes the change in applied voltage, hence the opposition to the change in current. Since the current changes more rapidly with increasing frequency, the inductive effect also increases with frequency.

Inductance, Mutual—If the current change causes induced voltage and an opposing effect in a second conductor, there is mutual inductance.

Inductance, Self—If the preceding effect occurs in the same conductor as that carrying the current, there is self-inductance. The self-inductance of a straight conductor at power frequency is almost negligible because the changing flux will not induce any appreciable voltage, but self-inductance increases rapidly if the conductor is in the form of a coil and more so if the coil is wound on iron.

Inductive—Having inductance, e.g., inductive circuit and inductive load. Circuits containing iron or steel that is magnetized by the passage of current are highly inductive.

Inductive Reactance—Reactance due to inductance expressed in ohms. The inductive reactance varies directly with the frequency.

Instrument Transformer—A transformer that reproduces in its secondary circuit in a definite and known proportion, the voltage or current of its primary circuit with the phase relation substantially preserved.

Instrument Transformer, Accuracy Class—The limits of transformer correction factor in terms of percent error, that have been established to cover specific performance ranges for line power factor conditions between 1.0 and 0.6 lag.

Instrument Transformer, Accuracy Rating for Metering—The accuracy class together with the standard burden for which the accuracy class applies.

Instrument Transformer, Burden—The impedance of the circuit connected to the secondary winding. For voltage transformers it is convenient to express the burden in terms of the equivalent voltamperes and power factor at its specified voltage and frequency.

Instrument Transformer, Correction Factor—The factor by which the reading of a wattmeter or the registration of a watthour meter must be multiplied to correct for the effects of the error in ratio and the phase angle of the instrument transformer. This factor is the product of the ratio and phase-angle correction factors for the existing conditions of operation.

Instrument Transformer, Marked Ratio—The ratio of the rated primary value to the rated secondary value as stated on the name-plate.

Instrument Transformer, Phase Angle—The angle between the current or voltage leaving the identified secondary terminal and the current or voltage entering the identified primary terminal. This angle is considered positive when the secondary circuit or voltage leads the primary current or voltage.

Instrument Transformer, Phase Angle Correction Factor—The factor by which the reading of a wattmeter or the registration of a watthour meter, operated from the secondary of a current transformer, or a voltage transformer, or both, must be multiplied to correct for the effect of phase displacement of secondary current, or voltage, or both, with respect to primary values. This factor equals the ratio of true power factor to apparent power factor and is a function of both the phase angle of the instrument transformer and the power factor of the primary circuit being measured.

Instrument Transformer, Ratio Correction Factor—The factor by which the marked ratio of a current transformer or a voltage transformer must be multiplied to obtain the true ratio. This factor is expressed as the ratio of true ratio to marked ratio. If both the current transformer and the voltage transformer are used in conjunction with a wattmeter or watthour meter, the resultant ratio correction factor is the product of the individual ratio correction factors.

Instrument Transformer, True Ratio—The ratio of the magnitude of the primary quantity (voltage or current) to the magnitude of the corresponding secondary quantity.

Joule's Law—The rate at which heat is produced in an electric circuit of constant resistance which is proportional to the square of the current.

Kilo—A prefix meaning one thousand of a specified unit (kilovolt, kilowatt). 1000 watts = 1 kilowatt.

KVA—The common abbreviation for kilovoltampere (equal to 1000 voltamperes).

KYZ Output—A three-wire pulse output from a metering device to drive external control or recording equipment. Each pulse or transition represents a predetermined increment of energy or other quantity. Average power can be determined with a known pulse count over a specified period and a given energy pulse value.

Lagging Current—An alternating current which, in each half-cycle, reaches its maximum value a fraction of a cycle later than the maximum value of the voltage which produces it.

Laminated Core—An iron core composed of sheets stacked in planes parallel to its magnetic flux paths in order to minimize eddy currents.

Leading Current—An alternating current which, in each half-cycle, reaches its maximum value a fraction of a cycle sooner than the maximum value of the voltage which produces it.

Lenz's Law—The induced voltage and resultant current flow in a conductor as a result of its motion in a magnetic field which is in such a direction as to exert a mechanical force opposing the motion.

Light Emitting Diode (LED)—A device used to provide a light signal in a pulse initiator. Also used as an information display format.

Liquid Crystal Display (LCD)—A type of information display format used with solid-state registers and solid-state meters.

Load, Artificial—See Phantom Load.

Load, System—The load of an electric system is the demand in kilowatts.

Load Compensation—That portion of the design of a watthour meter which provides good performance and accuracy over a wide range of loads. In modern, self-contained meters, this load range extends from load currents under 10% of the rated meter test amperes to 667% of the test amperes for class 200 meters.

Load Control—A procedure for turning off portions of customers' loads based on predetermined time schedules, system demand thresholds, or other circumstances.

Load Factor—The ratio of average load over a designated time period to the maximum demand occurring in that period.

Loading Transformer—A transformer of low secondary voltage, usually provided with means for obtaining various definite values of current, whereby the current circuit of the device under test and of the test standard can be energized.

Loss Compensation—A means for correcting the reading of a meter when the metering point and point of service are physically separated resulting in measurable losses, including I^2R losses in conductors and transformers, and iron-core losses. These losses may be added to, or subtracted from, the meter registration.

Magnetomotive Force—The force which produces magnetic flux. The magnetomotive force resulting from a current is directly proportional to the current.

Mega—A prefix meaning one million of a specified unit (megawatt, megohm). 1 megohm = 1,000,000 ohms.

Memory—Electronic devices which store digital information such as computer instructions and data.

(a) **Volatile memory** can be written to and read from repeatedly. Random access memory (RAM) requires uninterrupted power to retain its contents.

(b) **Non-volatile memory**, also known as Read Only Memory (ROM), is able to retain information in the absence of power. ROMs are programmed and may (only) be read repeatedly and are typically used to store firmware in dedicated systems.

Meter, Excess—A meter that records, either exclusively or separately, that portion of the energy consumption taken at a demand in excess of a predetermined demand.

Meter Sequence—Refers to the order in which a meter, service switch, and fuses are connected. Meter-switch-fuse is a common modern sequence. Switch-fuse-meter sequence is also used.

Meter Type—Term used to define a particular design of meter, manufactured by one manufacturer, having:

a) similar metrological properties;

b) the same uniform construction of parts determining these properties;

c) the same ratio of the maximum current to the reference current;

d) the same number of ampere-turns for the current winding at basic current and the same number of turns per volt for the voltage winding at reference voltage (for an electromechanical meter).

Micro—A prefix meaning one millionth part of a specified unit (microfarad, microhm). 1 microhm = 0.000001 ohm.

Mil—A unit of length equal to one thousandth of an inch.

Milli—A prefix meaning one thousandth part of a specified unit (milliampere, millihenry, millivolt). 1 millivolt = 0.001 volt.

Modem—An internal or external device used to modulate/demodulate (or transfer) electronic data between two locations.

Multi-function Meter—A meter that displays more than one electricity-related quantity. Typically an electronic meter.

Multi-rate Meter—An energy meter provided with a number of registers, each becoming operative at specified time intervals corresponding to different tariff rates.

National Electrical Code (N.E.C.)—A regulation covering the electric wiring systems on the customer's premises particularly in regard to safety. The code represents the consensus of expert opinion as to the practical method and materials of installation to provide for the safety of person and property in the use of electrical equipment.

Ohm—The practical unit of electrical resistance. It is the resistance which allows one ampere to flow when the impressed electromotive force is one volt.

Ohm's Law—Ohm's Law states that the current which flows in an electrical circuit is directly proportional to the electromotive force impressed on the circuit and inversely proportional to the resistance in a direct current circuit or the impedance in an alternating current circuit.

Optical Port—A communications interface on metering products which allows the transfer of information, while providing electrical isolation and metering security. The communications medium is typically infrared light transmitted and received through the meter cover.

Optical Probe—An interface device which mates with the optical port of the meter, to read data or to program the meter.

Peak Load—The maximum demand on an electric system during any particular period. Units may be kilowatts or megawatts.

Percent Error—The percent error of a meter is the difference between its percent registration and one hundred percent.

Percent Registration—The percent registration of a meter is the ratio of the actual registration of the meter to the true value of the quantity measured in a given time, expressed as a percent. Also referred to as the accuracy of the meter.

Phantom Load—A device which supplies the various load currents for meter testing, used in portable form for field testing. The power source is usually the service voltage which is transformed to a low value. The load currents are obtained by suitable resistors switched in series with the isolated low voltage secondary and output terminals. The same principle is used in most meter test boards.

Phase Angle—The phase angle or phase difference between a sinusoidal voltage and a sinusoidal current is defined as the number of electrical degrees between the beginning of the cycle of voltage and the beginning of the cycle of current.

Phase Sequence—The order in which the instantaneous values of the voltages or currents of a polyphase system reach their maximum positive values.

Phase Shifter—A device for creating a phase difference between alternating currents and voltages or between voltages.

Phasor (Vector)—A quantity which has magnitude, direction, and time relationship. Phasors are used to represent sinusoidal voltages and currents by plotting on rectangular coordinates. If the phasors were allowed to rotate about the origin, and a plot made of ordinates against rotation time, the instantaneous sinusoidal wave form would be represented by the phasor.

Phasor Diagram—A phasor diagram contains two or more phasors drawn to scale showing the relative magnitude and phase or time relationships among the various voltages and currents.

Photoelectric Tester (or Counter)—This device is used in the shop testing of meters to compare the revolutions of a watthour meter standard with a meter under test. The device receives pulses from a photoelectric pickup which is actuated by the anti-creep holes in the meter disk or the black spots on the disk. These pulses are used to control the standard meter revolutions on an accuracy indicator by means of various relay and electronic circuits.

Polarity—The relative direction of current or voltage in a circuit at a given instant in time.

Power, Active—The time average of the instantaneous power over one period of the wave. For sinusoidal quantities in a two-wire circuit, it is the product of the voltage, the current, and the cosine of the phase angle between them. For nonsinusoidal quantities, it is the sum of all the harmonic components, each determined as above. In a polyphase circuit it is the sum of the active powers of the individual phases.

Power, Apparent—The product of the root-mean-square current and root-mean-square voltage for any waveform. For sinusoidal quantities, apparent power is the square root of the sum of the squares of the active and reactive powers.

Power, Reactive—For sinusoidal quantities in a two-wire circuit, reactive power is the product of the voltage, the current, and the sine of the phase angle between them with the current taken as reference. With nonsinusoidal quantities, it is the sum of all the harmonic components, each determined as above. In a polyphase circuit, it is the sum of the reactive powers of the individual phases.

Power Factor—The ratio of the active power to the apparent power.

Power Line Carrier—A type of communication where data may be transmitted through existing electrical power lines.

Primary-Secondary—In distribution and meter work, primary and secondary are relative terms. The primary circuit usually operates at the higher voltage. For example, a distribution transformer may be rated at 14,400 volts to 2,400 volts, in which case the 14,400-volt winding is the primary and the 2,400-volt winding is the secondary. Another transformer may be rated 2,400 volts to 240 volts, in which case the 2,400-volt winding is the primary. Thus, in one case the 2,400-volt rating is secondary while in the latter case it is a primary value.

Pulse—An electrical signal which departs from an initial level for a limited duration of time and returns to the original level. Example: A sudden change in voltage or current produced by the opening or closing of a contact.

Pulse Device (for Electricity Metering)—The functional unit for initiating, transmitting, re-transmitting, or receiving electric pulses, representing finite quantities, such as energy, normally transmitted from some form of electricity meter to a receiver unit.

Pulse Initiator—Any device, mechanical or electrical, used with a meter to initiate pulses, the number of which are proportional to the quantity being measured. It may include an external amplifier or auxiliary relay or both.

Q-Hour Meter—An electricity meter that measures the quantity obtained by lagging the applied voltage to a watthour meter by 60 degrees, or for electronic meters by delaying the digitized voltage samples by a time equivalent to 60 electrical degrees.

Quadergy—The integral of reactive power with respect to time. (ANSI C12.1 definition.)

Reactance—The measure of opposition to current flow in an electric circuit caused by the circuit properties of the inductance and capacitance. Reactance is normally expressed in ohms.

Reactiformer—A phase-shifting auto transformer used to shift the voltages of a watthour meter 90 degrees when reactive voltampere measurement is wanted.

Reactive Energy—The reactive energy in a single-phase circuit is the time integral of the reactive power.

Reactive Voltamperes—The out-of-phase component of the total voltamperes in a circuit which includes inductive or capacitive reactance. For sinusoidal quantities in a two-wire alternating current circuit, reactive voltamperes are the product of the total voltamperes and the sine of the angle between the current and voltage. The unit of reactive voltamperes is the VAR.

Reactor—A device used for introducing reactance into a circuit for purposes such as motor starting, paralleling transformers, and controlling currents.

Rectifier—A device which permits current to flow in one direction only, thus converting alternating current into unidirectional current.

Reference Meter—A meter used to measure the unit of electric energy. It is usually designed and operated to obtain the highest accuracy and stability in a controlled laboratory environment.

Reference Performance—A test used as a basis for comparison with performances under other conditions of the test. (ANSI C12.1 definition.)

Register—An electromechanical or electronic device which stores and displays information. A single display may be used with multiple electronic memories to form multiple registers.

Register Constant—The number by which the register reading is multiplied to obtain kilowatthours. The register constant on a particular meter is directly proportional to the register ratio, so any change in ratio will change the register constant.

Register Freeze—The function of a meter or register to make a copy of its data, and perhaps reset its demand, at a pre-programmed time after a certain event (such as demand reset) or upon receipt of an external signal. Also called: Self-Read, Auto-Read, and Data Copy.

Register Ratio—The number of revolutions of the gear meshing with the worm or pinion on the rotating element for one revolution of the first dial pointer.

Registration—The registration of the meter is equal to the product of the register reading and the register constant. The registration during a given period of time is equal to the product of the register constant and the difference between the register readings at the beginning and the end of the period.

Resistance—The opposition offered by a substance or body to the passage of an electric current. Resistance is the reciprocal of conductance.

Retarding Magnet—A permanent magnet placed near the outer edge of a meter disk to regulate the disk's rotation.

Rheostat—An adjustable resistor so constructed that its resistance may be changed without opening the circuit in which it is connected.

SE Cable—A service entrance cable usually consists of two conductors, with conventional insulation, laid parallel with a third stranded bare neutral conductor (which may or may not be insulated). The final covering is a flame retarding and waterproof braid. ASE cable is a variant of the SE cable in which a flat steel strip is inserted between the neutral conductor and the outside braid.

Self-Contained Meter—A watthour meter that is connected directly to the supply voltage and is in series with the customer loads.

Service—The conductors and equipment for delivering electric energy from a street distribution system to, and including, the service equipment of the premises served.

Service Conductors—The conductors which extend from a street distribution system, transformers on private property, or a private generating plant outside the building served, to the point of connection with the service equipment.

Service Drop—That portion of the overhead service conductors between the last pole or other aerial support and the first point of attachment to the building or structure.

Service Entrance Conductors—For an overhead service, that portion of the service conductors which connect the service drop to the service equipment. The service entrance conductors for an underground service are that portion of the service conductors between the terminal box located on either the inside or outside building wall, or the point of entrance in the building if no terminal box is installed, and the service equipment.

Service Equipment—The necessary equipment, usually consisting of one or more circuit breakers or switches and fuses, and their accessories, intended to constitute the main control and means of disconnecting the load from the supply source.

Shaft Reduction (Spindle Reduction, First Reduction)—The gear reduction between the shaft or spindle of the rotating element and the first gear of the register.

Shop, Meter—A place where meters are inspected, repaired, tested, and adjusted.

Short Circuit—A fault in an electric circuit, instrument, or utilization equipment such that the current follows a lower resistance by-pass instead of its intended course.

Socket (Trough)—The mounting device consisting of jaws, connectors, and enclosure for socket-type meters. A mounting device may be a single socket or a trough. The socket may have a cast or drawn enclosure, the trough an assembled enclosure which may be extensible to accommodate more than one mounting unit.

Solid-State Meter—A meter in which current and voltage act on electronic (solid-state) elements to produce an output proportional to the energy to be measured. Also called static meter.

Standard, Basic Reference—Those standards with which the value of electrical units are maintained in the laboratory, and which serve as the starting point of the chain of sequential measurements carried out in the laboratory.

Stator—The unit which provides the driving torque in a watthour meter. It contains a voltage coil, one or more current coils, and the necessary steel to provide the required magnetic paths. Other names used for stator are element or driving element.

Sub-Metering—The metering of individual loads within a building for billing or load control purposes. For billing applications, usually the building is metered by a master meter and the property owner desires to meter and charge individual tenants for their portion of the electricity consumed.

Switchboard-Mount Meter—A meter mounted in a drawn-out case where the meter may be removed as a functional module, with provisions to properly shunt current paths before meter disconnection, leaving behind the outer case to which service connections are permanently made.

Synchronism—This expresses the phase relationship between two or more periodic quantities of the same period when the phase difference between them is zero. A generator must be in synchronism with the system before it is connected to the system.

Temperature Compensation—For a watthour meter, this refers to the factors included in the design and construction of the meter which make it perform with accuracy over a wide range of temperatures. In modern meters this range may extend from −20°F to +140°F.

Test Output—An output signal, optical, mechanical, or electrical, which provides a means to check calibration level and verify operation of the meter.

Test-Switch—A device that can be opened to isolate a watthour meter from the voltage and current supplying it so that tests or maintenance can be performed.

Testing, Statistical Sample—A testing method which conforms to accepted principles of statistical sampling based on either the variables or attributes method. The following expressions are associated with statistical sample testing:

(a) **Method of Attributes**—A statistical sample testing method in which only the percent of meters tested found outside certain accuracy limits is used for determining the quality or accuracy of the entire group of meters;

(b) **Method of Variables**—A statistical sample testing method in which the accuracy of each meter tested is used in the total results for determining the quality or accuracy of the entire group of meters;

(c) **Bar X**—A mathematical term used to indicate the average accuracy of a group of meters tested;

(d) **Sigma**—A mathematical term used to indicate the dispersion of the test results about the average accuracy (Bar X) of a group of meters tested.

Thermocouple—A pair of dissimilar conductors so joined that two junctions are formed. An electromotive force is developed by the thermoelectric effect when the two junctions are at different temperatures.

Thermoelectric Effect (Seebeck Effect)—One in which an electromotive force results from a difference of temperature between two junctions of dissimilar metals in the same circuit.

Thermoelectric Laws—(1) The thermoelectromotive force is, for the same pair of metals, proportional through a considerable range of temperature to the excess of temperature of the junction over the rest of the circuit. (2) The total thermoelectromotive force in a circuit is the algebraic sum of all the separate thermoelectromotive forces at the various junctions.

Three-Wire System (Direct Current, Single-Phase, or Network Alternating Current)—A system of electric supply comprising three conductors, one of which, known as the neutral wire, is generally grounded and has the same approximate voltage between it and either of the other two wires (referred to as the outer or "hot" conductors). Part of the load may be connected directly between the outer conductors; the remainder is divided as evenly as possible into two parts, each of which is connected between the neutral and one outer conductor.

Time Division Multiplication—An electronic measuring technique which produces an output signal proportional to two inputs, for example, voltage and current. The width or duration of the output signal is proportional to one of the input quantities; the height is proportional to the other. The area of the signal is then proportional to the product of the two inputs, for example, voltage and current.

Time-of-Use Metering—A metering method which records demand during selected periods of time so consumption during different time periods can be billed at different rates.

Torque of an Instrument—The turning moment produced by the electric quantity to be measured acting through the mechanism.

Total Harmonic Distortion (THD)—The ratio of the root-mean-square of the harmonic content (excluding the fundamental) to the root-mean-square value of the fundamental quantity, expressed as a percentage. (ANSI C12.1 definition.)

Transducer—A device to receive energy from one system and supply energy, of either the same or a different kind, to another system, in such a manner that the desired characteristics of the energy input appear at the output.

Transformer—An electric device without moving parts which transfers energy from one circuit to one or more other circuits by means of electromagnetic fields. The name implies, unless otherwise described, that there is complete electrical isolation among all windings of a transformer, as contrasted to an autotransformer.

Transformer Ratio—A ratio that expresses the fixed relationship between the primary and secondary windings of a transformer.

Transformer-Rated Meter—A watthour meter that requires external instrument transformer(s) to isolate or step-down the current and possibly the voltage.

VAR—The term commonly used for voltampere reactive.

VARhour Meter—An electricity meter that measures and registers the integral, with respect to time, of the reactive power of the circuit in which it is connected. The unit in which this integral is measured is usually the kiloVARhour.

Volt—The practical unit of electromotive force or potential difference. One volt will cause one ampere to flow when impressed across a one ohm resistor.

Voltampere—Voltamperes are the product of volts and the total current which flows because of the voltage. See Power, Apparent.

Voltage Circuit—The internal connections of the meter, part of the measuring element and, in the case of electronic meters, part of the power supply, supplied with the voltage of the circuit to which the meter is connected.

Voltage Transformer—An instrument transformer intended for measurement or control purposes which is designed to have its primary winding connected in parallel with a circuit, the voltage of which is to be measured or controlled.

Watt—The practical unit of active power which is defined as the rate at which energy is delivered to a circuit. It is the power expended when a current of one ampere flows through a resistance of one ohm.

Watthour—The practical unit of electric energy which is expended in one hour when the average power during the hour is one watt.

Watthour Meter—An electricity meter that measures and registers the integral, with respect to time, of the active power of the circuit in which it is connected. This power integral is the energy delivered to the circuit during the interval over which the integration extends, and the unit in which it is measured is usually the kilowatthour.

Watthour Meter Portable Standard—A special watthour meter used as the reference for tests of other meters. The standard has multiple current and voltage coils or electronic equivalents, so a single unit may be used in the field or in the shop for tests of any normally rated meter. The portable standard watthour meter is designed and constructed to provide better accuracy and stability than would normally be required in customer meters. The rotating standard has an electromechanical dial rotating at a specified watthour per revolution; the solid-state standard has a digital display of 1 watthour per revolution, or, essentially, a measured watthour.

CHAPTER 3

MATHEMATICS FOR METERING
(A Brief Review)

BASIC LAWS OF EQUATIONS

AN EQUATION is a statement of equality in mathematical form. In the study of electricity one of the most familiar equations is the expression of Ohm's Law for DC circuits:

$$V = IR$$

Where: V = voltage in volts
I = current in amperes
R = resistance in ohms

This law, in equation form, states that the voltage is equal to the current multiplied by the resistance.

To understand equations and to make them useful, certain rules must be remembered. One important rule states that when the identical operation is performed on both sides of the equal sign, the equation remains true.

If both sides of the equation are multiplied by the same quantity or divided by the same quantity, the equation is still true, as shown in the following examples.

With the equation $I = \frac{V}{R}$, multiply both sides by R to give

$$I \times R = \frac{V}{R} \times R$$

which simplifies to $IR = V$, since $\frac{R}{R} = 1$.

With the equation $IR = V$, if the value of R is wanted, divide both sides by I to give

$$\frac{IR}{I} = \frac{V}{I}$$

which simplifies to

$$R = \frac{V}{I}$$

The same quantity may be added to or subtracted from both sides of an equation without violating the state of equality.

For example, in a parallel circuit the total current is equal to the sum of the currents in the branches. With three resistors connected in parallel, the equation for the total circuit current may be expressed as follows:

$$I_{Total} = I_1 + I_2 + I_3$$

To determine the value of I_2, subtract I_1 and I_3 from both sides of the equation:

$$I_{Total} - I_1 - I_3 = I_1 + I_2 + I_3 - I_1 - I_3$$

which simplifies to

$$I_{Total} - I_1 - I_3 = I_2$$

The preceding example illustrates another general rule which states that any complete term may be shifted from one side of an equation to the other by changing its sign. This must be a complete term or the equation is no longer true. In the example, the $+I_1$ and $+I_3$ terms were shifted from the right to left side where they became negative.

To summarize:

If $x = 2y$, and C is any constant except zero, then the following equations are also true:

$$x + C = 2y + C$$
$$x - C = 2y - C$$
$$Cx = 2Cy$$
$$\frac{x}{C} = \frac{2y}{C}$$

Parentheses

In an expression such as $IR_1 + IR_2 + IR_3$, the subscripts 1, 2, and 3 after the symbol R indicate that R does not necessarily have the same value in each term. Since the symbol I does not have subscripts, it does have the same value in each term. Such a series can be written $I(R_1 + R_2 + R_3)$ which means that the total quantity inside the parentheses is to be multiplied by I.

The equation $V = IR_1 + IR_2 + IR_3$ states that the voltage across three resistors in series is equal to the sum of the products of the current times each of the resistances. If V, R_1, R_2, and R_3 are all known and the value of I is wanted, the equation may be rearranged as follows:

$$V = IR_1 + IR_2 + IR_3$$

$$V = I(R_1 + R_2 + R_3)$$

Dividing both sides by $(R_1 + R_2 + R_3)$ gives

$$\frac{V}{(R_1 + R_2 + R_3)} = I$$

When removing parentheses, pay attention to the laws of signs which are summarized as follows:

$$a \times b = ab$$
$$a \times (-b) = -ab$$
$$-a \times b = -ab$$
$$-a \times (-b) = ab$$

No sign before a term implies a + sign.

A minus sign before a parenthetical expression is equivalent to multiplication by –1 and means all signs within the parentheses must be changed when the parentheses are removed.

THE GRAPH

A graph is a pictorial representation of the relationship between the magnitudes of two quantities. A graph may represent a mathematical equation, or the relationship between the quantities may be such that it cannot be expressed by a simple equation.

An example of a graph which may be used in metering is the calibration curve for an indicating instrument. Figure 3-1 shows a typical graph of voltmeter corrections. When the voltmeter reads 120 volts, reference to the correction curve shows that at this point, marked × in Figure 3-1, the correction to be applied is +1 volt and the true voltage is 121 volts. With a scale reading of 100 volts, the correction is +0.5 volts, shown by ○ and the true voltage is 100.5. With a scale reading of 70 volts, the correction is −0.5 volts, shown by □, to give 69.5 true volts.

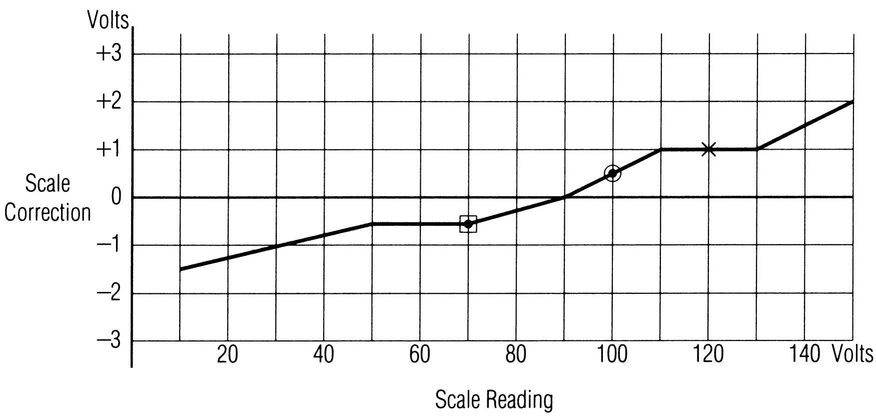


Figure 3-1. Graph of Voltmeter Corrections.

The sine wave has important applications in alternating-current circuit theory. The equation of a sine wave, $y = \sin x$, is shown graphically in Figure 3-2. The x quantity is commonly expressed in angular degrees or radians and the y values which are plotted on the graph are the sine values of the corresponding angles. Thus, for any particular angular value, it is possible to use the graph to determine its sine. For example, the sine of 30 degrees is equal to 0.5, as shown by the dotted lines on Figure 3-2.

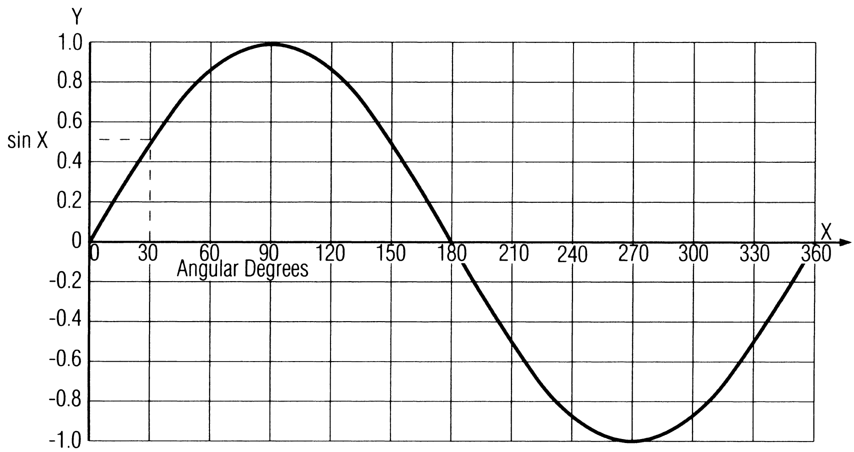


Figure 3-2. Graph of Sine Wave.

THE RIGHT TRIANGLE

A right triangle is a triangle having one right (90°) angle. The side opposite the right angle is termed the hypotenuse (c) of the triangle and the two sides forming the right angle are known as the legs (a and b) of the triangle. In every right triangle a definite relation exists between the sides of the triangle, so that when the lengths of two of the sides are known, the length of the third can be calculated using the right triangle formula. Mathematically this relationship is stated in the formula:

$$c^2 = a^2 + b^2$$

The relationship between the sides of the right triangle in Figure 3-3 are:

$$a^2 = c^2 - b^2 \text{ or } a = \sqrt{c^2 - b^2}$$
$$b^2 = c^2 - a^2 \text{ or } b = \sqrt{c^2 - a^2}$$
$$c^2 = a^2 - b^2 \text{ or } c = \sqrt{a^2 - b^2}$$

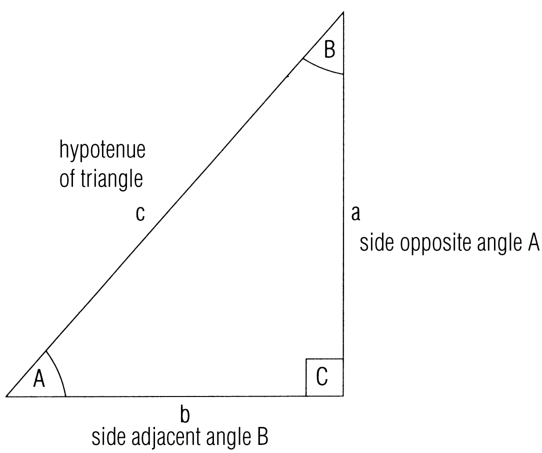


Figure 3-3. The Right Triangle.

TRIGONOMETRIC FUNCTIONS

Sine, cosine, and tangent are three of the six relationships existing between the sides of a right triangle. The six possible ratios between the sides of a right triangle are called trigonometric functions. In the solution of alternating-current problems requiring the use of trigonometric functions, the following tabulation of their definitions and relationships will be useful.

In the right triangle of Figure 3-3, side *a* is opposite angle *A*; side *b* is adjacent to angle *A*; side *a* is adjacent to angle *B*; and side *b* is opposite angle *B*. The ratios between the length of sides of the triangle determine the trigonometric functions of the angle *A* follows:

By definition, the ratios are named:

$$\frac{a}{c} = \frac{\text{opposite}}{\text{hypotenuse}} = \text{sine } A \textit{ or } \sin A$$

$$\frac{b}{c} = \frac{\text{adjacent}}{\text{hypotenuse}} = \text{cosine } A \textit{ or } \cos A$$

$$\frac{a}{b} = \frac{\text{opposite}}{\text{adjacent}} = \text{tangent } A \textit{ or } \tan A$$

Similarly:

$$\cos A = \frac{\mathrm{b}}{\mathrm{c}} = \frac{\mathrm{b} \times \mathrm{a}}{\mathrm{c} \times \mathrm{a}} = \frac{\frac{\mathrm{a}}{\mathrm{c}}}{\frac{\mathrm{a}}{\mathrm{b}}} = \frac{\sin A}{\tan A}$$

$$\tan A = \frac{\mathrm{a}}{\mathrm{b}} = \frac{\frac{\mathrm{a}}{\mathrm{c}}}{\frac{\mathrm{b}}{\mathrm{c}}} = \frac{\sin A}{\tan A}$$

While $\frac{a}{c}$ is the sine of *A*, it is also the cosine of *B*, since *a* is adjacent to angle *B*. Therefore, it will be seen that:

$$\sin A = \cos B$$
$$\cos A = \sin B$$

Numerical values for the functions of every angle are computed from the ratios of the sides of a right triangle containing that angle. In a right triangle, which is a triangle containing one right (90°) angle, the sum of the other two angles must equal 90°, since the sum of the three angles of any triangle must be 180°. Also, the sum of the squares of the two shorter sides must equal the square of the longer side or hypotenuse (the side opposite the 90° angle). *Regardless of the values which may be assigned to the sides of a right triangle, the ratio of any two sides for any given angle is always the same.*

The functions of 30° and 60° may be derived from Figure 3-4. The triangle ABC of Figure 3-4 is equilateral (all sides equal). Therefore, it is also equiangular (all angles equal), so that each angle equals 60°.

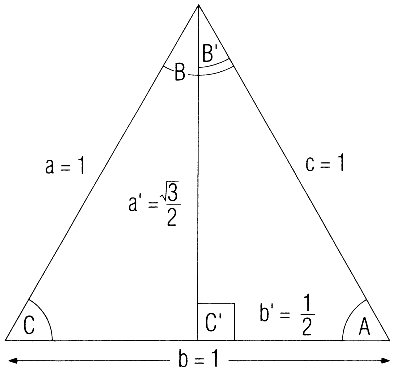


Figure 3-4. Functions of 30° and 60°.

If a line is drawn from the midpoint of the base to the vertex as shown, then $b' = 1/2$ and angle $B' = 30°$. In the triangle $AB'C'$:

$$\sin 30° = \cos 60° = \frac{b'}{c} = \frac{\frac{1}{2}}{1} = \frac{1}{2} = 0.500$$

$$\cos 30° = \sin 60° = \frac{a'}{c} = \frac{\sqrt{1^2 - \left(\frac{1}{2}\right)^2}}{1} = \frac{\frac{1}{2}\sqrt{3}}{1} = \frac{1}{2}\sqrt{3} = 0.866$$

$$\tan 30° = \frac{\sin 30°}{\cos 30°} = \frac{\frac{b'}{c}}{\frac{a'}{c}} = \frac{b'}{a'} = \frac{1}{\frac{1}{2}\sqrt{3}} = \frac{1}{\sqrt{3}} = 0.577$$

The functions of 45° may be derived from Figure 3-5. In this triangle, $a = b = 1$, and $c = \sqrt{a^2 + b^2} = \sqrt{2}$. From geometry, angle A must equal angle B, or one-half of 90°, or 45°.

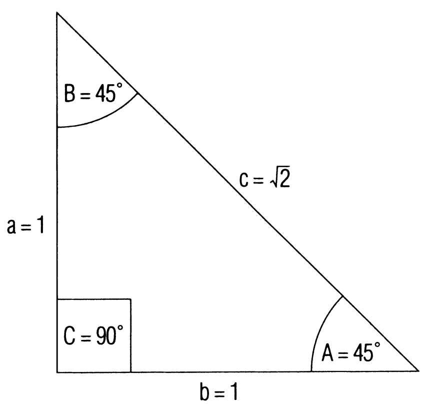


Figure 3-5. Functions of 45°.

$$\sin A = \sin B = \sin 45° = \frac{1}{\sqrt{2}} = \frac{\sqrt{2}}{2} = 0.707$$

$$\cos A = \cos B = \cos 45° = \frac{1}{\sqrt{2}} = \frac{\sqrt{2}}{2} = 0.707$$

$$\tan A = \tan B = \tan 45° = \frac{1}{1} = 1 = 1.000$$

To determine the functions of an angle greater than 90° and less than 180°, subtract the given angle from 180° and refer to a table of functions. For an angle greater than 180° and less than 270°, subtract 180° from the angle and refer to the table. For an angle greater than 270° and less than 360°, subtract the angle from 360° and refer to the table.

The algebraic sign of the functions of all angles between 0 and 90° is +; beyond 90° the signs can be determined from Table 3-1.

Table 3-1. Signs of the Functions of Angles.

	sin	cos	tan
1st Quadrant (0° to 90°)	+	+	+
2nd Quadrant (90° to 180°)	+	–	–
3rd Quadrant (180° to 270°)	–	–	+
4th Quadrant (270° to 360°)	–	+	–

From the preceding formulas, it is evident that if two sides of a right triangle are known, the third side and the angles can be calculated. Also, if one side and either angle A or B are known, the other sides and angle can be calculated.

Example 1:

To find a, given c and b: $a = \sqrt{c^2 - b^2}$

To find a, given c and A: $a = c \times \sin A$

To find b, given a and A: $b = \dfrac{a}{\tan A}$

To find B, given a and c: $B =$ angle whose cosine is $\frac{a}{c}$

In electric circuits with single non-distorted frequencies, the voltamperes, watts, and VARs are in proportion to the sides of a right triangle and may be represented as shown in Figure 3-6. Trigonometry may also be used to calculate these quantities.

$$\text{Power factor} = \text{cosine of phase angle } \theta = \frac{\text{watts}}{\text{voltamperes}}$$

Example 2: Voltmeter reads 120, ammeter 5, wattmeter 300.

$$\text{pf} = \frac{300}{120 \times 5} = 0.5$$

Power factor = 50%.

In the above example a lagging or leading power factor is not specified because it is unknown whether the load is inductive or capacitive. If the load is inductive, the power factor is lagging, and if the load is capacitive, the power factor is leading. This topic is covered in more detail in Chapter 4.

From Figure 3-6:

$$\text{Tangent of phase angle: } \tan\theta = \frac{\text{VARs}}{\text{watts}} = \frac{\text{VARhours}}{\text{watthours}}$$

Example 3: VARhour meter reads 3733, watthour meter 9395, what is the power factor?

$$\frac{3733}{9395} = 0.3973 = \text{tangent of phase angle } \theta = \text{tangent } 21.7°.$$

Power factor = cosine of phase angle θ = cos 21.7° = 0.93 or 93%.

To find watts, given voltamperes and VARs:

$$\text{watts} = \sqrt{(\text{voltamp})^2 - (\text{VARs})^2}$$

To find power factor, given VARs and voltamperes:

$$\text{Power factor} = \text{cosine of angle whose sine} = \frac{\text{VARs}}{\text{voltamp}}$$

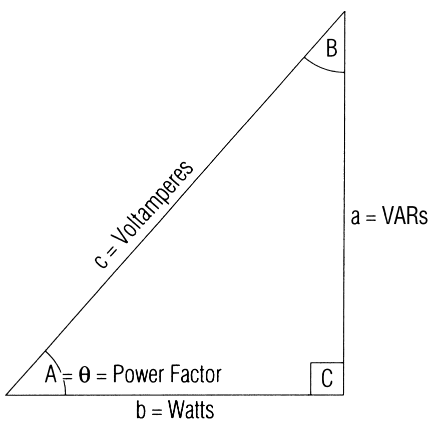


Figure 3-6. Relationship of Right Triangle to Voltamperes, Watts, and VARs.

To find VARs, given power factor and watts:

$$\theta = \text{angle whose cosine equals the power factor}$$

$$\text{VARs} = \text{watts} \times \tan\theta$$

To find voltamperes, given power factor and VARs:

$$\theta = \text{angle whose cosine equals the power factor}$$

$$\text{voltamperes} = \frac{\text{VARs}}{\sin\theta}$$

SCIENTIFIC NOTATION

Scientific notation is a form of mathematical shorthand. It is a method of indicating a number having a large number of zeros before or after the decimal point and it is based on the theory of exponents. Some powers of ten are shown in Table 3-2.

Any number may be expressed as a power of ten by applying the following rules:

1. To express a decimal fraction as a whole number times a power of ten, move the decimal point to the right and count the number of places back to the original position of the decimal point. The number of places moved is the correct negative power of ten.

Example 4:

$$0.00756 = 7.56 \times 10^{-3}$$
$$0.000095 = 9.5 \times 10^{-5}$$
$$0.866 = 86.6 \times 10^{-2}$$
$$0.0866 = 86.6 \times 10^{-3}$$

2. To express a large number as a smaller number times a power of ten, move the decimal point to the left and count the number of places back to the original position of the decimal point. The number of places moved is the correct positive power of ten.

Table 3-2. Powers of Ten.

Number	Power of Ten	Expressed in English	Prefix
0.000001	10^{-6}	ten to the negative sixth power	micro
0.00001	10^{-5}	ten to the negative fifth power	
0.0001	10^{-4}	ten to the negative fourth power	
0.001	10^{-3}	ten to the negative third power	milli
0.01	10^{-2}	ten to the negative second power	centi
0.1	10^{-1}	ten to the negative first power	deci
1.0	10^{0}	ten to the zero power	
10.0	10^{1}	ten to the first power	deca
100.0	10^{2}	ten to the second power	hecto
1000.0	10^{3}	ten to the third power	kilo
10000.0	10^{4}	ten to the fourth power	
100000.0	10^{5}	ten to the fifth power	
1000000.0	10^{6}	ten to the sixth power	mega

Example 5:

$$
\begin{aligned}
746. &= 7.46 \times 10^2 \\
95. &= 9.5 \times 10^1 \\
866. &= 86.6 \times 10^1 \\
8{,}660. &= 8.66 \times 10^3
\end{aligned}
$$

COMPLEX NUMBERS

Complex numbers are a special extension of our real number system. All complex numbers can be represented as points in the complex plane as shown in Figure 3-7 below. The real axis, horizontal from left to right, can only represent real numbers. The *j*– or imaginary axis, vertical from bottom to top, can only represent imaginary numbers. For all other complex numbers having a real part and an imaginary part, we can plot their coordinates in the complex plane as shown below.

COMPLEX NUMBERS IN RECTANGULAR FORM

In general, all complex numbers can be expressed in the form $z = x + jy$. This is called rectangular form. The real number x is called the "real part" of the complex number z. The real number y is called the "imaginary part" of the complex number z. The imaginary operator is defined as $j = \sqrt{-1}$. It too is a complex number $z = 0 + j1 = j$. You should convince yourself that $j^2 = -1$. Note for the complex number $z = 1 + j1$ in Figure 3-7, the real numbers $x = 1$ and $y = 1$ correspond to coordinates (1,1) in the complex plane. The coordinates (1,1) pinpoint the complex number z in the complex plane just like we use latitude and longitude to pinpoint a specific location on the earth's surface. Formally,

$$x = \text{Real part } \{z\} = \Re\{z\}$$

$$y = \text{Imaginary part } \{z\} = \Im\{z\}$$

Now that we understand how we define complex numbers, and what they look like in the complex plane, we next need to learn how to add, subtract, multiply, and divide complex numbers.

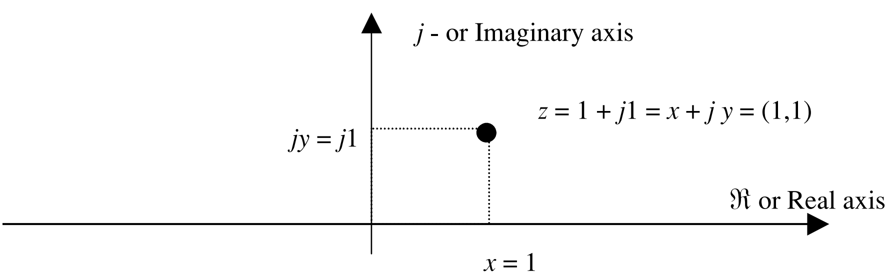


Figure 3-7. Complex Number $z = 1 + j1$ Represented by a Single Point in the Complex Plane.

ADDITION AND SUBTRACTION OF COMPLEX NUMBERS

The addition and subtraction of complex numbers is easily done when the complex numbers are expressed in rectangular form. To add two complex numbers, add the real parts and the imaginary parts separately.

Example 6: If $z_1 = 2 + j3$ and $z_2 = -5 - j4$, then find $z_1 + z_2$.
Solution: $z_1 + z_2 = (2 - 5) + j(3 - 4) = -3 + j(-1) = -3 - j1$.

To subtract the same two complex numbers, subtract the real parts and the imaginary parts separately.

Example 7: If $z_1 = 2 + j3$ and $z_2 = -5 - j4$, then find $z_1 - z_2$.
Solution: $z_1 - z_2 = (2 - (-5)) + j(3 - (-4)) = (2 + 5) + j(3 + 4) = 7 + j7$.

MULTIPLICATION OF COMPLEX NUMBERS

The multiplication of complex numbers is more easily done when the complex numbers are expressed in polar form. Although we don't know what polar form is yet, let us look at how to multiply two complex numbers expressed in rectangular form. If $z_1 = a + jb$ and $z_2 = c + jd$, then

$$\begin{aligned} z_1 z_2 &= (a + jb)(c + jd) \\ &= ac + jad + jbc + j^2bd \\ &= ac + jad + jbc + (-1)bd \\ &= (ac - bd) + j(ad + bc) \end{aligned}$$

Example 8: If $z_1 = a + jb = 7 + j1$ and $z_2 = c + jd = -3 + j8$, then find $z_1 z_2$.
Solution: $z_1 = a + jb = 7 + j1$ and $z_2 = c + jd = -3 + j8$, then $z_1 z_2 = (-21 - 8) + j(56 + (-3)) = -29 + j53$. Although this is not difficult, it is a bit tedious.

Example 9: If $z = 0 + jb$, then what is $z^2 = z{\cdot}z$?
Solution: $z^2 = z{\cdot}z = (0 + jb)(0 + jb) = 0 + 0 + 0 + j^2b^2 = -b^2$.

DIVISION, CONJUGATION, AND ABSOLUTE VALUE OF COMPLEX NUMBERS

Dividing two complex numbers in rectangular form is very tedious. In virtually all cases of interest, we will not need to divide complex numbers in rectangular form. This will become clear once we understand how to represent complex numbers in polar form which appears in the next section.

The complex conjugate of $z = x + jy$, called z^* or $\bar{z}$, is defined as

$$z^* = \bar{z} = x - jy$$

In other words, z^* is nothing more than z with its imaginary part "changed in sign." In Figure 3-8 below, it is easy to see that z^* is the reflection of z about the x axis. Another way to say this is that z^* is the "mirror image" of z.

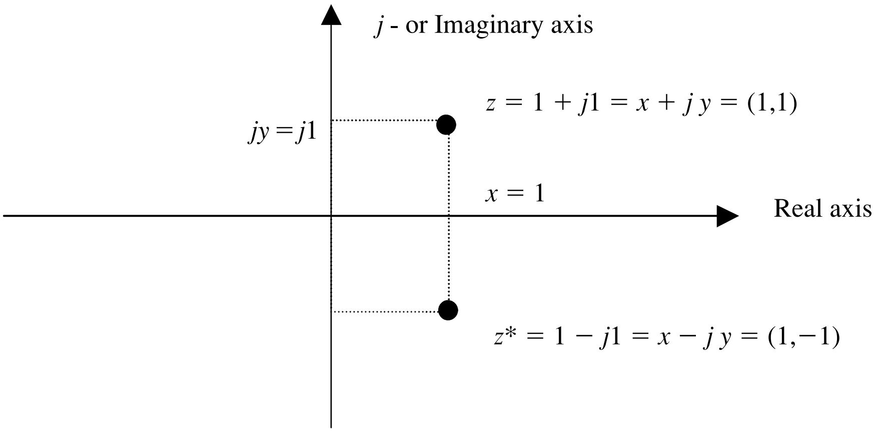


Figure 3-8. Complex Conjugate of *z* is *z*.*

Example 10: What is the conjugate of $z = -4 - j5$?
Solution: $z^* = -4 - j(-5) = -4 + j5$.

Example 11: What is the conjugate of $z = 12$?
Solution: Since $z = 12$ is the same as $z = 12 + j0$, then $z^* = 12 - j0 = 12$. Thus, the conjugate of a complex number with no imaginary part is just that number.

Example 12: What do we get if we compute the product of z and its conjugate z^*?
Solution: If $z = x + jy$ and $z^* = x - jy$, then $zz^* = (x + jy)(x - jy) = x^2 - jxy + jyx - j^2y^2 = x^2 + y^2$ since the second and third terms cancel each other. In the next section, you will see that $zz^* = x^2 + y^2$ is a real and positive number. This real and positive number is related to $|z|$ discussed below.

COMPLEX NUMBERS WRITTEN IN POLAR FORM

When a complex number z is expressed by a vector having a length $|z|$ at a given angle θ with the positive real axis, then the complex number z is said to be written in polar form. The length $|z|$ is also known as the absolute value, magnitude, or modulus of the complex number z.

A complex number z written in rectangular and polar form are related in the following way

$$z = x + jy = |z| \underline{/\theta}$$

$$x = |z| \cos\theta \qquad y = |z| \sin\theta$$

and

$$|z| = \sqrt{x^2 + y^2} \qquad \theta = \tan^{-1}\frac{y}{x}$$

where the term $\tan^{-1}$ is referred to as inverse tangent, and $\tan^{-1}\frac{y}{x}$ defines the angle whose tangent is $\frac{y}{x}$.

Most engineering calculators have built-in functions for these relationships. Note that the magnitude of the complex number z, $|z|$, is the distance from the origin to the point z in the complex plane. Figure 3-9 below provides additional examples.

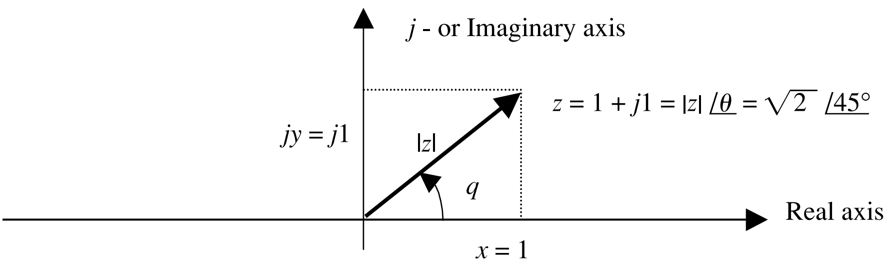


Figure 3-9. Complex Number $z = 1 + j1$ Represented in Rectangular and Polar Forms.

Example 13: Write the imaginary number $z = j$ in polar form.

Solution: Since $z = j = \sqrt{-1} = 0 + j1$, then $|z| = \sqrt{(0^2 + 1^2)} = 1$. What is the angle θ? It is the inverse tangent of the imaginary part divided by the real part of z. That is, $\theta = \tan^{-1}(1/0)$. What angle does θ make with the positive real axis? What is the angle from the positive real axis to the positive imaginary axis? We must move through the angle of 90°. Thus, $z = j = \sqrt{-1} = 0 + j1 = 1\ \angle 90°$.

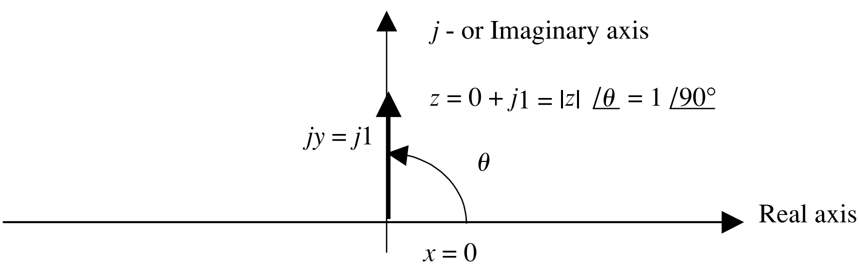


Figure 3-10. A Complex Number $z = j$ Represented in Rectangular and Polar Forms.

Example 14: Write the imaginary number $z = -1$ in polar form.

Solution: Since $z = -1 = -1 + j0$, then $|z| = \sqrt{[(-1)^2 + 0^2]} = 1$. What is the angle θ? It is the inverse tangent of the imaginary part divided by the real part of z. That is, $\theta = \tan^{-1}(0/{-1})$. What angle does θ make with the positive real axis? What is the angle from the positive real axis to the negative real axis? We must move through the angle of $\pm 180°$. Thus, $z = -1 = -1 + j0 = 1\ \angle \pm 180°$. Note that there are two ways to get from the positive real axis to the negative real axis. One way is 180° in the counter-clockwise direction. Similarly, and just as correct, is 180° in the clockwise direction. This is the reason for the $\pm 180°$.

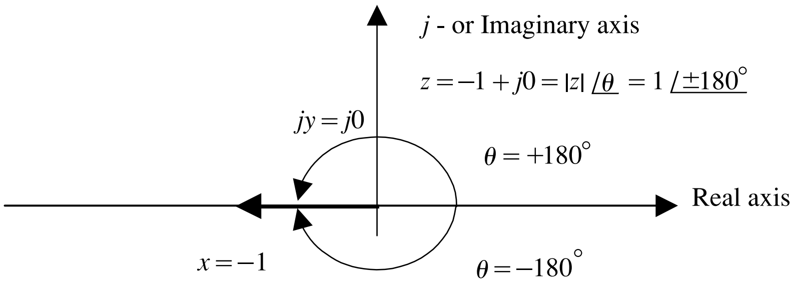


Figure 3-11. Complex Number $z = -1$ Represented in Rectangular and Polar Forms.

Example 15: Write the imaginary number $z = 1$ in polar form.

Solution: Since $z = 1 = 1 + j0$, then $|z| = \sqrt{[(1)^2 + 0^2]} = 1$. What is the angle θ? It is the inverse tangent of the imaginary part divided by the real part of z. That is, $\theta = \tan^{-1}(0/1)$. What angle does θ make with the positive real axis? What is the angle from the positive real axis to the positive real axis? We must move through the angle of 0°! Thus, $z = 1 = 1 + j0 = 1 \underline{/0°}$.

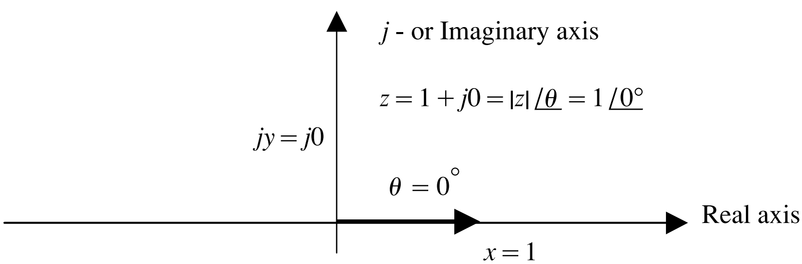


Figure 3-12. Complex Number $z = 1$ Represented in Rectangular and Polar Forms.

Now that we understand how to convert a complex number z from rectangular to polar form, we can revisit the idea of how to multiply and divide complex numbers.

MULTIPLICATION OF COMPLEX NUMBERS IN POLAR FORM

Multiplication and division of complex numbers is easier when both are written in polar form. Why? *To multiply two complex numbers, multiply their magnitudes (absolute values) and add their angles.* If we have two complex numbers, $z_1 = |z_1| \underline{/\theta_1}$ and $z_2 = |z_2| \underline{/\theta_2}$, then

$$z_1 z_2 = |z_1||z_2| \angle(\theta_1 + \theta_2)$$

Example 16: Let $z_1 = 2 + j3$ and $z_2 = -4 - j5$, find the product $z_1 z_2$.

Solution: Convert z_1 and z_2 to polar form. $|z_1| = \sqrt{(2^2 + 3^2)} = \sqrt{13} \approx 3.61$. The angle of z_1 is $\theta_1 = \tan^{-1}(3/2) = 56.3°$. $|z_2| = \sqrt{[(-4)^2 + (-5)^2]} = \sqrt{41} \approx 6.40$. The angle of z_2 is $\theta_2 = \tan^{-1}(-5/-4) = 231.3°$.

$$z_1 z_2 = |z_1||z_2| \underline{/\theta_1} + \theta_2 = (3.61)(6.40)\ \underline{/56.3^\circ} + 231.30 = 23.10\ \underline{/287.6^\circ} = 7 - j22$$

When finding the arc-tangent or inverse tangent of an angle (i.e., $\tan^{-1}\theta$), most calculators will return a "principal" angle between −90° and +90°. Thus, as long as a complex number is in quadrant I or IV, no adjustment is ever necessary. But, *if the complex number is in quadrants II or III, then the 180° adjustment may be necessary.*

In the above example, the use of a calculator in determining the angle θ_2 will result in $\theta_2 = 51.3°$. However, the complex number z_2 is in quadrant III. When $x < 0$ and $y < 0$, you are in quadrant III and your angle must lie between 180° and 270°. To determine the correct angle in quadrant III from the angle your calculator returned, add 180°. Thus, 51.3° + 180° = 231.3°, the correct answer.

DIVISION OF COMPLEX NUMBERS IN POLAR FORM

In a similar way, *dividing two complex numbers requires dividing the magnitudes (absolute values) and subtracting the angles.* If we have two complex numbers, $z_1 = |z_1|\ \underline{/\theta_1}$ and $z_2 = |z_2|\ \underline{/\theta_2}$, then

$$\frac{z_1}{z_2} = \frac{|z_1|}{|z_2|} \angle(\theta_1 - \theta_2)$$

Example 17: Let $z_1 = 2 + j3$ and $z_2 = -4 - j5$, find z_1/z_2.

Solution: From the previous example,

$$\frac{z_1}{z_2} = \frac{3.61}{6.40} \angle(56.3^\circ - 231.3^\circ) = 0.56\ \underline{/-175^\circ} = -0.56 - j0.05.$$

Example 18: Let $z_1 = 2 - j6$ and $z_2 = 5\underline{/30^\circ}$, find $z_1 z_2$.

Solution: In general, when multiplying or dividing two complex numbers, both of them should be in polar form. The first one is not but the second is. First, convert z_1 to polar form. $z_1 = 6.32\ \underline{/-71.56^\circ}$ or $6.32\ \underline{/288.44^\circ}$; both are correct. Next, multiply the magnitudes and add the phase angles. So, $z_1 z_2 = (6.32)(5)\ \angle(288.44^\circ + 30^\circ) = 31.62\ \underline{/318.44^\circ}$ (or $-41.56°$) $= 23.66 - j20.98$.

Example 19: What is z_1/z_2?

Solution: Divide the magnitudes and subtract the phase angles. Then, $z_1/z_2 = (6.32)/(5)\ \angle(288.44^\circ + 30^\circ) = 1.26\ \underline{/258.44^\circ}$.

Example 20: Given three complex numbers, $z_1 = 6 - j2$, $z_2 = 7\underline{/15^\circ}$ and $z_3 = 10\ \underline{/2.2^\circ}$.

(a) Find $|z_1 z_2|$.

Solution: $|z_1 z_2| = |(6 - j2)(7\underline{/15^\circ})| = |(6.32\ \underline{/-18.4^\circ})(7\underline{/15^\circ})| = |(6.32)(7)| = 44.2$.

(b) Find z_2^*.

Solution: $z_2^* = (7\underline{/15^\circ})^* = (6.76 + j1.81)^* = 6.76 - j1.81 = 7\underline{/-15^\circ}$.

Is it by accident that $z_2 = 7\underline{/15^\circ}$ and $z_2^* = 7\underline{/-15^\circ}$? Refer to Figure 3-8. Plot a vector from the origin to z and another vector from the origin to z^*. What is the relationship between the angles of z and z^* when written in polar form? In polar form, $z = |z|\ \underline{/\theta}$ and $z^* = |z|\ \underline{/-\theta}$. So, the angles differ only in sign!

(c) Evaluate $z_1/(z_2 - z_3)$.

Solution: This is basically a division problem. Convert the numerator (i.e., the top) and the denominator (i.e., the bottom) to polar form. First, convert the numerator from rectangular to polar form. Then, convert the complex numbers in the denominator to rectangular form. Perform the subtraction in the denominator. Convert the denominator from rectangular form to polar form. Last, perform the division with numerator and denominator in polar form.

$z_1/(z_2 - z_3) = (6.32 \underline{/-18.4°})/[(6.76 + j1.81)-(9.99 + j0.38)] = (6.32 \underline{/-18.4°})/(-3.23 + j1.43) = (6.32 \underline{/-18.4°}) / (3.53 \underline{/156.2°}) = 1.79 \underline{/-174.6°} = -1.78 - j0.17$.

Example 21: What is the conjugate of $z = 8 \underline{/-48°}$?

Solution: $z^* = 8 \underline{/48°}$.

When adding or subtracting complex numbers, the rectangular form should be used because the real and imaginary parts can be added and subtracted separately. When multiplying or dividing complex numbers, the polar form should be used because the magnitudes are multiplied or divided and the angles are added or subtracted.

To understand and analyze alternating current circuits, it is mandatory to master the mathematics of complex numbers. When analyzing these circuits, the various techniques require changes between rectangular and polar format. Tables 3-3 and 3-4 provide examples of how the mathematics of this chapter relate to the representation of electrical components and circuit variables. The analysis of electrical circuits is reviewed in greater detail and is the topic of Chapter 4.

BASIC COMPUTATIONS USED IN METERING

Before presenting typical metering computations, the following definitions should be reviewed.

The percent registration of a meter is the ratio, expressed as a percent, of the registration in a given time to the true kilowatthours.

The percent error of a meter is the difference between its percent registration and one hundred percent.

The correction factor is the number by which the registered kilowatthours must be multiplied to obtain the true kilowatthours.

Table 3-5 illustrates the numerical relationships of these quantities.

Calculating Percent Registration Using A Rotating Standard

When no correction is to be applied to the rotating standard readings, the percent registration of the watthour meter under test is calculated as follows:

$$\text{Percent registration} = \frac{k_h \times r \times 100}{K_h \times R}$$

Table 3-3. Relationship of Registration, Percent Error, and Correction Factor.

Percent Registration	Percent Error	Correction Factor
100.4	+0.4	0.996
100.2	+0.2	0.998
100.0	0.0	1.000
99.8	−0.2	1.002
99.6	−0.4	1.004

The procedure may be simplified by introducing an additional symbol R_o where R_o is the number of revolutions the standard should make when the meter under test is correct. The values of R_o may be given to metering personnel in tabular form.

The number of revolutions of two watthour meters on a given load vary inversely with their disk constants.

$$\frac{R_o}{r} = \frac{k_h}{K_h} \qquad \text{Ro} = \frac{k_h \times r}{K_h}$$

Substituting R_o in the equation for percent registration:

$$\text{Percent registration} = \frac{R_o}{R} \times 100.$$

Example 23:

The watthour meter under test and the standard have the following constants:

Meter $k_h = 7.2$
Standard $K_h = 6\,^2/_3$

The number of revolutions of the meter under test, r, equals 10.

$$\text{Then } R_o = \frac{7.2 \times 10}{6\,^2/_3} = 10.80 \text{ revolutions.}$$

That is, for ten revolutions of the meter under test, the standard should make 10.80 revolutions. Assume the standard actually registered 10.87 revolutions. Then:

$$\text{Percent registration} = \frac{10.80}{10.87} \times 100 = 99.4\%.$$

It is frequently easier to calculate mentally the percent error of the meter, then add it algebraically to 100 percent to determine the percent registration of the meter.

$$\text{Percent error} = \frac{R_o - R}{R} \times 100.$$

Using the same values as in the preceding example, then,

$$\text{Percent error} = \frac{10.80 - 10.87}{10.87} \times 100 = -0.6\%, \text{ and}$$

$$\text{Percent registration} = 100.0 - 0.6 = 99.4\%.$$

When a correction is to be applied to the readings of the standard, the percent registration is calculated as follows:

If A = percent registration of the standard, then

$$\text{Percent meter registration} = \frac{k_h \times r \times A}{K_h \times R}.$$

Using the same values as in the preceding examples, and assuming the percent registration of the standard is 99.5%, then

$$\text{Percent meter registration} = \frac{7.2 \times 10 \times 99.5}{6\,^2\!/_3 \times 10.87} = 98.9\%.$$

To save time, the percent error of the rotating standard is calculated and applied to the indicated percent of meter registration to determine the true percent meter registration.

Percent meter registration = indicated percent meter registration + percent standard error. That is, the percent standard error is added to the apparent percent registration of the meter under test if the percent standard error is positive and subtracted if negative. Then, for this example

$$\text{Percent standard error} = 99.5\% - 100\% = -0.5\%.$$

Referring to computations made earlier, if a rotating standard with a −0.5% error is used, then percent registration of the meter is 99.4% − 0.5% = 98.9%. Use this method when the percent error does not exceed 3%.

Calculating Percent Registration Using Indicating Instruments

$$\text{Percent registration} = \frac{k_h \times r \times 3{,}600 \times 100}{P \times s}$$

Where P = true watts (corrected readings of instruments)
k_h = watthour constant of self-contained watthour meter
r = number of revolutions of meter disk
s = time in seconds for r revolutions

Example 24:

Let P = 7,200
k_h = 7.2
r = 10
s = 36.23

$$\text{Percent registration} = \frac{7.2 \times 10 \times 3{,}600 \times 100}{7{,}200 \times 36.23} = 99.4\%$$

The seconds for 100 percent accuracy (S_s) may be determined from:

$$S_s = \frac{3{,}600 \times r \times k_h}{P}$$

For 100 percent accuracy

$$S_s = \frac{3{,}600 \times 10 \times 7.2}{7{,}200} = 36.00 \text{ and}$$

Since percent registration $= \dfrac{S_s \times 100}{s}$

Percent registration $= \dfrac{36.00 \times 100}{36.23} = 99.4\%$

The correction for instrument error may be applied similarly to the correction for rotating standards, where *P* equals the observed reading of the wattmeter.

Assume the observed reading of a wattmeter is 7,200 watts and true watts are 7,236. Then the wattmeter indicates:

$$\frac{7{,}200}{7{,}236} = 99.5\% \text{ of true watts.}$$

This percent indication may be used for *A* in the formula:

Percent registration $= \dfrac{k_h \times r \times 3{,}600 \times A}{P \times S}$

Percent registration $= \dfrac{7.2 \times 10 \times 3{,}600 \times 99.5}{7{,}200 \times 36.23} = 98.9\%$

If the preceding meter had been a direct-current meter, the test could have been made with a voltmeter and ammeter.

Assume an observed ammeter reading of 30 amperes and true current is 30.2 amperes. Then:

Percent indication $= \dfrac{30}{30.2} \times 100 = 99.3\%$

Assume an observed voltmeter reading of a 240 volts, and true voltage is 239.5 volts. Then:

Percent indication $= \dfrac{240}{239.5} \times 100 = 100.2\%$

Indicated watts $= 240 \times 30 = 7{,}200$ watts

Actual watts $= 239.5 \times 30.2 = 7{,}233$ watts

Percent indication $= \dfrac{7{,}200}{7{,}233} \times 100 = 99.5\%$

Again, the 99.5% calculated could be used for *A* in the formula the same as the 99.5% obtained as the percent indication of the wattmeter.

In either case, the percent registration is the sum of the apparent percent indication and the percent error. The percent registration = 99.4% + (−0.5%) = 98.9%.

Register Formulas and Their Applications

R_r = register ratio
K_h = watthour constant
R_s = gear reduction between worm or spur gear on disk shaft and meshing gear wheel of register
K_r = register constant
R_g = gear ratio = $R_r \times R_s$
CTR = current transformer ratio
VTR = voltage transformer ratio
TR = transformer ratio (*CTR* × *VTR*)
PK_h = primary watthour constant = $K_h \times TR$

Example 25: Self-contained meter, $K_h = 7.2$, 100 teeth on first wheel or register, 1 pitch worm on shaft, register constant 10.

To find the Register Ratio:

$$R_r = \frac{10{,}000 \times K_r}{K_h \times R_s \times TR} = \frac{10{,}000 \times 10}{7.2 \times 100 \times 1} = 138\,^8/_9$$

To check the Register Constant:

$$K_r = \frac{K_h \times R_r \times R_s \times TR}{10{,}000} = \frac{7.2 \times 138\,^8/_9 \times 100 \times 1}{10{,}000} = 10$$

To determine the Gear Reduction:

$$R_g = R_r \times R_s$$

$$R_g = 138\,^8/_9 \times \frac{100}{1} = \frac{1{,}250}{9} \times 100 = 13{,}888\,^8/_9$$

Example 26: Transformer-rated meter installed with 400/5 (80/1) CTR, register constant (K_r) 100, $K_h = 1.8$, 100 teeth on first wheel, 2 pitch worm on shaft.

$$R_r = \frac{10{,}000 \times K_r}{PK_h \times R_s} = \frac{10{,}000 \times K_r}{(K_h \times TR) \times R_s} = \frac{10{,}000 \times 100}{(1.8 \times 80) \times \frac{100}{2}} = 138\,^8/_9$$

$$K_r = \frac{PK_h \times R_r \times R_s}{10{,}000} = \frac{(K_h \times TR) \times R_r \times R_s}{10{,}000}$$

$$= \frac{(1.8 \times 80) \times 138\,^8/_9 \times \frac{100}{2}}{10{,}000} = 100$$

$$R_g = 138\,^8/_9 \times \frac{100}{2} = \frac{1{,}250}{9} \times 50 = 6{,}944\,^4/_9$$

Example 27: Transformer rated meter installed with 50/5 (10/1) CTR, 14,400/120 (120/1) VTR, register constant (K_r) 1,000, $K_h = 0.6$, and 100 teeth on first wheel, with 1 pitch worm on shaft.

$$R_r = \frac{10{,}000 \times 1{,}000}{0.6 \times 10 \times 120 \times 100} = 138\,^8/_9$$

$$K_r = \frac{0.6 \times 10 \times 120 \times 138\,^8/_9 \times 100}{10{,}000} = 1{,}000$$

$$R_g = 138\,^8/_9 \times 100 = \frac{1{,}250}{9} \times 100 = 13{,}888\,^8/_9$$

CHAPTER 4
ELECTRICAL CIRCUITS

DIRECT CURRENT

INTRODUCTION TO DIRECT-CURRENT ELECTRIC CIRCUITS

DIRECT-CURRENT (DC) ELECTRIC CIRCUITS are those where the applied voltage and current do not change with time; they are constant or fixed values. An example of a DC electric circuit is one which contains a battery and other passive components. Your trusty flashlight or your car's starting circuit are examples.

Direct-current distribution systems do not exist in this country. However, high-voltage DC (HVDC) transmission systems do exist; the Pacific Intertie (i.e., the DC transmission line between the Pacific Northwest and California) and the multiple connections between Texas and the remainder of the United States are examples. One might wonder why we would want to study DC electric circuits at all? Direct-current circuit analysis techniques are basic to all types of electric circuits problems. These methods, if understood for DC electric circuits, can be directly applied to alternating-current (AC) electric circuits.

PHYSICAL BASIS FOR CIRCUIT THEORY

Electric circuit theory consists of taking real-world electrical systems, modeling them using mathematics, solving for the unknown variables using existing laws, and then analyzing the results to determine whether or not they are consistent with the original physical problem. In almost all cases, voltages and currents are the unknown variables of interest. Once all voltages and currents in an electric circuit are known, then other useful pieces of information can be calculated. Some of these include: instantaneous power, energy, active power, reactive power, apparent power, complex power, etc.

Current is the movement of charges with respect to time. That is, current is charges in motion, like water flowing through a pipe. Voltage is the work done by the electrical system in moving charges from one point to another in a circuit divided by the amount of charge. It is the force acting on the charges along a length of a conductor and is sometimes referred to as the electromotive force (emf). This is similar to the pressure required to deliver the water from a water tower to your home faucet.

RESISTANCE AND OHM'S LAW AS APPLIED TO DC CIRCUITS

Using the same analogy, when water flows through a pipe, there is friction or "resistance" to the water flow by the water pipe surfaces. The same thing occurs as the electrons attempt to flow through a conductor. Ohm's Law states that the current flowing in a DC circuit is directly proportional to the total voltage applied to the circuit and inversely proportional to the total circuit resistance.

$$I = \frac{V}{R} = \frac{\text{Volts}}{\text{Ohms}} = \text{Amperes (A)}$$

$$R = \frac{V}{I} = \frac{\text{Volts}}{\text{Amperes}} = \text{Ohms } (\Omega)$$

$$V = \text{IR} = \text{Amperes} \times \text{Ohms} = \text{Volts (V)}$$

Example: With a voltage of 112 V across a resistance of 8 Ω, what current would flow?

Solution: The voltage V and resistance R are given. We wish to solve for the current I. Using the first equation above, substitute the given values for V and R and solve for I.

$$I = \frac{V}{R} = \frac{112}{8} = 14 \text{ A}$$

Example: What resistance is necessary to obtain a current of 14 A at an applied voltage of 112 V?

Solution: The current I and voltage V are given. We wish to solve for the resistance R. Using the second equation above, substitute the given values for I and V and solve for R.

$$R = \frac{V}{I} = \frac{112}{14} = 8\ \Omega$$

Example: What applied voltage is required to produce a flow of 14 A through a resistance of 8 Ω?

Solution: The current I and resistance R are given. We wish to solve for the voltage V. Using the third equation above, substitute the given values for I and R and solve for V.

$$V = 14 \times 8 = 112 \text{ V}$$

The resistance of a piece of conductor is dependent on its diameter, length, and material. Conductor materials each have a physical property called resistivity. For example, copper is a better conductor than aluminum because it has a lower resistivity. For many types of conductors, the resistivity (resistance) is substantially constant with current, and thus, the current increases in direct proportion to the voltage applied across the conductor.

Example: The resistance of a copper wire 1 foot long and 1 circular mil (cmil) in cross-section is 10.371 Ω at 20°C (National Bureau of Standards). The value of 10.4 Ω is used for practical calculations.

The resistance, R, is equal to the length of the conductor multiplied by 10.4 and divided by the cross-sectional area

$$R = \frac{2 \times \ell \times 10.4}{A}\ \Omega$$

where the term ℓ indicates the length of the circuit in feet and A is the cross-sectional area with units of cmil. Note that the number of feet of wire in the circuit is double to account for the return.

What would be the voltage drop in a circuit of #12 conductor carrying 20 A for a distance of 50 feet? (The cross-sectional area of #12 copper wire is 6530 circular mils or 6.53 kcmils.) Using Ohm's Law,

$$V = IR = 20 \times \frac{2 \times 50 \times 10.4}{6530} = 3.18\ V$$

or approximately 2.65% on a 120 volt circuit.

KIRCHHOFF'S CURRENT LAW

For current to flow, there must be a closed path or circuit. A simple circuit can be used to illustrate this principle. In the flashlight circuit shown in Figure 4.2, the current passes from the positive terminal of the battery, moves through the wires to the lamp and then back to the negative post of the battery. The current measurement at the positive terminal of the battery is equal to the current measurement at the negative post. In other words, there is no current lost in the circuit. G.R. Kirchhoff (1824-87), a German physicist, discovered this principle in the late 1800s.

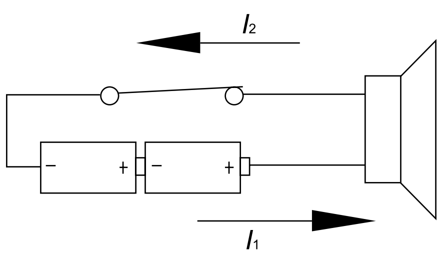


Figure 4-1. Flashlight Circuit.

Kirchhoff's Current Law (KCL) can be stated in three ways:

1. The sum of the currents leaving a junction of conductors is zero at all times.
2. The sum of the currents entering a junction of conductors is zero at all times.
3. The sum of the currents entering a junction of conductors is equal to the sum of the currents leaving the junction of conductors.

If this were not so, current would collect at the junction. Since we know from experiment that current cannot be continuously stored at, or removed from a junction, the law is true. In the flashlight circuit shown in Figure 4-1, it is obvious that the current flowing into the junction of the wire and lamp terminal are equal.

This simple circuit is fairly obvious. However, this principle provides a way to analyze more complicated circuits.

In Figure 4-2, two more lights have been added to the circuit shown in Figure 4-1. There are two junctions of conductors or nodes. If a negative value is arbitrarily assigned to current flowing into a node and a positive value to current flowing out from the node, the following equation can be written:

$$-I_1 + I_2 + I_3 + I_4 = 0$$

This principle can be used to solve complex circuits which will be demonstrated later in this chapter.

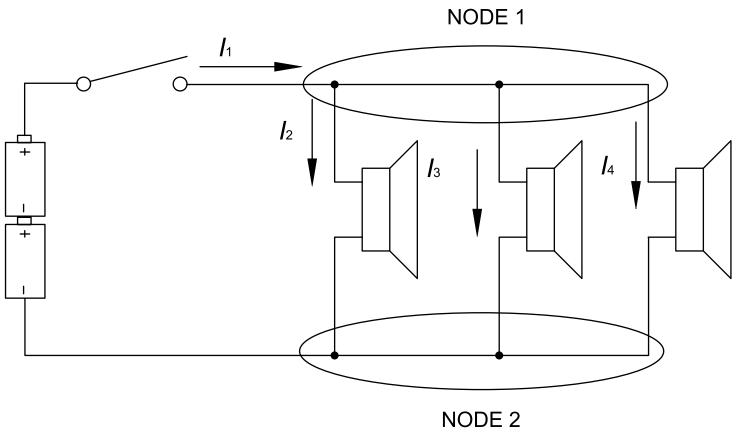


Figure 4-2. Multiple Light Circuit.

KIRCHHOFF'S VOLTAGE LAW

As in the analogy of water flowing through a pipe given at the beginning of this chapter, work is required to move charges around a circuit. The work is measured as a potential (voltage) difference between Points A and B in a circuit. Kirchhoff's Voltage Law (KVL) states that the algebraic sum of the voltages around any closed loop is equal to zero. If this were not so, a single point on a circuit could be at two different voltages at the same time relative to the same fixed reference point. Since experiment shows that each point can have only one voltage at any instant relative to a fixed reference point, the law is true.

In other words, the sum of the voltages around a circuit is equal to the supply voltage. Again referring to the Figure 4-3 Flashlight Circuit, since there is only one load on the circuit, all of the supply voltage is "dropped" across the light.

$$V_{\text{Lamp}} = V_{\text{Source}}$$

Subtracting V_{Lamp} from both sides yields:

$$0 = V_{\text{Source}} - V_{\text{Lamp}}$$

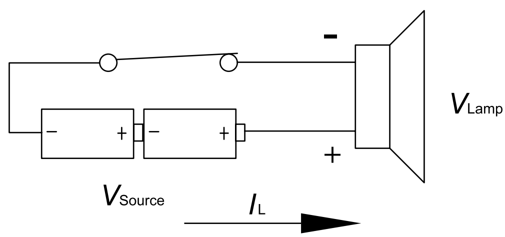


Figure 4-3. Flashlight Circuit.

Therefore the work generated by the batteries is equal to the light and heat emanated from the light bulb, and is necessary to sustain the current flow in the circuit. Another way to represent the light bulb is by showing it as a resistance to the work that the battery wants to do. The circuit can then be redrawn in figurative terms as shown in Figure 4-4. By using these symbols, the circuit can be diagramed more easily than drawing the actual devices. This law can be illustrated by solving for the current in the circuit shown in Figure 4-4.

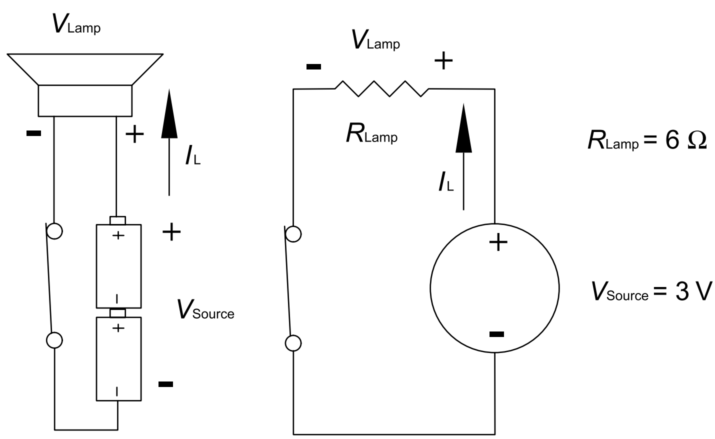


Figure 4-4. Flashlight Circuit Schematic.

$$0 = V_{\text{Source}} - V_{\text{Lamp}}$$

Using Ohm's Law, the current can be determined in the circuit.

$$V_{\text{Source}} = I_{\text{Lamp}} \times R_{\text{Lamp}} = V_{\text{Lamp}}$$

Substituting: $3\ V = I_{\text{Lamp}} \times 6\ \Omega \Rightarrow I_{\text{Lamp}} = \dfrac{3\ V}{6\ \Omega} = 0.5\ A$

The following problem will help drive home the laws just discussed.

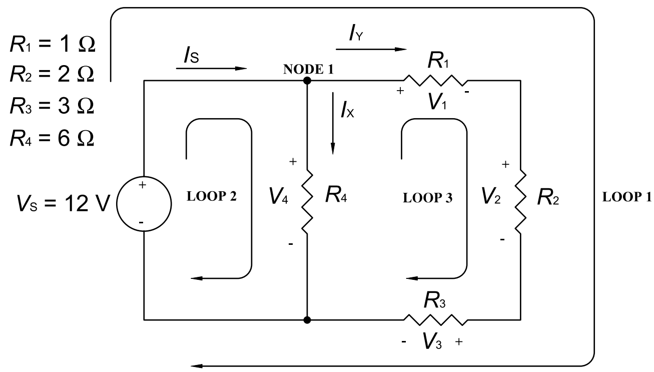


Figure 4-5. Schematic.

Determine the current and voltages I_S, I_X, I_Y, V_1, V_2, and V_3 for the circuit shown in Figure 4-5.

Solution:

Step 1: Arbitrarily assign directions for the currents in the circuit. In this case I_S is coming into Node 1, while I_X and I_Y are assumed out of Node 1.

Step 2: Assign voltage polarity markings (i.e., +, –) to each circuit element which is NOT a voltage source. Voltage sources have their own polarity markings. Note here that current always enters the positive terminal of a circuit element; this is called the passive sign convention.

Step 3: Apply Kirchhoff's Voltage Law. Therefore, the number of possible closed circuits or loops is found to be three. These are illustrated in Figure 4.6. However, any two of these three loops are sufficient to solve this circuit. Then the following equations can be written for Loop 1 and Loop 2 respectively:

$$0 = +V_S - V_1 - V_2 - V_3 \text{ and } 0 = +V_4 - V_S$$

or

$$V_S = V_1 + V_2 + V_3 \text{ and } V_S = V_4$$

Step 4: Apply Ohm's Law:

$$V_S = R_1 I_Y + R_2 I_Y + R_3 I_Y \text{ and } V_S = V_4 = R_4 \times I_X$$

Since each equation has a single unknown, we can solve each for the unknown currents I_X and I_Y.

$$I_X = \frac{V_S}{R_4} = \frac{12}{6} = 2\,A$$

$$V_S = R_1 I_Y + R_2 I_Y + R_3 I_Y = (R_1 + R_2 + R_3)\, I_Y$$

$$I_Y = \frac{V_S}{(R_1 + R_2 + R_3)} = \frac{12}{1+2+3} = \frac{12}{6} = 2\,A$$

Step 5: Knowing two of the three currents at Node 1, leaves only one unknown, I_S. Kirchhoff's Current Law can now be applied:

$$0 = -I_S + I_X + I_Y \text{ or } I_S = I_X + I_Y$$

Substituting and solving for I_S:

$$I_S = 2 + 2 = 4\,A$$

Step 6: Solve for the voltage drops V_1, V_2, and V_3 by Ohm's Law.

$$V_S = R_1 \times I_Y = 1 \times 2 = 2\,V;\; V_2 = R_2 \times I_Y = 2 \times 2 = 4\,V;$$

$$V_3 = R_3 \times I_Y = 3 \times 2 = 6\,V$$

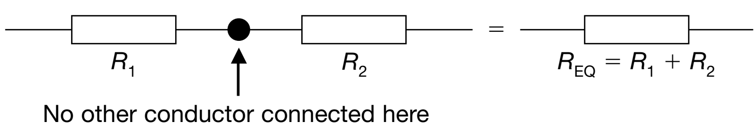
In general, resistances in a DC circuit can be connected in one of four ways: in series, in parallel, in series-parallel, or as a network of series and parallel circuits. In all cases, the equivalent resistance, R_{EQ}, seen by the source, is the total effect of all the resistances in a circuit opposing the source current flow.

RESISTANCES CONNECTED IN SERIES

When resistances are connected in series these rules apply:

1. The current in a series circuit is the same in all parts of the circuit.
2. The input or source voltage to a series circuit is equal to the sum of the voltage drops across all resistances in the circuit by KVL.
3. In a series circuit, the equivalent resistance is equal to the sum of the individual resistances since resistances in series are added.

How does one identify whether or not two resistors are "in series?" A resistor is a two-terminal electric circuit component. Its behavior is modeled by and subject to Ohm's Law. If two resistors are in series, then they will only share one of their terminals, and no other conductors will exist at that junction.



A series circuit consisting of three resistors is shown in Figure 4-6. According to Rule 1, the current *I* through the voltage source and three resistors will be the same. According to Rule 2, the total voltage drops across the 10, 20, and 30 Ω resistors must equal the source voltage. According to Rule 3, we can replace the three series resistors with one resistor having a value which is equal to their sum.

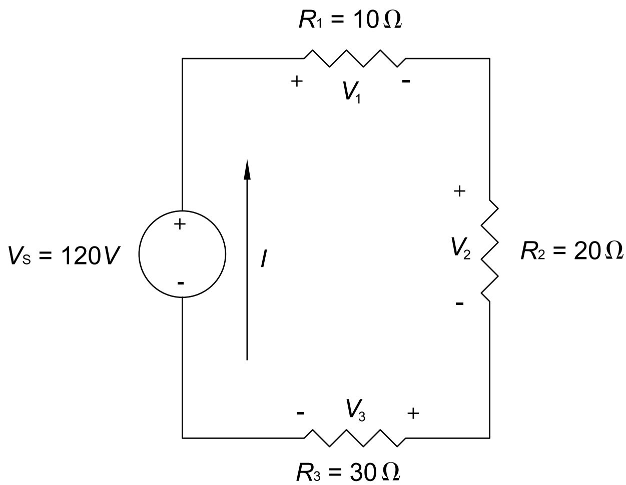


Figure 4-6. Resistors Connected in Series.

Solution:

Step 1. Find the total or equivalent resistance of the circuit.

$$R_{EQ} = R_{TOTAL} = R_1 + R_2 + R_3$$

$$\mathrm{R_{EQ}} = 10\,\Omega + 20\,\Omega + 30\,\Omega = 60\,\Omega$$

Step 2. Use Ohm's Law to find the current *I* passing through all circuit elements.

$$I = \frac{V_S}{R_{EQ}} = \frac{120}{60} = 2\,A$$

Step 3. Use Ohm's Law to find the voltage drop across each resistor and then verify that the sum of all voltage drops equals the source voltage.

$$V_{R_1} = IR_1 = (2)(10) = 20\,V$$

$$V_{R_2} = IR_2 = (2)(20) = 40\,V$$

$$V_{R_3} = IR_3 = (2)(30) = 60\,V$$

$$V_S = V_{R_1} + V_{R_2} + V_{R_3} = 20\,V + 40\,V + 60\,V = 120\,V$$

RESISTANCES CONNECTED IN PARALLEL

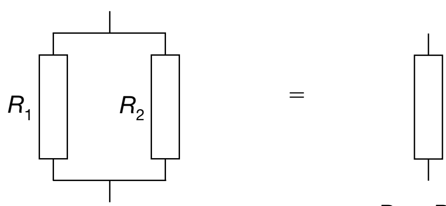
When resistances are connected in parallel:

1. The voltage drop across all resistors is the same.
2. The total current supplied by the source in a parallel circuit is the sum of the currents through all of the branches by KCL.
3. The equivalent resistance of a parallel circuit is always less than that of the smallest resistive branch.
4. The equivalent resistance of resistors connected in parallel equals one divided by the sum of the conductances connected in parallel.

$$R_{EQ} = \frac{1}{G_{EQ}} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_N}} = \frac{1}{G_1 + G_2 + G_3 + \cdots + G_N}$$

5. Conductance is a measure of how easily a current will flow through a conductor or component, and is the reciprocal of resistance, which is one divided by the resistance. As an example: If the resistance is 10 Ω, the conductance is 1/10 mho. (Mho is Ohm spelled backwards; one Mho = 1 Ω^{-1} = 1 Siemen.)
6. Another method for computing the equivalent resistance of a circuit composed of many parallel branches is to calculate the current through each branch, add the currents, and determine the equivalent resistance by Ohm's Law.

How does one identify whether or not two resistors are "in parallel?" If two resistors are in parallel, then they both will share the same terminals.



$$R_{EQ} = \frac{R_1 \times R_2}{R_1 + R_2} = R_1 \parallel R_2$$

Above, $R_1 \parallel R_2$ is read as "R_1 is in parallel with R_2"

The lights of a travel trailer electrical circuit are connected in parallel. The current at the circuit breaker panel is the sum of the currents through the lamps. Each lamp on this circuit has the same voltage impressed on it, nominally 12 volts. A parallel circuit consisting of three resistors connected in parallel to model three different lamps is shown in Figure 4-7.

Solution:

Step 1. Find the total or equivalent resistance of the circuit.

$$R_{EQ} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} = \frac{1}{\frac{1}{10} + \frac{1}{20} + \frac{1}{60}}\,\Omega$$

Find the common denominator for the fractions in R_{EQ}. Since 60 is divisible by 20 and 10, the common denominator is 60. The above equation becomes

$$R_{EQ} = \frac{1}{\frac{1}{60} + \frac{3}{60} + \frac{6}{60}}\ \Omega = \frac{1}{\frac{10}{60}} = \frac{60}{10} = 6\ \Omega$$

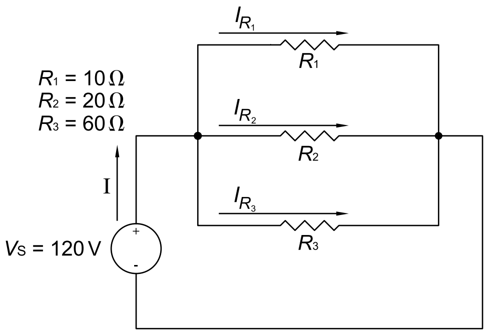


Figure 4-7. Resistors Connected in Parallel.

Step 2. Use Ohm's Law to find the current *I* supplying the one equivalent resistor.

$$I = \frac{V_S}{R_{EQ}} = \frac{12}{6} = 2\,A$$

Step 3. Use Ohm's Law to find the current through each resistor and then verify that the sum of all currents equals the total in Step 2.

$$I_{R_1} = \frac{V_S}{R_1} = \frac{12}{10} = 1.2\,A$$

$$I_{R_2} = \frac{V_S}{R_2} = \frac{12}{20} = .6\,A$$

$$I_{R_3} = \frac{V_S}{R_3} = \frac{12}{60} = .2\,A$$

$$I = I_{R_1} + I_{R_2} + I_{R_3} = 1.2\text{ A} + .6\,A + .2\,A = 2.0\,A$$

RESISTANCES IN SERIES-PARALLEL CIRCUITS

A series-parallel circuit consisting of two parallel branches and two series resistors is shown in Figure 4-8.

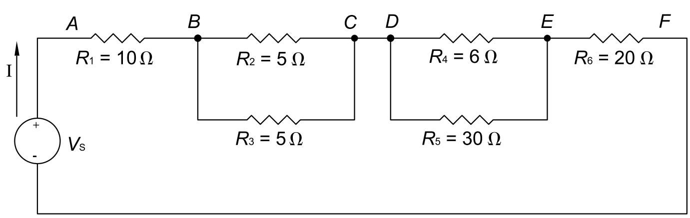


Figure 4-8. Circuit Connected in Series Parallel.

Solution:

Step 1. Find the equivalent resistance for the two parallel resistors between B-C and D-E of the original circuit. For the BC circuit:

$$R_{EQ,BC} = \frac{1}{\frac{1}{R_2}+\frac{1}{R_3}} = \frac{1}{\frac{1}{5}+\frac{1}{5}} = \frac{1}{\frac{2}{5}} = \frac{5}{2} = 2.5\ \Omega$$

Note that the equivalent resistance of two resistors in parallel having the same value will always equal one-half their original value. For the D-E circuit:

$$R_{EQ,DE} = \frac{1}{\frac{1}{R_4}+\frac{1}{R_5}} = \frac{1}{\frac{1}{6}+\frac{1}{30}} = \frac{1}{\frac{5}{30}+\frac{1}{30}} = \frac{1}{\frac{6}{30}} = 5\ \Omega$$

The original circuit in Figure 4-8 is equivalent to Figure 4-8a. (This circuit now contains resistances in series which was solved in a previous example.)

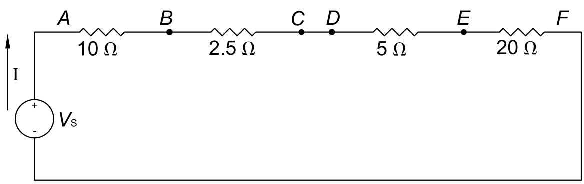


Figure 4-8a. Circuit Redrawn as a Series Circuit.

Step 2. Find the total or equivalent resistance of the circuit in Figure 4-8a.

$$R_{EQ} = R_{TOTAL} = R_1 + R_{EQ,BC} + R_{EQ,DE} + R_6$$

$$R_{EQ} = 10\ \Omega + 2.5\ \Omega + 5\ \Omega + 20\ \Omega = 37.5\ \Omega$$

Step 3. Use Ohm's Law to find the current I passing through all circuit elements.

$$I = \frac{V_S}{R_{EQ}} = \frac{120}{37.5} = 3.2\ A$$

Step 4. Use Ohm's Law to find the voltage drop across each resistor and then verify that the sum of all voltage drops equals the source voltage.

$$V_{R_1} = IR_1 = (3.2)(10) = 32\ V$$

$$V_{R_{EQ,BC}} = IR_{EQ,BC} = (3.2)(2.5) = 8\ V$$

$$V_{R_{EQ,DE}} = IR_{EQ,DE} = (3.2)(5) = 16\ V$$

$$V_{R_6} = IR_6 = (3.2)(20) = 64\ V$$

$$V_S = V_{R_1} + V_{R_{EQ,BC}} + V_{R_{EQ,DE}} + V_{R_6} = 32\ V + 8\ V + 16\ V + 64\ V = 120\ V$$

The equivalent resistance of a series-parallel circuit equals the equivalent resistances of each group or branch of parallel resistances, added to the resistances connected in series. Computation to determine the equivalent resistance of a series-parallel circuit can be simplified if, by inspection, it can be determined which resistances are connected in parallel and which resistances are connected in series.

POWER AND ENERGY IN DC CIRCUITS

Voltage is defined as the total work necessary to move the total charge around a circuit or the work per charge, and current is defined as electron flow or the time rate of change of charges. Power is defined as work done per unit time, or the rate of energy exchange in an electric circuit.

$$\text{Power, } P \text{ (Watts)} = V \text{ (Volts)} \times I \text{ (Amperes)} = \frac{\text{Work}}{\text{Charge}} \times \frac{\text{Charge}}{\text{Time}} = \frac{\text{Work}}{\text{Time}}$$

For elements in an electric circuit, power can either be used (dissipated, absorbed) or generated (produced). If we know the voltage across a circuit component and the current through that element, we can determine the power into or out of that component by multiplying voltage and current.

Using Ohm's Law, we can substitute for voltage, $V = IR$, or current, $I = V/R$, to get the following formulas:

$$P = I^2 \times R = \frac{V^2}{R}$$

Power is measured in Watts or kiloWatts (kW); one kiloWatt equals 1000 Watts.

Energy is defined as work done or power used over time.

$$\text{Energy, } E \text{ (Joules)} = \frac{\text{Work}}{\text{Time}} \times \text{Time} = P \times T = \text{Work}$$

This is expressed as Watthours (Wh) or kiloWatthours (kWh), which is 1000 Wh.

Example: Again referring to Figure 4-5, calculate the power dissipated in each of the loads.

Solution: Substituting and applying Ohm's Law:

$$P_1 = V_1 \times I_Y \Rightarrow P_1 = (R_1 \times I_Y) \times I_Y = I_Y^2 \times R_1$$

$$P_2 = V_2 \times I_Y \Rightarrow P_2 = (R_2 \times I_Y) \times I_Y = I_Y^2 \times R_2$$

$$P_3 = V_3 \times I_Y \Rightarrow P_3 = (R_3 \times I_Y) \times I_Y = I_Y^2 \times R_3$$

$$P_4 = V_4 \times I_X \Rightarrow P_4 = (R_4 \times I_X) \times I_X = I_X^2 \times R_4$$

For brevity, only the power dissipated in R_1 will be calculated:

$$P_1 = I_Y^2 \times R_1 = 2^2 \times 1 = 4\ W$$

THREE-WIRE EDISON DISTRIBUTION SYSTEM

Thomas Edison discovered that if the positive conductor of one generator and the negative conductor of another generator having an equal output voltage were combined, one conductor of the four from the two generators could be eliminated between the station and the customer. This system resulted in a savings of copper and a reduction in distribution losses.

With balanced loads between the outside conductors and the common conductor, no current flows in the common conductor (neutral), as shown in Figure 4.9a. If the loads are imbalanced, the neutral will carry the amount of imbalanced current to or away from the generator, depending on which side of the system is more heavily loaded. This is illustrated in Figures 4-9b and 4-9c.

When the neutral is carrying current due to an imbalanced load condition, the opening of the neutral conductor results in a lower voltage across the larger load (lower resistive load) and a higher voltage across the smaller load (higher resistive load). This condition is explained by the use of Ohm's Law in Figure 4-9d.

Figure 4-9d is the same as Figure 4-9c except that the neutral is open and the 5 Ω and l0 Ω resistances are in series with 240 V across the line conductors.

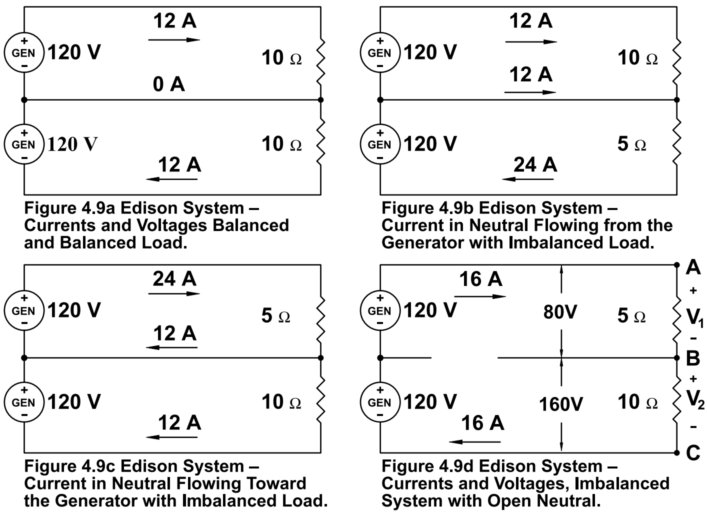


Figure 4.9a Edison System – Currents and Voltages Balanced and Balanced Load.

Figure 4.9b Edison System – Current in Neutral Flowing from the Generator with Imbalanced Load.

Figure 4.9c Edison System – Current in Neutral Flowing Toward the Generator with Imbalanced Load.

Figure 4.9d Edison System – Currents and Voltages, Imbalanced System with Open Neutral.

Figure 4.9a – 4.9d. Three-Wire Edison DC Distribution System.

The current through the total 15 Ω is:

$$I = \frac{V}{R} = \frac{240}{15} = 16\,A$$

The voltage from A to B $= V_1 = I \times R_{AB} = 16 \times 5 = 80\ V$

The voltage from B to C $= V_2 = I \times R_{BC} = 16 \times 10 = 160\ V$

SUMMARY OF DC CIRCUIT FORMULAS

The following formulas are useful in DC circuit calculations:

Current: $I = \dfrac{V}{R} = \dfrac{P}{V} = \sqrt{\dfrac{P}{R}}$

Resistance: $R = \dfrac{V}{I} = \dfrac{V^2}{P} = \dfrac{P}{I^2}$

Voltage: $V = I \times R = \dfrac{P}{I} = \sqrt{P \times R}$

Power: $P = V \times I = I^2 \times R = \dfrac{V^2}{R}$

Energy: $E = P \times T = V \times I \times T = I^2 \times R \times T = \dfrac{V^2 T}{R}$

where T is time and E is energy with units of joules or watthours.

ALTERNATING-CURRENT SINGLE-PHASE CIRCUITS

INTRODUCTION TO ALTERNATING-CURRENT CIRCUITS

Although DC is necessary for some industrial purposes such as electrolytic processes, arc furnaces, and for all digital logic circuits, practically all electric energy today is generated and transmitted as alternating current. Alternating current (AC) permits the use of static transformers by which voltages can readily be raised or lowered, allowing the transmission of energy at high voltages and the usage of energy at low voltages. Transformers operate on the principle of induction. They transfer energy using magnetic circuits and electric circuits.

In an AC circuit, voltage and current vary from instant to instant. Instantaneous power is still calculated by the product of the voltage and current, but the voltage and current must be determined for each instance in time. Although solid-state Watthour meters work on this principle, it is not convenient for circuit analysis. To understand what is occurring in an AC circuit, frequency, time relations, and wave shapes must be studied.

SINUSOIDAL FUNCTIONS

Most everyone has been introduced to the sine and cosine functions in high-school geometry class. Later, in a high-school physics course or an advanced mathematics course, the topic of sinusoidal waveforms was presented. Sinusoidal functions can be either *cosine* or *sine functions.* Electrical engineers have adopted the cosine function as the standard mathematical function for AC circuit analysis. If a sine wave is given, subtract 90° from the angle to convert it to a cosine function. In AC electric circuits, voltages and currents are no longer fixed, constant values of time $v(t) = V$ and $i(t) = I$. They take on a specific form where the functions change value as a function of time (t).

$$v(t) = V_p \cos(2\pi ft + \theta_v)\ V$$

$$i(t) = I_p \cos(2\pi ft + \theta_i)\ A$$

Sinusoidal time-domain functions are completely described by their peak amplitude, frequency, and phase angle. The peak value, magnitude or amplitude of the voltage and current are V_p and I_p, respectively. If the magnitude of the sinusoidal function is negative, make it positive by adding or subtracting 180° from the cosine function's argument. (The argument appears in the parentheses in the two equations above.) The sinusoids repeat with a period T (in seconds) which determines their fundamental frequency f. The phase angles θ_v and θ_i allow the sinusoidal functions to shift left and right along the time axis. This discussion represents any general sinusoid. The phase is related to an arbitrary time reference when using a mathematical description, but in an AC circuits problem, we are interested in the relative phases of the various sinusoidal voltages and currents. This is often referenced to a particular voltage.

Example: A sinusoidal function repeats itself every 21.6 ms. Its peak-to-peak value is 20 mA. The waveform has no shift associated with it. Express this sinusoid in the standard form above.

Solution: In the problem statement, the period, T, is given as 21.6 ms. Since $f = 1/T$, the frequency of the sinusoid is $1/21.6 \times 10^{-3} = 46.3$ Hz. The peak value of the sinusoidal function is one-half the given peak-to-peak value, or 20 mA/2 = 10 mA. The phase angle is given as 0°. Thus, $i(t) = 10 \cos(2\pi 46.3t + 0°)$ mA.

FUNDAMENTAL FREQUENCY

A cycle consists of one complete pattern of change of the AC wave; that is, the period from any point on an AC wave to the next point of the same magnitude and location at which the wave pattern begins to repeat itself. See Figure 4-10.

If the usual alternating voltage or current is plotted against time, it produces the curve in Figure 4-10. A single cycle covers a definite period of time and is completed in 360°. This period of time may be expressed in terms of an angle $\theta = 2\pi f t$ radians. Note that for $t = T$ (one period or 360°), $\theta = 2\pi$ radians. Since 360° = 2π radians, 180° = π radians.

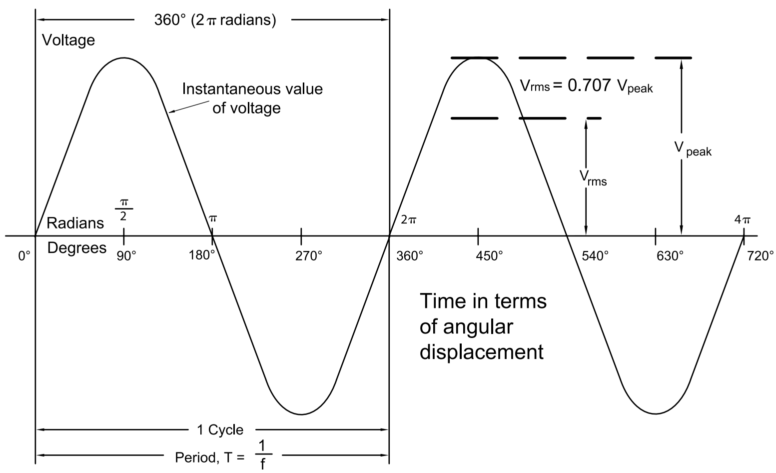


Figure 4-10. Sine-Wave Relationships.

The number of cycles completed per second is the frequency of the waveform expressed in Hertz (Hz). Higher frequencies may be expressed in either kiloHertz (kHz) or megaHertz (MHz).

The frequency in Hertz (Hz) is $f = 1/T$. In the previous equations for $v(t)$ and $i(t)$, we can substitute ω for $2\pi f$, to obtain the angular frequency having units of radians per second. Since $f = 1/T$, then $\omega = 2\pi/T$.

$$v(t) = V_p \cos(\omega t + \theta_v)\ V$$

$$i(t) = I_p \cos(\omega t + \theta_i)\ A$$

Table 4-1. Application Frequencies.

Application	Frequency
Direct current	0 Hz
Standard AC power (Europe influenced parts of the world)	50 Hz
Standard AC power (USA influenced parts of the world)	60 Hz
Audio sound	16 to 16,000 Hz
AM radio broadcasts	535 to 1,605 kHz
FM radio broadcasts	88 to 108 MHz
Television (Channels 2-13)	55 to 216 MHz
Communication satellites	5 GHz

The mathematical argument of the cosine and sine functions should be expressed in radians or degrees. A common mistake is to mix these units in the argument during a calculation. However, by convention, the phase angle, θ_v or θ_i, is usually expressed in degrees to be more understandable.

A sinusoidal voltage can be assigned a value in three ways:

1. By the maximum (V_{max}) or peak value (V_p). This value is used in insulation stress calculations;
2. By the average value (V_{avg}) which is equal to the average value of v for the positive half (or negative half) of the cycle. This value is often used in rectification problems. The average value of a cosine waveform over one period is zero. That is, in one period, there is just as much area above the x-axis as there is below;
3. By the root-mean-square (V_{rms}) or the effective value (V_{eff}). The term V_{rms} is generally used. In electricity, the effective value of an alternating current is that value of current which gives the same heating effect in a given resistor as the same value of direct current. Unless some other description is specified, when alternating currents or voltages are mentioned, it is always the rms value that is meant.

PHASORS

If two sine waves of the same frequency do not coincide with respect to time, they are said to be out of phase with each other. In Figure 4-11, the current waveform *I*, is $\theta°$ out of phase with the voltage waveform. As shown, it is behind or lagging the voltage waveform by the angle θ. It reaches its peak value at $\theta°$ after the voltage waveform reaches its peak. The trigonometric cosine of this angle between the voltage and current is the displacement power factor of the circuit.

$$\text{Displacement Power Factor} = \text{DPF} = \cos(\theta_v - \theta_i) = \cos \phi_{pf}$$

Here, θ_v and θ_i are the phase angles of the 60 Hz voltage and current waveforms, respectively. The Displacement Power Factor (DPF) should be identified as either leading or lagging. As will be seen later, current always lags the voltage for an inductive load or circuit. And, for a capacitive load or circuit, the current will always lead the voltage. An easy way to remember this is the saying, "ELI the ICE man." It says for an inductor L, the voltage (i.e., E = emf = electromotive force) leads the current. Alternatively, it says that the current lags behind the voltage. For a capacitor C, the current leads the voltage, which is the same as saying the voltage lags behind the current. When θ_v and θ_i are equal, the DPF = 1.0, and the voltage and current are "in phase."

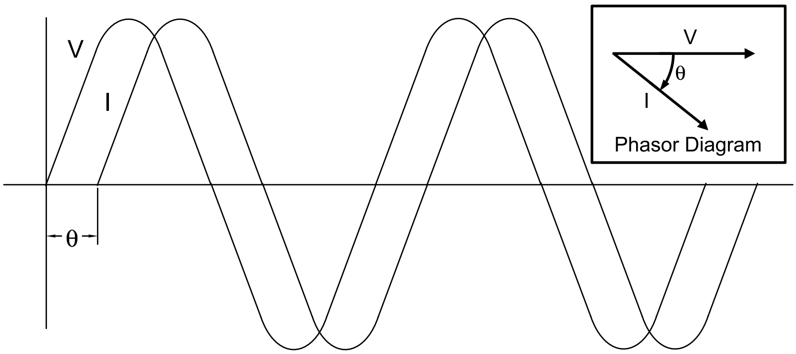


Figure 4-11. Current Wave Lagging Voltage Wave.

Example: Calculate the displacement power factor if the voltage *v(t)* and current *i(t)* are

$$v(t) = \sqrt{2}\ 226 \cos(2\pi 60t + 0°)\ V$$

$$i(t) = \sqrt{2}\ 15.6 \cos(2\pi 60t - 34.1°)\ A$$

Solution: Using the definition above, take the phase angle of the voltage and subtract the phase angle of the current to obtain the displacement power factor angle ϕ_{pf}, 0° – (−34.1°) = 34.1°. The cosine of 34.1° is 0.828. One piece of information is missing for our answer. Is the power factor leading or lagging? The answer is lagging. Refer to the DPF explanation to see why this is so.

Example: The angle between the voltage *v(t)* and current *i(t)* is 25.5°. The voltage is leading the current. What is the displacement power factor?

Solution: The cosine of 25.5° is 0.903. Since the voltage is leading the current, or the current is behind the voltage, then the displacement power factor is lagging.

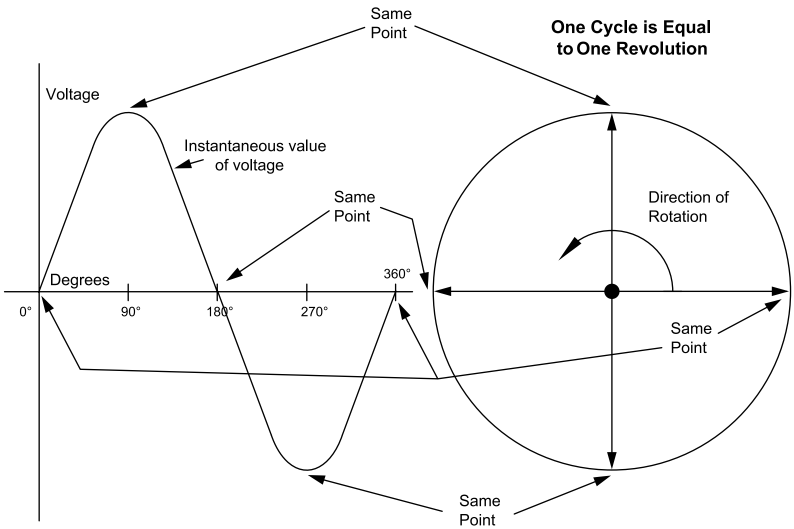


Figure 4-12. Voltage Phasor.

The mathematical representation of electrical quantities by sinusoidal functions is unwieldy and time consuming. The preferred method is to represent currents and voltages by phasor diagrams in which rotating vectors are substituted for cosine waveforms. These rotating vectors, called phasors, are drawn as vectors in the complex plane and considered to rotate in the counter clockwise direction one complete revolution (360°), while the cosine wave passes through one cycle (360°). Thus, the phasors are rotating at an angular frequency, $\omega = 2\pi f$ radians per second.

The phasor's length is defined either as the peak or rms value of the sine wave of the current or voltage. It is extremely important that whatever convention is adopted, it is followed for all calculations. The phase angle indicates the position of the phasor relative to a previously defined reference phasor. The reference phasor is usually the phase A line-to-neutral voltage having an angle of 0°. **Because power equipment is normally specified by its rms quantities, in the remainder of this chapter, all magnitudes are assumed to be rms. As such, if *v(t)* or *i(t)* are given by their peak or maximum amplitude, it will be necessary to convert them to their rms values by dividing by $\sqrt{2}$.**

One method of phasor notation is $\boldsymbol{I} = I_{rms} \underline{/\theta°}$ meaning the phasor $\boldsymbol{I}$ is at an angle of $\theta°$ counterclockwise from the positive x-axis (Figure 4-13).

Example: What are the phasors representing $-6\cos(\omega t - 30°)$ and $5\sin(\omega t - 10°)$?

Solution: The first is $6\ \underline{/-30° \pm 180°} = 6\ \underline{/150°}$ or $6\ \underline{/-210°}$. The second must first be converted from a sine function to a cosine function. We do this by subtracting 90°. Therefore, $5\ \underline{/-10° - 90°} = 5\ \underline{/-100°}$.

Example: If the phasor $V_S = 8.00 \angle{-38.7°}\ V$, what is $v_s(t)$?

Solution: The answer is $v_s(t) = 8.00 \cos(\omega t - 38.7°)\ V$.

Phasors representing currents or voltages can be resolved into vertical and horizontal components, (Figure 4-13) using the information provided in the complex number section of Chapter 3. Because phasors are complex numbers written in polar form, use the methods presented in Chapter 3 to perform addition, subtraction, multiplication, and division.

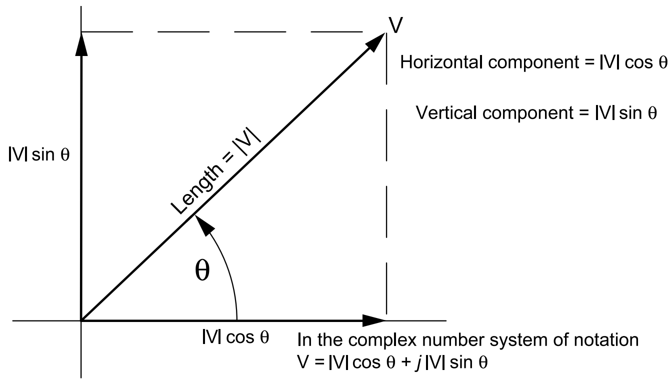


Figure 4-13. Phasor Voltage Resolved into Components.

INDUCTANCE

Any conductor which is carrying current is cut by the flux of its own field when the current changes in value. A voltage is thereby induced in the conductor, which, by Lenz's Law, opposes the change in current in the conductor. If the current is decreasing, the polarity of the induced voltage tries to maintain the current; if the current is increasing, the induced voltage tends to keep the current down. The amount of induced voltage depends upon the change in the number of flux lines cutting the conductor, which in turn, depends upon the rate of change of current in the conductor. The proportionality factor between the induced voltage and the rate of change of current is the inductance, L, of the circuit.

By equipment design, the inductance of a circuit can generally be considered dependent on the current magnitude in the circuit and on the physical characteristics of the circuit. A conductor in the form of a coil cuts more flux lines and has a greater inductance than a straight conductor. Magnetic material versus air in the flux path further concentrates the flux lines to the conductor, allowing the conductor to cut more flux lines, which further increases the inductance.

Inductance is expressed in Henries (H). A more common unit is the milli-Henry (mH), which is one-thousandth of a Henry.

In direct-current circuits inductance has no effect except when current is changing. Consider a pure resistive DC circuit (Figure 4-14a). When a voltage is impressed, the current instantly assumes its steady-state value determined by (V/R), as shown in Figure 4-14b.

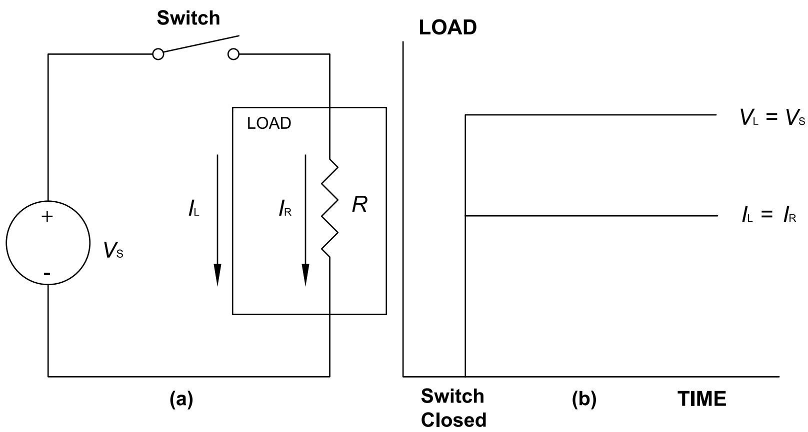


Figure 4-14. Direct Current in a Resistance Circuit.

If an inductance is inserted in series with the same resistor, the current does not increase instantly to its steady-state value when the switch is closed. Instead, there is a time delay before the current reaches the same steady-state value as before, shown in Figure 4-15b. The induced voltage in the inductor opposing the rising current causes this effect.

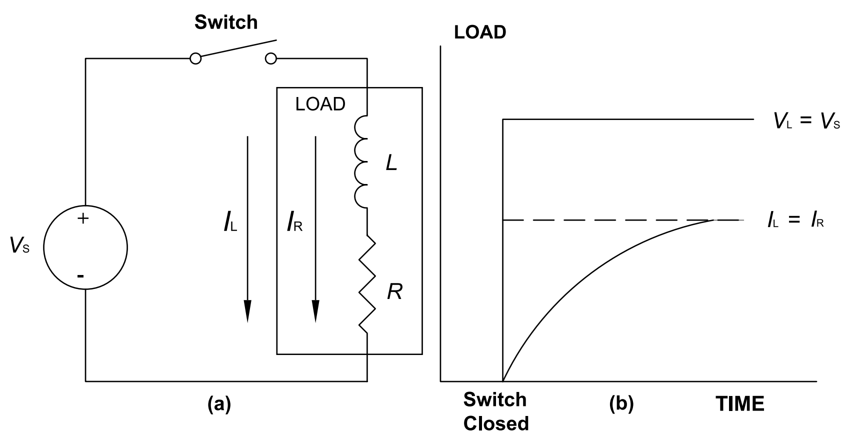


Figure 4-15. Direct Current in an Inductive Circuit.

The larger the value of the circuit inductance, the longer the time required for the current to reach its steady-state value. However, once this value has been reached, the inductance has no further effect and only the resistance limits the magnitude of circuit current.

With alternating current the instantaneous current is always changing, so in an inductive circuit the inductive effect is always present. For every quarter cycle of the line frequency, energy is being stored to or released from the magnetic field.

Inductance has a very definite current-limiting effect on alternating current as contrasted with steady-state direct current. This effect is directly proportional to the magnitude of the inductance *L*. It is also proportional to the rate of change of current, which is a function of the frequency of the supply voltage. The total opposing, or limiting effect of inductance on current may be calculated by the following equation and is called the inductive reactance

$$X_L = 2\pi f L = \omega L$$

where X_L = inductive reactance in Ω, f = frequency in Hz, and L = inductance in H.

In a purely inductive AC circuit, the maximum rate of change of current occurs when the current passes through zero. At this instant of zero magnitude but maximum change, there is maximum induced voltage and the voltage wave is at its peak value. When the current reaches its peak value, the rate of change of current is zero and the induced voltage is zero. As shown in Figure 4-16, the current wave *lags* the voltage wave by 90°.

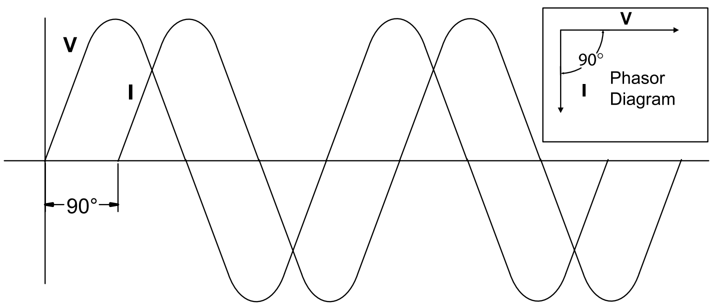


Figure 4-16. Phase Relationships in a Circuit of Pure Inductance.

When two inductors are in series, they may be replaced by a single equivalent inductor. In this way, they are similar to a resistor. When L_1 is in series with L_2, then $L_{EQ} = L_1 + L_2$. Similarly, inductors in parallel add like resistors in parallel,

$$L_{EQ} = L_1 \parallel L_2 = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2}} = \frac{L_1 L_2}{L_1 + L_2}$$

CAPACITANCE

Electric current flow is generally considered to be a movement of negative charges, or electrons, in a conductor. In conducting materials some of the electrons are loosely attached to the atoms so that when a voltage is applied to a closed circuit these electrons are separated from the atoms and their movement constitutes a current flow.

The electrons in an insulator are much more firmly bonded to the atoms than in a conductor. When a voltage is applied to an insulator, the electrons seek to leave the atoms but cannot do so. However, the electrons are displaced by an amount dependent upon the force applied, the voltage difference. When voltage changes, the displacement also changes. When this electron motion takes place, a displacement current flows through the dielectric and there is a charging-current flow throughout the entire circuit.

Consider the circuit of Figure 4-17a which has a small insulating gap between the ends of the wires. When the switch is closed there is no continuous current flow in the circuit. However, a very small current may be measured with an extremely sensitive instrument for a short time. Electrons move through the circuit to build up an electrical charge across the gap, which is equal to the impressed voltage V_S. Once the charge has been established there is no further electron movement.

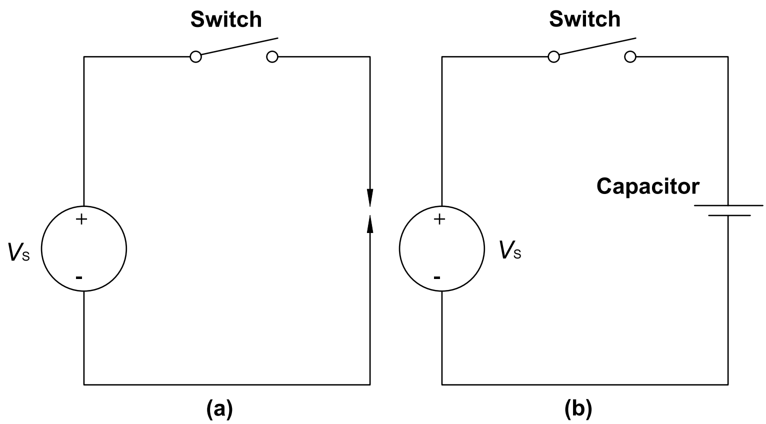


Figure 4-17. Capacitive Circuit.

If, instead of a small gap, the area is enlarged by connecting plates to each of the conductors, as in Figure 4-17b, the current required to raise the charge to a given level is increased because a greater movement of electrons is required. Such devices, consisting of large conducting areas separated by thin insulating materials such as air, mica, glass, etc., are called capacitors. Any two conductors separated by insulation constitute a capacitor, but normally the capacitance effect is negligible unless the components and their arrangement have been specifically designed to provide capacitance.

The capacitance, C, is a function of the physical characteristics of the capacitor, such as the plate area, the distance, and the type of insulation between the plates. Capacitance is expressed in Farads. A more common, smaller unit is the microFarad (μF), which is one-millionth of a Farad (F).

Capacitors may be connected in parallel or in series. The total capacitance of capacitors connected in parallel is the sum of the individual capacitances.

$$C_{EQ} = C_1 + C_2 + C_3$$

For a series connection, the net capacitance is found by a formula similar to that for parallel resistances.

$$C_{EQ} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}} = \frac{C_1 C_2}{C_1 + C_2}$$

In a DC circuit, current flows through a capacitor only when the voltage across it changes. In an AC circuit, the voltage is continually changing and current flows through a capacitor as long as the alternating voltage is applied. The current magnitude is proportional to the rate of change of voltage. With a sinusoidal voltage, the maximum rate of change occurs when the voltage crosses zero and the peak value of current occurs at this instant. When the voltage is at its peak, its rate of change is zero and the current magnitude is zero. Therefore, there is a 90-degree phase displacement between current and voltage in a capacitor. When the rate of change of voltage is positive, the current must be in the positive direction to supply the increasing positive charge. Therefore, the current leads the voltage in a capacitor. These relationships are shown in Figure 4-18.

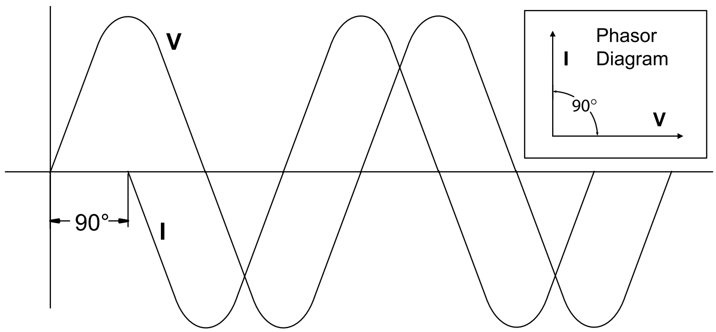


Figure 4-18. Phase Relationship in a Circuit of Pure Capacitance.

The current-limiting effect of a capacitor, its reactance, is dependent on two quantities: capacitance and frequency. Charging current increases with increasing capacitance, so with a given voltage the reactance must be inversely proportional to capacitance. Rate of change of voltage is proportional to frequency, hence charging current is also proportional to frequency and reactance is inversely proportional. Capacitive reactance may be calculated from the following equation:

$$X_C = \frac{-1}{2\pi f C} = \frac{-1}{\omega C}$$

where X_C = capacitive reactance in Ω, f = frequency in Hz, and C = capacitance in F.

Capacitive reactance causes leading current and a leading power factor while inductive reactance causes lagging current and a lagging power factor. Capacitors are often used to balance some of the inductive reactance (e.g., motors and transformers) of a circuit and therefore to increase the circuit power factor. They are also used to balance some of the inductive voltage drop in a circuit and therefore increase the available voltage.

RESISTANCE AND OHM'S LAW AS APPLIED TO AC CIRCUITS

Resistance in an AC circuit has the same effect as it has in a DC circuit. An AC current flowing through a resistance results in a power loss in the resistor. This real power loss is expressed as $I_{rms}^2 R$.

With AC, a given resistor or coil may have a higher equivalent AC resistance than its DC resistance due to the *skin effect*. The skin effect is a phenomenon whereby AC current wants to flow on the surface (i.e., the outside) of the conductor rather than through the total cross-sectional area. As a result, in general,

$$R_{AC} \geqslant R_{DC}$$

This is especially true in coils with magnetic cores. Here, there is not only a power loss in the winding itself, but there is also a heat loss in the magnetic core caused by eddy currents. The total loss is represented by $I_{rms}{}^2R$ where R is now the equivalent AC resistance of the coil.

Ohm's Law as applied to AC circuits is

$$\boldsymbol{V} = Z\boldsymbol{I}$$

where $\boldsymbol{V}$ and $\boldsymbol{I}$ are phasors, and Z is termed the impedance as shown in figure 4-19.

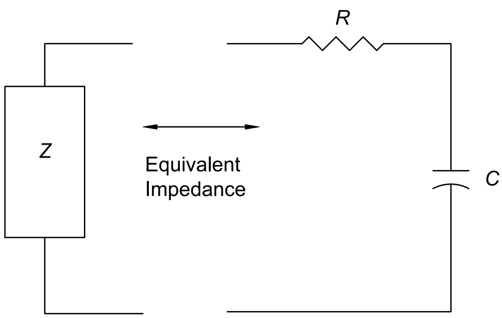


Figure 4-19. Example Schematic.

IMPEDANCE

In alternating currents, then, there are three quantities that limit or impede the flow of current: resistance, R; inductive reactance, X_L; and capacitive reactance, X_C. Each of these quantities are a specific part of a more generic quantity called impedance. Impedance, Z, is defined as the ratio of the phasor voltage divided by the phasor current through the circuit of interest.

$$Z = \frac{\boldsymbol{V}}{\boldsymbol{I}}$$

This is Ohm's Law restated for AC circuits, $\boldsymbol{V} = Z\boldsymbol{I}$. Note that Z is not a phasor! Since each variable in the equation above is a complex number, the following equations are true:

$$|Z| = \frac{V_{rms}}{I_{rms}} \text{ and } \theta_Z = \phi_{pf} = \theta_V - \theta_I$$

Because the impedance Z in AC circuits is like R in DC circuits, combining impedances in parallel and impedances in series is identical to combining resistors in parallel and resistors in series. That is, for impedances in series

$$Z_{EQ} = Z_1 + Z_2 + Z_3 + \cdots + Z_N$$

And, for impedances in parallel, we have

$$Z_{EQ} = \frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_1} + \cdots + \frac{1}{Z_N}}$$

We can also define the impedance associated with *R*, *L*, or *C*. The impedance of a resistor is:

$$Z_R = \frac{\boldsymbol{V}_R}{\boldsymbol{I}_R} = R + j0 = R\ \Omega$$

The impedance of an inductor is:

$$Z_L = \frac{\boldsymbol{V}_L}{\boldsymbol{I}_L} = jX_L = X_L \angle 90^\circ = j\omega L = \omega L \angle 90^\circ = j2\pi fL = 2\pi fL \angle 90^\circ\ \Omega$$

In polar form j is $1 \angle 90^\circ$. The impedance of a capacitor is:

$$Z_C = \frac{\boldsymbol{V}_C}{\boldsymbol{I}_C} = jX_C = X_C \angle 90^\circ = j\frac{-1}{\omega C} = \frac{1}{\omega C} \angle -90^\circ = j\frac{-1}{2\pi fC} = \frac{1}{2\pi fC} \angle -90^\circ\ \Omega$$

By definition, X_C is negative and $-1 = 1 \angle \pm 180^\circ$ in polar form.

Example: Find the impedance of a 10 mH inductor at a frequency of 360 Hz.

Solution: The impedance as given by one of the above equations is:

$$Z_L = jX_L = j\omega L = j2\pi \times 360 \times 0.01 = j22.6\ \Omega$$

Example: A simple series AC circuit consists of a 10 μF capacitor and a 500 Ω resistor. What is the equivalent impedance seen by the source in a 60 Hz system?

Solution: Because the impedances are in series, add them together.

$$Z_{EQ} = R + jX_C = 500 + j\frac{-1}{2\pi 60\ (10 \times 10^{-6})} = 500 - j265\ \Omega$$

Example: A load has a voltage of $10\cos(120\pi t + 12^\circ)$ V and a current of $2.5\cos(120\pi t - 37^\circ)$ A. What is the reactance of the load?

Solution: The reactance is the imaginary part of the impedance *Z*. Find *Z*.

$$Z = \frac{\boldsymbol{V}}{\boldsymbol{I}} = \frac{10 \angle 12^\circ}{2.5 \angle -37^\circ} = 4 \angle 49^\circ = 2.62 + j3.02\ \Omega$$

The reactance of the load is the imaginary part of *Z* or 3.02 Ω.

In a series *RLC* circuit, the equivalent impedance, Z_{EQ}, and its magnitude, $|Z_{EQ}|$, as seen by the source is:

$$Z_{EQ} = R + j(X_L + X_C)$$

$$|Z_{EQ}| = \sqrt{R^2 + (X_L + X_C)^2}$$

By definition, X_C *is a negative number*.

Impedance may also be represented by the impedance triangles (Figure 4-20).

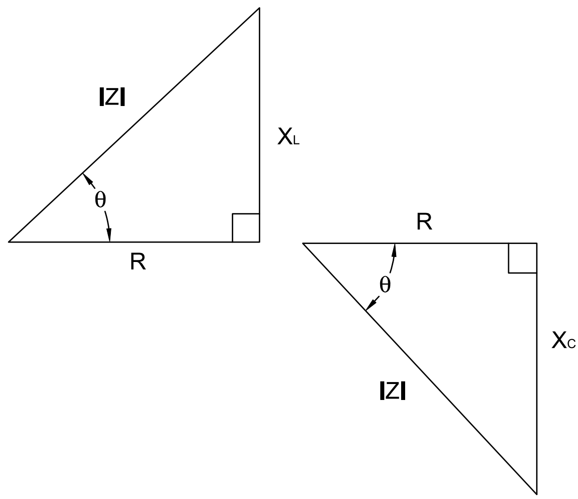


Figure 4-20. Impedance Triangles for a Series Circuit.

From these triangles, other trigonometric relationships between *Z*, *R*, and *X* can be obtained. See Table 4-2.

The various components of the impedance *Z* determine not only the amount of current flowing in a circuit, but also the phase relationship between the voltage and the current. That is, $\theta_Z = \phi_{pf} = \theta_V - \theta_I$.

If the circuit has only resistance, *R*, the current is in phase with the voltage and the circuit is said to have a unity displacement power factor.

If the inductive reactance, X_L, exceeds the capacitive reactance, $|X_C|$, in a series circuit, the current lags the voltage and the circuit has a lagging displacement power factor.

If the capacitive reactance, $|X_C|$, exceeds the inductive reactance, X_L, in a series circuit, the current leads the voltage and the circuit has a leading displacement power factor.

If the inductive reactance, X_L, and the capacitive reactance, $|X_C|$, are equal in a series circuit, the circuit is said to be in resonance, and the current flow is limited only by the resistance and the circuit power factor is unity.

Table 4-2. Polar and Rectangular Representation of Impedance of Circuit Elements.

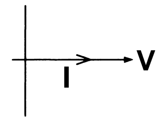
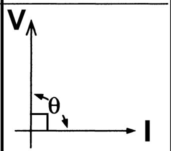
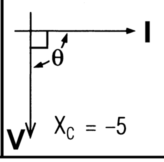
Circuit Element	Phasor Orientation	Rectangular Form	Polar Form
$R = 5\,\Omega$  R		$Z = 5 + j0\,\Omega$ $\tan\theta = \frac{0}{5} = 0$ $\theta = 0°$	$Z_R = R\underline{/0°}\ \Omega$ $Z_R = 5\underline{/0°}\ \Omega$
$X_L = 5\,\Omega$  L		$Z = 0 + j5\ \Omega$ $\tan\theta = \frac{5}{0} = \infty$ $\theta = 90°$	$Z_L = X_L\underline{/90°}\ \Omega$ $Z_L = 5\underline{/90°}\ \Omega$
$X_C = -5\,\Omega$  C		$Z = 0 - j5\ \Omega$ $\tan\theta = \frac{-5}{0} = -\infty$ $\theta = -90°$	$Z_C = \lvert X_C\rvert\,\underline{/-90°}\,\Omega$ $Z_C = 5\underline{/-90°}\,\Omega$

Table 4-3. Polar and Rectangular Representation.

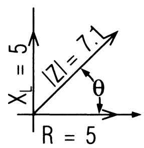
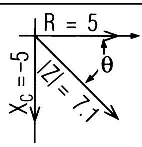
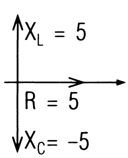
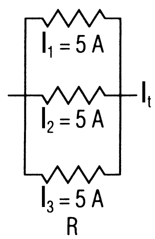
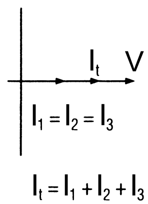
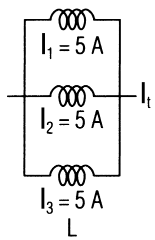
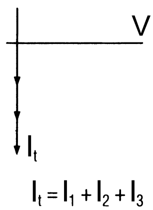
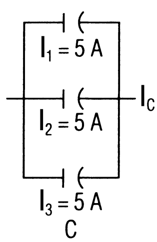
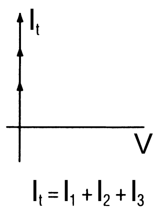
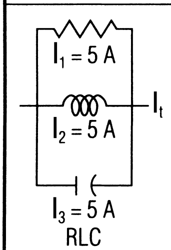
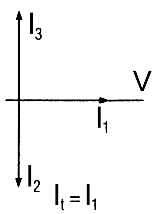
Circuit	Phasor Orientation	Rectangular Form	Polar Form
$R = 5\Omega$ $X_L = 5\Omega$ RL 		$R = 5\Omega$ $X_L = 0 + j5\Omega$ $Z = 5 + j5\Omega$ $\tan\theta = \frac{5}{5} = 1$ $\theta = 45°$	$\lvert Z\rvert = \sqrt{R^2 + X_L^2}\ \Omega$ $\tan\theta = \frac{X_L}{R}$ $\lvert Z\rvert = \sqrt{5^2 + 5^2} = 7.1\,\Omega$ $\tan\theta = \frac{5}{5} = 1;\ \theta = 45°$ $Z = 7.1\underline{/45°}\ \Omega$
$R = 5\Omega$ $X_C = -5\Omega$ RC 		$R = 5\Omega$ $X_C = 0 - j5\Omega$ $Z = 5 - j5\Omega$ $\tan\theta = \frac{-5}{5} = -1$ $\theta = -45°$	$\lvert Z\rvert = \sqrt{R^2 + X_C^2}\,\Omega$ $\tan\theta = \frac{X_C}{R}$ $\lvert Z\rvert = \sqrt{5^2 + 5^2} = 7.1\Omega$ $\tan\theta = \frac{-5}{5} = -1;\ \theta = -45°$ $Z = 7.1\underline{/-45°}\ \Omega$
$R = 5\Omega$ $X_C = -5\Omega$ $X_L = 5\Omega$ RLC 		$R = 5\Omega$ $X_C = 0 - j5\Omega$ $X_L = 0 + j5\Omega$ $Z = 5 + j0\Omega$ $\tan\theta = \frac{0}{5} = 0$ $\theta = 0°$	$\lvert Z\rvert = \sqrt{R^2 + (X_L - X_C)^2}\ \Omega$ $\tan\theta = \frac{X_L + X_C}{R}$ $\lvert Z\rvert = \sqrt{5^2 + (5-5)^2} = 5\,\Omega$ $\tan\theta = \frac{5-5}{5} = 0;\ \theta = 0°$ $Z = 5\underline{/0°}\,\Omega$

Table 4-4. Polar and Rectangular Representation of Currents in Parallel Circuits.

Circuit Load Current Flow	Phasor	Rectangular Form	Polar Form
 $I_1 = 5$ A $I_2 = 5$ A $I_3 = 5$ A I_t R	 I_t V $I_1 = I_2 = I_3$ $I_t = I_1 + I_2 + I_3$	$I_1 = 5 + j0$ A $I_2 = 5 + j0$ A $I_3 = 5 + j0$ A $I_t = 15 + j0$ A $\tan\theta = \frac{0}{15} = 0$ $\theta = 0°$	$I_t = 15\angle 0°$ A
 $I_1 = 5$ A $I_2 = 5$ A $I_3 = 5$ A I_t L	 V I_t $I_t = I_1 + I_2 + I_3$	$I_1 = 0 - j5$ A $I_2 = 0 - j5$ A $I_3 = 0 - j5$ A $I_t = 0 - j15$ A $\tan\theta = \frac{-15}{0} = -\infty$ $\theta = -90°$	$I_t = 15\angle -90°$ A
 $I_1 = 5$ A $I_2 = 5$ A $I_3 = 5$ A I_C C	 I_t V $I_t = I_1 + I_2 + I_3$	$I_1 = 0 + j5$ A $I_2 = 0 + j5$ A $I_3 = 0 + j5$ A $I_t = 0 + j15$ A $\tan\theta = \frac{15}{0} = \infty$ $\theta = 90°$	$I_t = 15\angle 90°$ A
 $I_1 = 5$ A $I_2 = 5$ A $I_3 = 5$ A I_t RLC	 I_3 V I_1 I_2 $I_t = I_1$	$I_1 = 5 + j0$ A $I_2 = 0 - j5$ A $I_3 = 0 + j5$ A $I_t = 5 + j0$ A $\tan\theta = \frac{0}{5} = 0$ $\theta = 0°$	$I_t = 5\angle 0°$ A

POWER AND ENERGY IN SINGLE-PHASE AC CIRCUITS

In sinusoidal AC circuits, the active, average, or real power is:

$$P = V_{\text{rms}} I_{\text{rms}} \cos(\theta_V - \theta_I) = V_{\text{rms}} I_{\text{rms}} \cos(\theta_Z) = V_{\text{rms}} I_{\text{rms}} \cos(\phi_{pf}) = V_{\text{rms}} I_{\text{rms}} \text{ DPF}$$

where $\cos\theta_Z = \cos\phi_{\text{pf}} = \cos(\theta_V - \theta_I)$ and is equal to the displacement power factor of the circuit. The units of P is Watts (W).

Table 4-5. Formulas for Single-Phase AC Series Circuits.

V Volts		$\frac{P}{I\cos\theta}$	IR				
I Amperes	$\frac{P}{V\cos\theta}$		$\frac{V}{\lvert Z\rvert}$	$\sqrt{\frac{P}{R}}$	$\sqrt{\frac{P}{\lvert Z\rvert\cos\theta}}$	
|Z| Ohms	$\frac{V}{I}$	$\frac{P}{I^2\cos\theta}$		$\frac{R}{\cos\theta}$	$\frac{V^2\cos\theta}{P}$	$\sqrt{R^2+X^2}$
R Ohms		$\frac{V}{I}\cos\theta$	$\lvert Z\rvert\cos\theta$		$\frac{P}{I^2}$	$\sqrt{\lvert Z\rvert^2-X^2}$
P Watts		$VI\cos\theta$	$I^2\lvert Z\rvert\cos\theta$	I^2R	$\frac{V^2}{R}$	
Cos θ Power Factor		$\frac{P}{I^2\lvert Z\rvert}$	$\frac{P\lvert Z\rvert}{V^2}$	$\frac{R}{\lvert Z\rvert}$	$\frac{P}{VI}$	$\frac{R}{\sqrt{R^2+X^2}}$
X Ohms	$X_L + X_C$		$2\pi fL-\frac{1}{2\pi fC}$			$\sqrt{\lvert Z\rvert^2-R^2}$

In sinusoidal AC circuits, the reactive or imaginary power represents the power that is circulating every quarter cycle of the line frequency between the magnetic and electrical circuits of the system. This power is not directly consumed although it will lead to additional line and equipment losses. It is calculated as:

$$Q = V_{\text{rms}}I_{\text{rms}}\sin(\theta_V - \theta_I) = V_{\text{rms}}I_{\text{rms}}\sin(\theta_Z) = V_{\text{rms}}I_{\text{rms}}\sin(\phi_{pf})$$

The units of Q is voltamperes reactive (VAR). Note that Q does not exist at a given instance in time, but represents the average instantaneous real power that is circulating in the system.

In sinusoidal AC circuits, the energy is:

$$E = PT$$

where T is time. Ohm's Law and the power equations are combined to give the various formulas for single-phase AC series circuits shown in Table 4-4.

In sinusoidal AC circuits, the power triangle is used to relate the active, real, or average power P, and the reactive or imaginary power Q, to a third important term called the complex power S, having units of voltamperes (VA). The complex power S is defined as:

$$S = P + jQ = \sqrt{P^2+Q^2}\ \underline{/\tan^{-1}}\left(\frac{Q}{P}\right) = |S|\ \underline{/\phi_{\text{pf}}}$$

in terms of the powers P and Q,

$$\text{and } S = \boldsymbol{VI}^{\phi} = I_{\text{rms}}^2 Z = \frac{V_{\text{rms}}^2}{Z^{\phi}}$$

$$S = |S|\ \underline{/\phi_{\text{pf}}} = |S|\ \underline{/\theta_V - \theta_I} = |S|\ \underline{/\theta_Z} = V_{\text{rms}}I_{\text{rms}}\ \underline{/\theta_V - \theta_I} = V_{\text{rms}}I_{\text{rms}}\ \underline{/\theta_Z} = V_{\text{rms}}I_{\text{rms}}\ \underline{/\phi_{pf}}$$

when written in terms of the voltage and current phasor magnitudes and phase angles. The magnitude of the complex power S, $|S|$, is known as the apparent power and is $V_{rms}\,I_{rms} = \sqrt{P^2 + Q^2}$. The units are also VA. The apparent power is a measure of the operating limits in electrical equipment such as transformers, motors, and generators.

The relationship between P, Q, and $|S|$ is best shown by the power triangle, Figure 4-21. Mathematically:

$S = P + jQ_L$ for an inductive load having a lagging power factor

$S = P + jQ_C$ for a capacitive load having a leading power factor

For the two cases above,

$$Q_C = I^2_{rms}X_C = \frac{V^2_{rms}}{X_C}$$

$$Q_L = I^2_{rms}X_L = \frac{V^2_{rms}}{X_L}$$

When a circuit is capacitive, (i.e., leading power factor), then Q is negative or less than zero since X_C is negative. When a circuit is inductive (i.e., lagging power factor), then Q is positive or greater than zero. Using trigonometry, many other expressions can be written from Figure 4-21. For example, the displacement power factor can be written as:

$$\text{DPF} = \cos(\theta_V - \theta_I) = \cos(\theta_Z) = \cos(\phi_{pf}) = \cos\left(\tan^{-1}\left(\frac{Q}{P}\right)\right) = \frac{P}{|S|} = \frac{P}{V_{rms}I_{rms}}$$

For metering applications, the complex power S is not a measurable quantity; however, the newer electronic meters can measure $|S|$ directly. The reactive power, Q, can be approximated but with great care, and then only for sinusoidal systems. In practice, measure $|S|$ and P, and then compute Q.

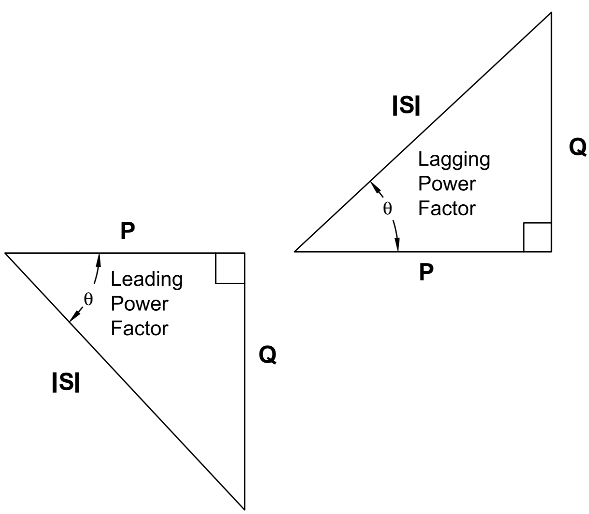


Figure 4-21. Single-Phase Power Triangles.

Example: A 230 V rms motor has a mechanical output power of three horsepower (hp). The input current, voltage, and power are measured as 226 V rms, 15.6 A rms, and 2920 W, respectively. Calculate the efficiency, the power factor, and the reactive power.

Solution: The measured apparent power is $|S| = V_{rms} I_{rms} = (226)(15.6) = 3530$ VA.

The measured power factor is DPF = P/|S| = 2920/3530 = 0.828. Is it leading or lagging? Since it is a motor, assume lagging. A DPF of 0.828 corresponds to a phase angle of $\cos^{-1}(0.828) = 34.1°$. The reactive power can be calculated by re-arranging the above formula for the apparent power.

$$Q = \sqrt{|S|^2 - P^2} = \sqrt{(3530)^2 - (2920)^2} = 1980 \text{ VARs}$$

The Percent Efficiency of a moter is $\eta = \left[\frac{P_{output}}{P_{input}}\right] \times 100 = \left[\frac{P_{output}}{V_{rms} I_{rms}}\right] \times 100$

The motor has a mechanical output of 3 hp. Since there are 746 watts per hp, the power output of the motor is 3 × 746 or 2,238 watts.

Therefore the efficieny, η, of the motor is $\left[\frac{2{,}238 \text{ watts}}{2{,}920 \text{ watts}}\right] \times 100 = 76.6\%$

TRANSFORMERS

Transformers operate on the principle of induction in which energy is transferred between electric and magnetic circuits. Because energy is alternately stored to and delivered from these magnetic circuits, current alternates and power circulates in the electrical circuits.

It is the influence of the magnetic circuit on the electric circuit with which it is associated that causes the major differences between the AC circuit and the DC circuit.

These devices are indispensable in AC power distribution systems. Their applications range from power conversion to small transducer applications. They utilize a mixture of magnetic and electrical properties to do this task. A transformer is a device that requires alternating current to perform its function as a "transforming" mechanism. It is primarily used to change voltage and current levels to values more usable or measurable. It typically consists of two windings or inductors that are magnetically coupled by a core of magnetic material. The input winding or coil is called the "primary" and the output winding or coil is called the "secondary." The secondary usually delivers power to a load or a measurable quantity to a metering or monitoring device.

The ideal transformer is called "ideal" because it has no electric or magnetic losses of any kind. Figure 4-22 illustrates an ideal two-winding, shell-type transformer. This device works only when AC voltage and current are applied to the primary, and appears as a short circuit to DC voltage and current. This property allows the device to isolate the secondary from the primary and vice-versa for DC voltage and current. With AC voltage applied to the primary, a magnetic field is generated in the core. This magnetic field or flux flow in the core is analogous to current flowing in a circuit. As it flows through the core inside the secondary winding, a voltage is induced into this winding. The magnitude of this induced voltage is proportional to the turns ratio of the transformer.

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \text{Turns Ratio} = \text{a}$$

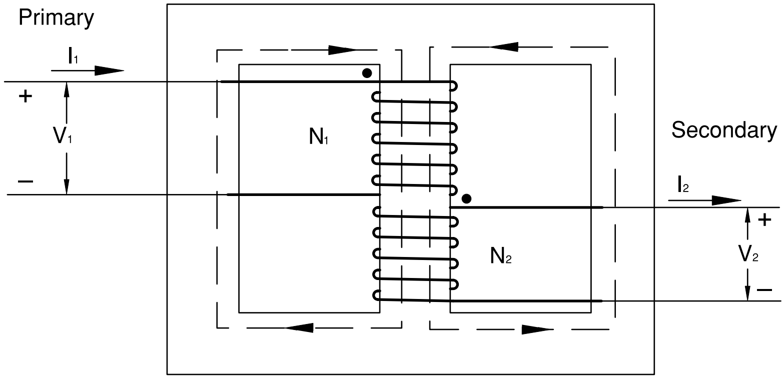


Figure 4-22. Idealized Two-Winding Transformer.

As in an electric circuit, work is required to move this flux. This magnetic form of work is called magneto-motive force (mmf). The mmf is equal to the number of turns in the winding times the current in the winding. The magnetic circuit of the ideal transformer is lossless, and therefore the mmf or work required to overcome the core circuit is zero. The mmfs of the two windings are equal and opposite in polarity.

$$N_1 \times I_1 = N_2 \times I_2 \text{ or } \frac{I_1}{I_2} = \frac{N_2}{N_1} = \frac{1}{\text{Turns Ratio}} = \frac{1}{a}$$

In an ideal transformer the secondary voltage times the turns ratio is directly proportional to the primary voltage and the secondary current is inversely proportional to the primary current.

$$V_P = V_1 \quad V_S = V_2 \qquad\qquad I_P = I_1 \quad I_S = I_2$$

$$V_P = V_S \times \text{a} \qquad \text{and} \qquad I_P = \frac{I_S}{\text{a}}$$

An ideal transformer also demonstrates conservation of power. The power into the ideal transformer will equal the power out of the ideal transformer.

$$S_P = V_P \times I_P$$

Substituting from the formulas above $S_P = (V_S \times a)\dfrac{I_S}{a}$

Reducing this equation $S_P = V_S \times I_S = S_S$

Lastly, polarity defines the convention of current flow in and out of a transformer. This is determined when the transformer is manufactured and is dictated by the placement of the windings on a core. It is marked on the nameplate and sometimes on the primary and secondary terminals as is the case of an instrument transformer used for metering or relaying. In Figure 4-22, the polarity marking is signified by a dot marked at the top of each winding. The primary current flows into the terminal marked with the polarity marking and out of the secondary terminal marked with the polarity marking.

Unfortunately, the transformers built today have a variety of losses that encompass the magnetic circuit and the electrical circuit. In a transformer designed to deliver power, these losses have been quantified in two categories; no load and full load. As their names imply, they pertain to losses at each of these two states of the unit. In transformers that are used to meter voltages and currents, these losses are quite small and are sometimes compensated by the devices to which they feed. These types of applications are covered later.

HARMONIC FREQUENCIES

In the ideal case, alternating voltages and currents are sinusoidal functions having a single frequency f or ω. This fundamental frequency, also known as the power frequency, is usually the lowest frequency component in the system.

In reality, there are a number of effects within the power system that may cause the cosine wave to become distorted or "polluted" to some extent. When we say distorted or polluted, we mean that the voltage and current *no longer* contain just the desired power frequency (50 or 60 Hz).

Any repeating AC waveform, no matter how distorted, may be represented by a combination of waveforms of the fundamental frequency plus one or more harmonics. A harmonic is a frequency which is an integer multiple of the power frequency, ($h\omega$, h = integer). In a 60 Hz system, examples of harmonics of the power frequency would be 180 Hz, 300 Hz, 420 Hz, 660 Hz, 780 Hz, etc. These higher frequencies are called the third, fifth, seventh, eleventh, and thirteenth harmonics of 60 Hz, respectively. The relative magnitude of the fundamental waveform and the number, magnitude, and phase displacement of the harmonic components determine the resultant waveform's shape.

For instance, Figure 4-23 shows a voltage waveform composed of a 100 V fundamental 60 Hertz waveform and a 20 Volt third harmonic. This waveform contains 100% or one per-unit 60 Hz and a 20% or .02 per-unit third-harmonic component. The third harmonic crosses the x-axis at the same instant in time as the fundamental waveform. Harmonics can be displaced in time from the fundamental, depending on circuit characteristics. For example, Figure 4-23 shows the 3rd harmonic 180^{o} out of phase with the fundamental.

Under certain circumstances, harmonics can be important and also troublesome. Electronic loads containing power semiconductor devices, which switch on and off to control the flow of energy between the source and load, typically cause power system harmonics. This switching on and off, hundreds to thousands of times every second, directly modulates the current and corrupts the voltage. In other words, the current modulation causes voltage drops across the impedance of the lines and distribution equipment resulting in the voltage being modulated as well. Thus, high-frequency harmonic components are injected into the power system. Examples include variable-speed motor drives, electronic lighting ballasts, and electronic equipment power supplies.

As a result, these loads can cause dangerous resonance conditions between the electronic load's step-down transformer and the utility's power factor correction capacitors. Harmonics will cause additional heating in wiring and other equipment, and will not be detected by most digital test meters unless they are true rms measuring devices. In addition, electromechanical meters typically under-register the energy being absorbed by these electronic loads. In general, solid-state meters do a better job of measuring the total energy being consumed by a customer's electronic load.

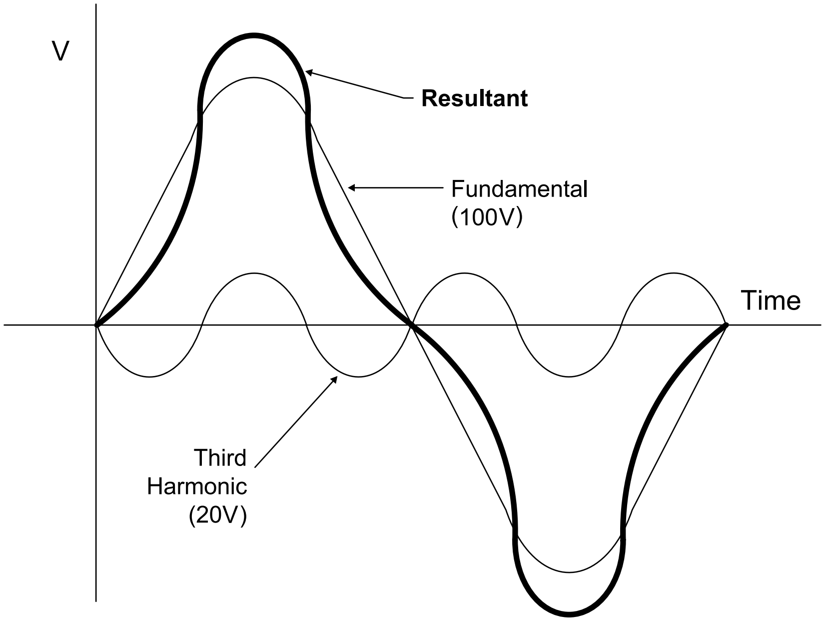


Figure 4-23. Sine Wave with 20% Third Harmonic.

ALTERNATING-CURRENT THREE-PHASE CIRCUITS

BALANCED THREE-PHASE SYSTEMS

A balanced three-phase system consists of three parts: a balanced three-phase source; a balanced three-phase transmission system; and a balanced three-phase load.

BALANCED THREE-PHASE SOURCES

A balanced three-phase source consists of three single-phase sources, A, B, and C, whose rms magnitudes are identical and whose phase angles are mutually displaced ± 120°.

The three-phase source may be wye (Y) or delta (Δ) connected. A wye connection has a set of line-to-neutral and line-to-line voltages. A delta connection only has a set of line-to-line voltages. The line-to-neutral voltages are related to the line-to-line voltages. If a set of line-to-neutral voltages are represented by:

$$\boldsymbol{V}_{an} = V_{an} \angle 0°$$

$$\boldsymbol{V}_{bn} = V_{bn} \angle -120°$$

$$\boldsymbol{V}_{cn} = V_{cn} \angle -240°$$

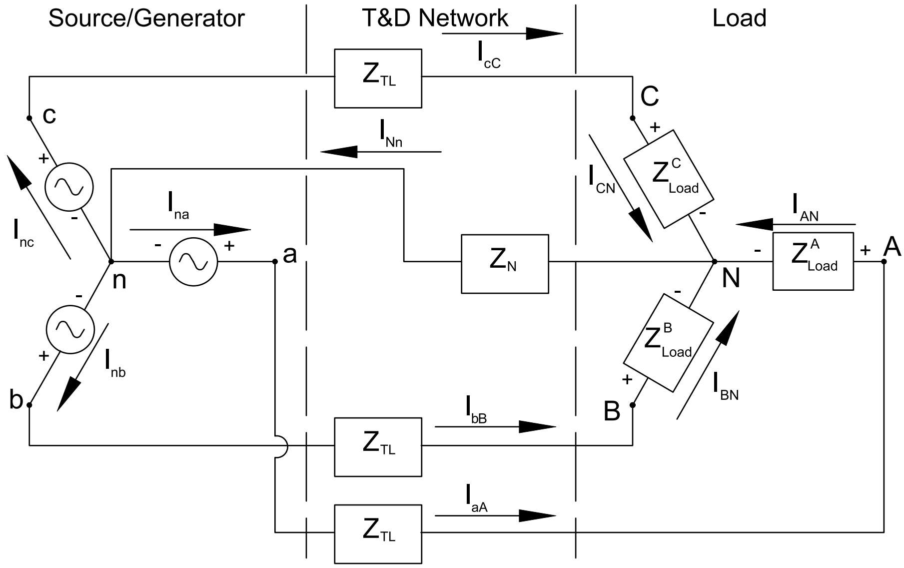


Figure 4-24. Balanced Three-Phase Four-Wire Wye Network Schematic.

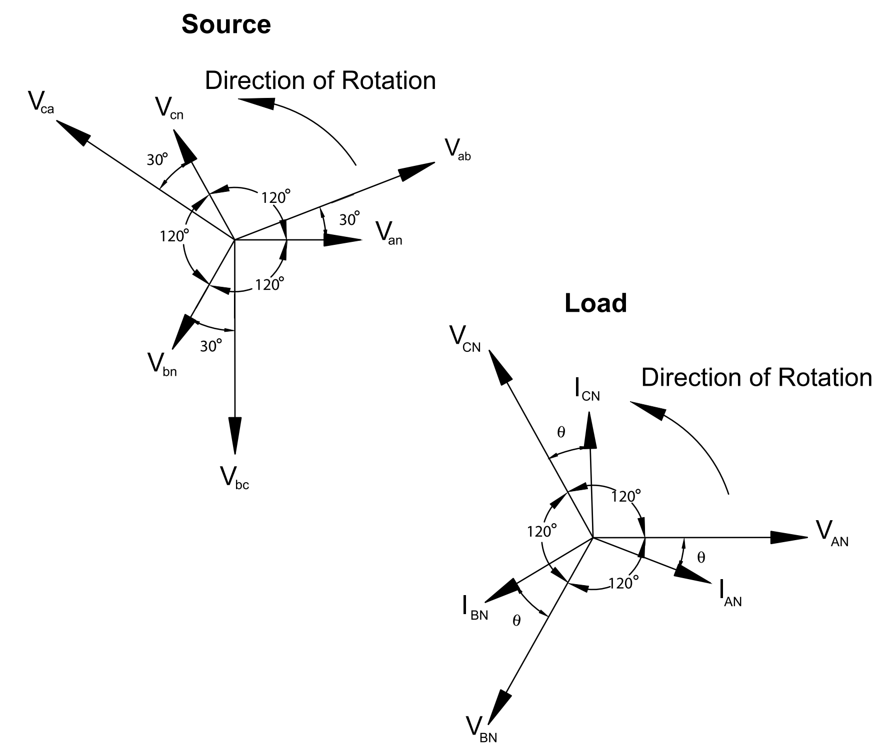


Figure 4-25. Balanced Three-Phase Four-Wire Wye Network Phasor Diagram.

then the line-to-line voltages are

$$\boldsymbol{V}_{ab} = \boldsymbol{V}_{an} - \boldsymbol{V}_{bn} = V_{ab} \angle 30°$$

$$\boldsymbol{V}_{bc} = \boldsymbol{V}_{bn} - \boldsymbol{V}_{cn} = V_{bc} \angle -90°$$

$$\boldsymbol{V}_{ca} = \boldsymbol{V}_{cn} - \boldsymbol{V}_{an} = V_{ca} \angle -210°$$

Note that $V_{an} = V_{bn} = V_{cn} = V_{ln}$ and $V_{ab} = V_{bc} = V_{ca} = V_{ll} = \sqrt{3}\ V_{ln}$. Also the line-to-line voltages *lead* the line-to-neutral voltages by 30°. Assuming that the line-to-neutral phasors are rotating in the counter-clockwise direction, there is a positive or *abc* sequence.

If, however, the line-to-neutral voltages are rotating in the clockwise direction, there is a negative or *acb* sequence. In this case, the following results:

$$\boldsymbol{V}_{an} = V_{an} \angle 0°$$

$$\boldsymbol{V}_{bn} = V_{bn} \angle -240°$$

$$\boldsymbol{V}_{cn} = V_{cn} \angle -120°$$

and

$$\boldsymbol{V}_{ab} = \boldsymbol{V}_{an} - \boldsymbol{V}_{bn} = V_{ab} \angle -30°$$

$$\boldsymbol{V}_{bc} = \boldsymbol{V}_{bn} - \boldsymbol{V}_{cn} = V_{bc} \angle -150°$$

$$\boldsymbol{V}_{ca} = \boldsymbol{V}_{cn} - \boldsymbol{V}_{an} = V_{ca} \angle -270°$$

Note again that $V_{an} = V_{bn} = V_{cn} = V_{ln}$ and $V_{ab} = V_{bc} = V_{ca} = V_{ll} = \sqrt{3}\ V_{ln}$. In this case, the line-to-line voltages *lag* the line-to-neutral voltages by 30°.

The current flowing through a phase of a wye connected three-phase source will be identical to the current flowing through that phase's line impedance. That is, the current flowing through each phase voltage is:

$$\boldsymbol{I}_{aA} = \boldsymbol{I}_{na} = \boldsymbol{I}_{na} \angle 0° + \theta$$

$$\boldsymbol{I}_{bB} = \boldsymbol{I}_{nb} = \boldsymbol{I}_{nb} \angle -120° + \theta$$

$$\boldsymbol{I}_{cC} = \boldsymbol{I}_{nc} = \boldsymbol{I}_{nc} \angle -240° + \theta$$

The source currents are referenced to the phase A line-to-neutral source voltage. The angle θ corresponds to the current angle as shown in figure 4-25.

The currents flowing through a delta- (Δ-) connected three-phase source will be related to the line currents by $\sqrt{3}$ and 30° for *abc* or positive sequence and $\sqrt{3}$ and −30° for *acb* or negative sequence. That is, the positive-sequence current flowing through the Δ-connected source phase voltages is:

$$\boldsymbol{I}_{ba} = \frac{1}{\sqrt{3}} \angle 30° \left(I_{an} \angle 0° + \theta\right)$$

$$\boldsymbol{I}_{cb} = \frac{1}{\sqrt{3}} \angle 30° \left(I_{bn} \angle -120° + \theta\right)$$

$$\boldsymbol{I}_{ac} = \frac{1}{\sqrt{3}} \angle 30° \left(I_{cn} \angle -240° + \theta\right)$$

This implies that, knowing the line currents, it is possible to get the Δ-connected source phase currents by shrinking the magnitude by $\sqrt{3}$ and shifting 30°.

The negative-sequence current flowing through the Δ-connected source phase voltages is:

$$\boldsymbol{I}_{\text{ba}} = \frac{1}{\sqrt{3}}\,\underline{/-30°}\,\left(I_{\text{an}}\,\underline{/0° + \theta}\right)$$

$$\boldsymbol{I}_{\text{cb}} = \frac{1}{\sqrt{3}}\,\underline{/-30°}\,\left(I_{\text{bn}}\,\underline{/-240° + \theta}\right)$$

$$\boldsymbol{I}_{\text{ac}} = \frac{1}{\sqrt{3}}\,\underline{/-30°}\,\left(I_{\text{cn}}\,\underline{/-120° + \theta}\right)$$

This implies that, knowing the line currents, it is possible to get the Δ-connected source phase currents by shrinking the magnitude by $\sqrt{3}$ and shifting $-30°$.

BALANCED THREE-PHASE LINES

Transmission and distribution lines transmit electric power between the source and load. Each phase of a three-phase line will have a line impedance, Z_{TL} A three-phase line will be balanced if and only if the impedance in each phase is the same. That is,

$$Z_{\text{TL}} = Z_{\text{TL},}{}^{\text{a}} = Z_{\text{TL},}{}^{\text{b}} = Z_{\text{TL},}{}^{\text{c}}$$

The line impedance normally consists of a resistive and inductive reactance component in series.

$$Z_{\text{TL}} = R_{\text{TL}} + jX_{\text{TL}}$$

A simpler model exists when the line resistance is ignored. More elaborate models do exist but will not be discussed here.

BALANCED THREE-PHASE LOADS

Each phase of a three-phase load will have an impedance, Z_{L}. A three-phase load will be balanced if and only if the load impedance in each phase is the same. That is,

$$Z_{\text{L}} = Z_{\text{L},}{}^{\text{a}} = Z_{\text{L},}{}^{\text{b}} = Z_{\text{L},}{}^{\text{c}}$$

The load impedance normally consists of a resistive and inductive reactance component in series.

$$Z_{\text{L}} = R_{\text{L}} + jX_{\text{L}}$$

In resistance models the active power, P is absorbed by the load, and in reactance models the reactive power, Q is absorbed or produced by the load. If Q is being absorbed, X_{l} will be positive (i.e., an inductor). If Q is being produced, X_{l} will be negative (i.e., a capacitor).

The three-phase load may be wye (Y) or delta (Δ) connected. A wye connection has a set of line-to-neutral and line-to-line voltages. A delta connection only has a set of line-to-line voltages. The line-to-neutral voltages are related to the line-to-line voltages. If a set of line-to-neutral voltages are

$$\boldsymbol{V}_{\text{AN}} = V_{\text{AN}}\,\underline{/0°}$$

$$\boldsymbol{V}_{\text{BN}} = V_{\text{BN}}\,\underline{/-120°}$$

$$\boldsymbol{V}_{\text{CN}} = V_{\text{CN}}\,\underline{/-240°}$$

then the line-to-line voltages are

$$\boldsymbol{V}_{\mathrm{AB}} = \boldsymbol{V}_{\mathrm{AN}} - \boldsymbol{V}_{\mathrm{BN}} = V_{\mathrm{AB}}\,\underline{/30^\circ}$$

$$\boldsymbol{V}_{\mathrm{BC}} = \boldsymbol{V}_{\mathrm{BN}} - \boldsymbol{V}_{\mathrm{CN}} = V_{\mathrm{BC}}\,\underline{/-90^\circ}$$

$$\boldsymbol{V}_{\mathrm{CA}} = \boldsymbol{V}_{\mathrm{CN}} - \boldsymbol{V}_{\mathrm{AN}} = V_{\mathrm{CA}}\,\underline{/-210^\circ}$$

Note that $V_{\mathrm{AN}} = V_{\mathrm{BN}} = V_{\mathrm{CN}} = V_{\mathrm{LN}}$ and $V_{\mathrm{AB}} = V_{\mathrm{BC}} = V_{\mathrm{CA}} = V_{\mathrm{LL}} = \sqrt{3}\ V_{\mathrm{LN}}$. Also note that the line-to-line voltages *lead* the line-to-neutral voltages by 30°. We have assumed that the line-to-neutral phasors are rotating in the counter-clockwise direction. Thus, we have a positive or *abc* sequence.

If however, the line-to-neutral voltages are rotating in the clockwise direction, then we have a negative or *acb* sequence. In this case, the following results,

$$\boldsymbol{V}_{\mathrm{AN}} = V_{\mathrm{AN}}\,\underline{/0^\circ}$$

$$\boldsymbol{V}_{\mathrm{BN}} = V_{\mathrm{BN}}\,\underline{/-240^\circ}$$

$$\boldsymbol{V}_{\mathrm{CN}} = V_{\mathrm{CN}}\,\underline{/-120^\circ}$$

and

$$\boldsymbol{V}_{\mathrm{AB}} = \boldsymbol{V}_{\mathrm{AN}} - \boldsymbol{V}_{\mathrm{BN}} = V_{\mathrm{AB}}\,\underline{/-30^\circ}$$

$$\boldsymbol{V}_{\mathrm{BC}} = \boldsymbol{V}_{\mathrm{BN}} - \boldsymbol{V}_{\mathrm{CN}} = V_{\mathrm{BC}}\,\underline{/-270^\circ}$$

$$\boldsymbol{V}_{\mathrm{CA}} = \boldsymbol{V}_{\mathrm{CN}} - \boldsymbol{V}_{\mathrm{AN}} = V_{\mathrm{CA}}\,\underline{/-150^\circ}$$

Again, note that $V_{\mathrm{AN}} = V_{\mathrm{BN}} = V_{\mathrm{CN}} = V_{\mathrm{LN}}$ and $V_{\mathrm{AB}} = V_{\mathrm{BC}} = V_{\mathrm{CA}} = V_{\mathrm{LL}} = \sqrt{3}\ V_{\mathrm{LN}}$. But, in this case, the line-to-line voltages *lag* the line-to-neutral voltages by 30°.

The current flowing through a phase of a wye-connected three-phase load will be identical to the current flowing through that phase's line impedance. That is, the current flowing through each phase voltage is

$$\boldsymbol{I}_{\mathrm{AN}} = I_{\mathrm{AN}}\,\underline{/0^\circ + \theta}$$

$$\boldsymbol{I}_{\mathrm{BN}} = I_{\mathrm{BN}}\,\underline{/-120^\circ + \theta}$$

$$\boldsymbol{I}_{\mathrm{CN}} = I_{\mathrm{CN}}\,\underline{/-240^\circ + \theta}$$

Note the load currents are still referenced to the phase A line-to-neutral load voltage.

The currents flowing through a Δ-connected three-phase load will be related to the line currents by $\sqrt{3}$ and 30° for *abc* or positive sequence and $\sqrt{3}$ and −30° for *acb* or negative sequence. The positive-sequence current flowing through the Δ-connected load phase voltages is

$$\boldsymbol{I}_{\mathrm{AB}} = \frac{1}{\sqrt{3}}\,\underline{/30^\circ}\,\left(I_{\mathrm{AN}}\,\underline{/0^\circ + \theta}\right)$$

$$\boldsymbol{I}_{\mathrm{BC}} = \frac{1}{\sqrt{3}}\,\underline{/30^\circ}\,\left(I_{\mathrm{BN}}\,\underline{/-120^\circ + \theta}\right)$$

$$\boldsymbol{I}_{\mathrm{CA}} = \frac{1}{\sqrt{3}}\,\underline{/30^\circ}\,\left(I_{\mathrm{CN}}\,\underline{/-240^\circ + \theta}\right)$$

This implies that if we know the line currents, it is possible to find the Δ-connected load phase currents by shrinking the magnitude by $\sqrt{3}$ and shifting 30°.

The negative-sequence current flowing through the Δ-connected load phase voltages is

$$I_{AB} = \frac{1}{\sqrt{3}} \angle{-30°} \left(I_{AN} \angle{0° + \theta}\right)$$

$$I_{BC} = \frac{1}{\sqrt{3}} \angle{-30°} \left(I_{BN} \angle{-240° + \theta}\right)$$

$$I_{CA} = \frac{1}{\sqrt{3}} \angle{-30°} \left(I_{CN} \angle{-120° + \theta}\right)$$

This implies that if we know the line currents, it is possible to find the Δ-connected load phase currents by shrinking the magnitude by $\sqrt{3}$ and shifting $-30°$.

PER-PHASE EQUIVALENT CIRCUITS

If a three-phase system is balanced as explained above, then the three-phase circuit can be simplified to an equivalent single-phase circuit. In this case, all the formulas developed for single-phase AC circuits can be used.

POWER AND ENERGY IN THREE-PHASE AC CIRCUITS

In AC circuits, the three-phase active, average, or real power is

$$P_{3\phi} = 3P = 3V_{rms}I_{rms}\cos(\theta_V - \theta_I) = 3V_{rms}I_{rms}\cos(\theta_Z) = 3V_{rms}I_{rms}\cos(\phi_{pf}) = 3V_{rms}I_{rms}\text{DPF}$$

where $\cos\theta_Z = \cos\phi_{pf} = \cos(\theta_V - \theta_I)$ and is equal to the displacement power factor of the circuit. Here, V_{rms} is equal to the rms value of the line-to-neutral voltage and I_{rms} is the rms value of the line current. The units of $P_{3\phi}$ is Watts.

In AC circuits, the three-phase reactive or imaginary power is

$$Q_{3\phi} = 3Q = 3V_{rms}I_{rms}\sin(\theta_V - \theta_I) = 3V_{rms}I_{rms}\sin(\theta_Z) = 3V_{rms}I_{rms}\sin(\phi_{pf})$$

The units of $Q_{3\phi}$ is voltamperes reactive.

Ohm's Law and the power equations are combined to give the various formulas for single-phase AC series circuits shown in Table 4-5.

In the case where the three-phase system is imbalanced, it is necessary to calculate the powers using conventional circuit analysis techniques and add them to find the total powers.

$$P_{3\phi} = P_A + P_B + P_C$$

$$Q_{3\phi} = Q_A + Q_B + Q_C$$

$$S_{3\phi} = P_{3\phi} + jQ_{3\phi} = S_A + S_B + S_C$$

$$|S_{3\phi}| = \sqrt{P_{3\phi}^2 + Q_{3\phi}^2}$$

POWER TRIANGLE

In sinusoidal AC circuits, the power triangle is used to relate the three-phase active, real, or average power $P_{3\phi}$ and the three-phase reactive or imaginary power

$Q_{3\phi}$ to a third important term called the three-phase complex power $S_{3\phi}$ having units of voltamperes. The complex power $S_{3\phi}$ is defined as

$$S_{3\phi} = P_{3\phi} + jQ_{3\phi} = \sqrt{P_{3\phi}^2 + Q_{3\phi}^2} \angle \tan^{-1}\left(\frac{Q_{3\phi}}{P_{3\phi}}\right) = |S_{3\phi}| \angle \phi_{pf}$$

in terms of the powers $P_{3\phi}$ and $Q_{3\phi}$ and

$$S_{3\phi} = 3S_{\phi} = 3V_{ln}I_{line}{}^{\phi} = 3I_{rms}^2 Z = \frac{3V_{rms}^2}{Z^{\phi}}$$

$$\begin{aligned} S_{3\phi} = 3S &= |S_{3\phi}| \angle \phi_{pf} = |S_{3\phi}| \angle \theta_V - \theta_I = |S_{3\phi}| \angle \theta_Z \\ &= 3V_{rms}I_{rms} \angle \theta_V - \theta_I = 3V_{rms}I_{rms} \angle \theta_Z = 3V_{rms}I_{rms} \angle \phi_{pf} \\ &= \sqrt{3}\, V_{ll}I_{rms} \angle \theta_V - \theta_I = \sqrt{3}\, V_{ll}I_{rms} \angle \theta_Z = \sqrt{3}\, V_{ll}I_{rms} \angle \phi_{pf} \end{aligned}$$

when written in terms of the voltage and current phasor magnitudes and phase angles. The magnitude of the three-phase complex power $S_{3\phi}$, $|S_{3\phi}|$, is known as the three-phase apparent power and is the product $3V_{rms}\, I_{rms} = \sqrt{P_{3\phi}^2 + Q_{3\phi}^2}$. It also has units of Voltamperes. The three-phase apparent power is a measure of the operating limits in electrical equipment such as transformers, motors, and generators.

The relationship between $P_{3\phi}$, $Q_{3\phi}$, and $|S_{3\phi}|$ is best shown by the power triangle, Figure 4-26. Mathematically,

$S_{3\phi} = P_{3\phi} + jQ_{3\phi,L}$ for an inductive load having a lagging power factor and

$S_{3\phi} = P_{3\phi} + jQ_{3\phi,C}$ for an capacitive load having a leading power factor

For the two cases immediately above,

$$Q_{3\phi,C} = 3I_{rms}^2 X_C = \frac{3V_{rms}^2}{X_C}$$

$$Q_{3\phi,L} = 3I_{rms}^2 X_L = \frac{3V_{rms}^2}{X_L}$$

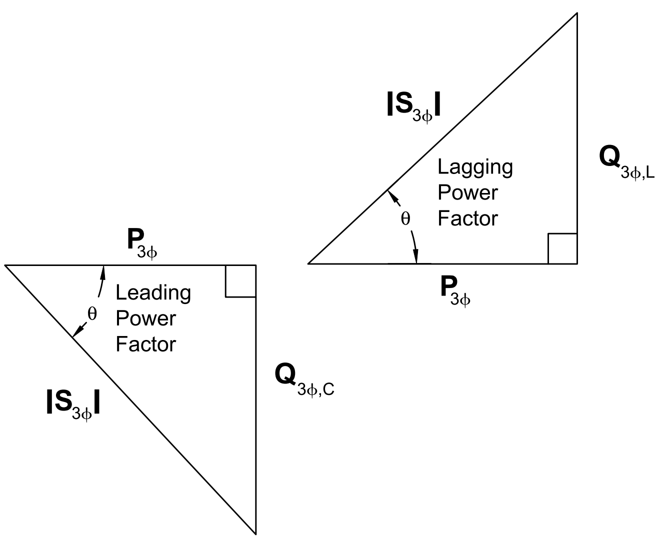


Figure 4-26. Power Triangles (Three Phase).

When a circuit is capacitive (i.e., leading power factor), then $Q_{3\phi,C}$ is negative or less than zero since X_C is negative. When a circuit is inductive (i.e., lagging power factor), then $Q_{3\phi,L}$ is positive or greater than zero. Using trigonometry, many other expressions can be written from Figure 4-26. For example, the displacement power factor can be written as

$$\mathrm{DPF} = \cos(\theta_V - \theta_I) = \cos(\theta_Z) = \cos(\phi_{pf}) = \cos\left(\tan^{-1}\left(\frac{Q_{3\phi}}{P_{3\phi}}\right)\right) = \frac{P_{3\phi}}{|S_{3\phi}|} = \frac{P_{3\phi}}{3V_{rms}I_{rms}}$$

For metering applications, the complex power $S_{3\phi}$ is not a measurable quantity. However, the newer electronic meters can measure $|S_{3\phi}|$ directly. The reactive power $Q_{3\phi}$ can be measured with care, and then only for sinusoidal systems. In practice, measure $|S_{3\phi}|$ and $P_{3\phi}$, and then compute $Q_{3\phi}$.

DISTRIBUTION CIRCUITS

WYE – WYE TRANSFORMER CONNECTIONS

A typical distribution transformer connection is wye – wye. This transformer connection provides no phase shift and is transparent to all electrical quantities. The following formulas apply for the voltage magnitudes:

$$|V_2| = \sqrt{3} \times |V_1| \qquad |V_1| = \frac{1}{\sqrt{3}} \times \frac{N_1}{N_2} \times |V_4| \qquad |V_2| = \frac{N_1}{N_2} \times |V_4|$$

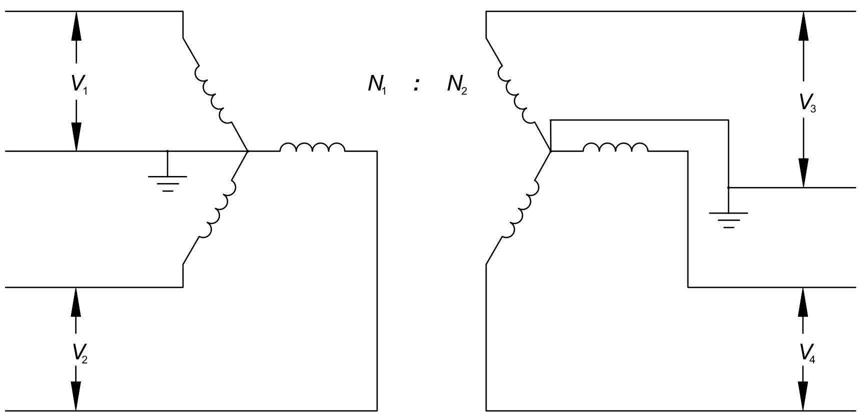


Figure 4-27. Three-Phase Wye – Wye Transformer Configuration.

WYE – DELTA TRANSFORMER CONNECTIONS

A typical distribution transformer connection is wye – delta. This transformer connection provides a leading 30° (−30°) phase shift from the primary to the secondary winding for positive (negative) sequence and is transparent to some electrical quantities. The following formulas apply:

$$V_2 = \sqrt{3} \times V_1 \qquad \sqrt{3} \times V_1 = \frac{N_1}{N_2} \times V_3$$

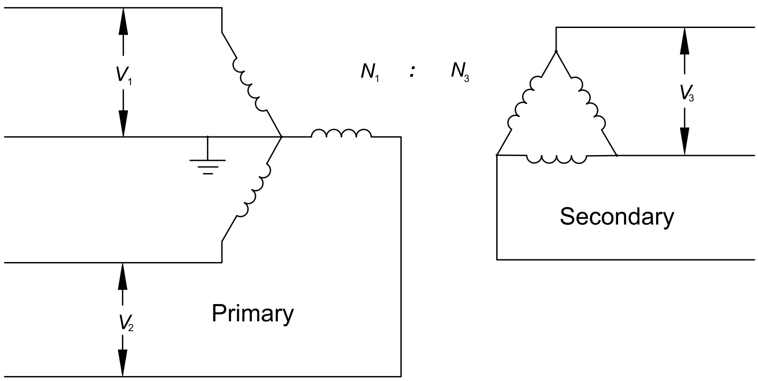


Figure 4-28. Three-Phase Wye – Delta Transformer Configuration.

DELTA – WYE TRANSFORMER CONNECTIONS

A typical distribution transformer connection is delta – wye. This transformer connection provides a leading 30° (−30°) phase shift from the primary to the secondary winding for positive (negative) sequence and is transparent to some electrical quantities. The following formulas apply:

$$V_2 = \sqrt{3} \times V_3 \qquad \frac{V_2}{\sqrt{3}} = V_3 \qquad V_1 = \left(\frac{N_1}{N_2}\right) V_2$$

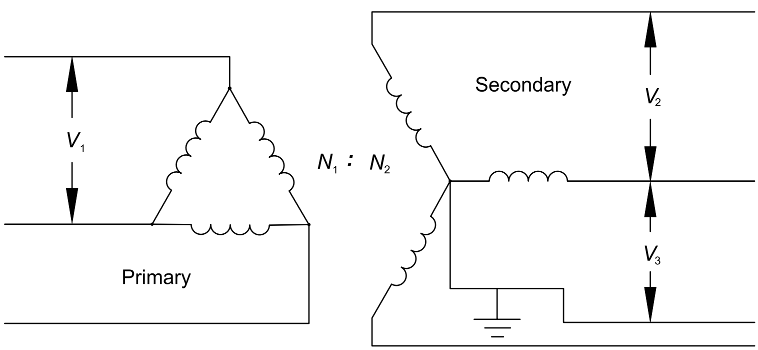


Figure 4-29. Three-Phase Delta – Wye Transformer Configuration.

DELTA – DELTA TRANSFORMER CONNECTIONS

A typical distribution transformer connection is delta – delta. This transformer connection provides no phase shift and is transparent to some electrical quantities. The following formula applies:

$$V_1 = \frac{N_1}{N_2} \times V_2$$

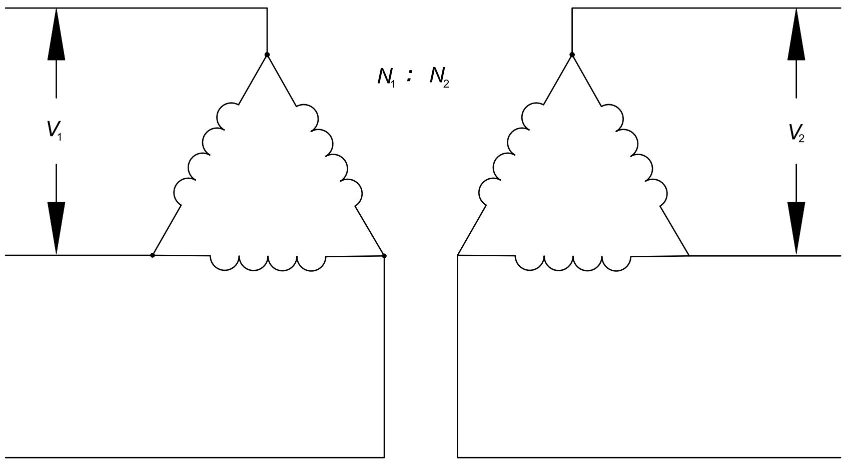


Figure 4-30. Three-Phase Delta – Delta Transformer Configuration.

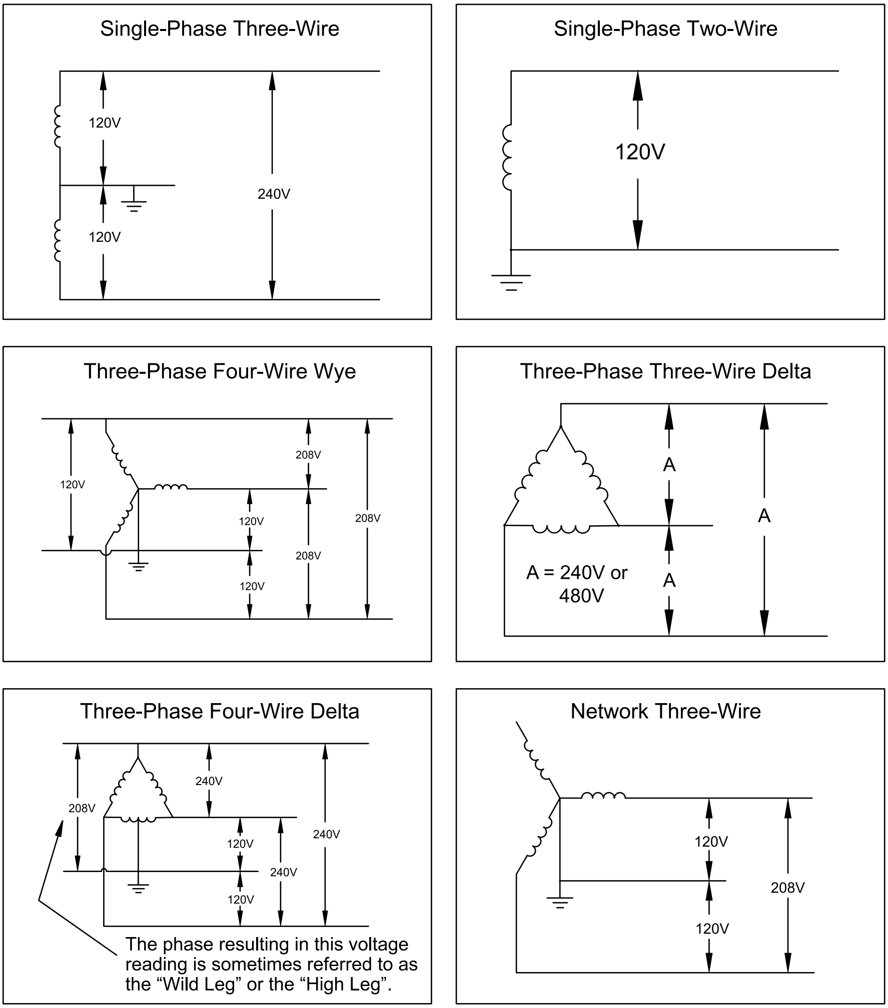


Figure 4-31. Common Distribution Circuits.

CHAPTER 5

SOLID-STATE ELECTRONICS

THIS CHAPTER DEALS WITH basic solid-state electronics as applied to modern metering devices. The information contained here is intended as a review for metering personnel with a background in electronics and as an introduction for those unfamiliar with the subject, with the intention of stimulating further study.

In the study of solid-state electronics it is necessary to understand the effects of combining semiconductors of differing atomic structures. For this reason the chapter begins with a discussion of the atom in order to introduce the concept of current flow across the semiconductor junction. Finally, the chapter introduces digital electronics including the microprocessor.

THE ATOM

Atomic structure is best demonstrated by the hydrogen atom, which is composed of a nucleus or center core containing one proton and a single orbiting electron. As the electron revolves around the nucleus it is held in orbit by two counteracting forces. One of these forces is centrifugal force, which tends to cause the electron to fly outward as it orbits. The second force is centripetal force, which tends to pull the electron toward the nucleus and is caused by the mutual attraction between the positive nucleus and negative electron. At some given radius the two forces will exactly balance each other providing a stable path for the electron. By virtue of its motion, the electron in the hydrogen atom has kinetic energy. Due to its position it also has potential energy.

The total energy of the electron (kinetic plus potential) is the factor which determines the radius of the electron orbit around the nucleus. The orbit shown in Figure 5-1 is the smallest possible orbit the hydrogen electron can have. For the electron to remain in this orbit is must neither gain nor lose energy.

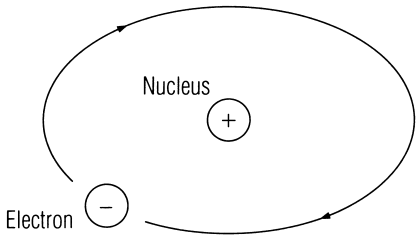


Figure 5-1. Hydrogen Atom.

The electron will remain in its lowest orbit until a sufficient amount of energy is available, at which time the electron will accept the energy and jump to one of a series of permissible orbits. An electron cannot exist in the space between permissible orbits or energy levels. This indicates that the electron will not accept energy unless it is great enough to elevate the electron to one of the allowable energy levels. Light and heat energy as well as collisions with other particles can cause the electron to jump orbit.

Once the electron has been elevated to an energy level higher than the lowest possible energy level, the atom is said to be in an excited state. The electron will not remain in this excited condition for more than a fraction of a second before it will radiate the excess energy and return to a lower energy orbit.

An alternative would be for the electron to return to the lower level in two jumps; from the third to the second, and then from the second to the first. In this case the electron would emit energy twice, once from each jump. Each emission would have less energy than the original amount which originally excited the electron.

Although hydrogen has the simplest of all atoms, the principles just developed apply to the atoms of more complex elements. The manner in which the orbits are established in an atom containing more than one electron is somewhat complicated and is part of a science known as Quantum Mechanics. In an atom containing two or more electrons, the electrons interact with each other and the exact path of any one electron is difficult to predict. However, each electron will lie in a specific energy band and the above-mentioned orbits will be considered as an average of the electrons' positions. Also, the various electron orbits found in large atoms are grouped into shells which correspond to fixed energy levels.

The number of electrons in the outermost orbit group or shell determines the valence of the atom and, therefore, is called the valence shell. The valence of an atom determines its ability to gain or lose an electron which, in turn, determines the chemical and electrical properties of the atom. An atom that is lacking only one or two electrons from its outer shell will easily gain electrons to complete its shell, but a large amount of energy is required to free any other electrons. An atom having a relatively small number of electrons in its outer shell in comparison to the number of electrons required to fill the shell will easily lose its valence electrons. Gaining or losing electrons in valence shells is called ionization. Atoms gaining electrons are negative ions and atoms losing electrons are positive ions.

SEMICONDUCTOR ELECTRONICS

Any element can be categorized as either a conductor, semiconductor, or insulator. Conductors are elements, such as copper or silver, which will conduct electricity readily. Insulators (non-conductors) do not conduct electricity to any great degree and are therefore used to prevent a flow of electricity. Rubber and glass are good insulators. Material such as germanium and silicon are not good conductors, but cannot be used as insulators either, since their electrical characteristics fall between those of conductors and insulators. These are called semiconductors.

The electrical conductivity of matter is ultimately dependent upon the energy levels of the atoms of which the material is constructed. In any solid material such as copper, the atoms which make up the molecular structure are bound together in a crystal lattice which is a rigid structure of copper atoms. Since the atoms of copper are firmly fixed in position within the lattice structure, they are not free to migrate through the material and therefore cannot carry the electricity through the conductor without application of some external force. However, by ionization, electrons could be removed from the influence of the parent atom and made to move through the copper lattice under the influence of external forces. It is by virtue of the movement of these free electrons that electrical energy is transported within the copper material. Since copper is a good conductor, it must contain vast numbers of free electrons.

HOLE CURRENT AND ELECTRON CURRENT

The degree of difficulty in freeing valence electrons from the nucleus of an atom determines whether the element is a conductor, semiconductor, or an insulator. When an electron is freed in a block of pure semiconductor material, it creates a hole which acts as a positively charged current carrier. Thus, an electron liberation creates two currents which are known as electron current and hole current.

When an electric field is applied, holes and electrons are accelerated in opposite directions. The life spans (time until recombination) of the hole and the free electron in a given semiconductor sample are not necessarily the same. Hole conduction may be thought of as the unfilled tracks of a moving electron. Because the hole is a region of net positive charge, the apparent motion is like the flow of particles having a positive charge.

If suitable impurity is added to the semiconductor, the resulting mixture can be made to have either an excess of electrons, causing more electron current, or an excess of holes, causing more hole current.

Depending upon the kind of impurity added to a semiconductor, it will have more (or fewer) free electrons than holes. Both electron current and hole current will be present, but a majority carrier will dominate. The holes are called positive carriers and the electrons, negative carriers. The one present in the greater quantity is called the majority carrier; the other is called the minority carrier. The quality and quantity of the impurity are carefully controlled by the doping process.

N AND P TYPE MATERIALS

When an impurity like arsenic is added to germanium it will change the germanium crystal lattice in such a way as to leave one electron relatively free in the crystal structure. Because this type of material conducts by electron movement, it is called a negative carrier (N-type) semiconductor. Pure germanium may be converted into an N-type semiconductor by doping it with a donor impurity consisting of any element containing five electrons in its outer shell. The amount of the impurity added is very small.

An impurity element can also be added to pure germanium to dope the material so as to leave one electron lacking in the crystal lattice, thereby creating a hole in the lattice. Because this semiconductor material conducts by the movement of holes which are positive charges, it is called a positive carrier (P-type) semiconductor. When an electron fills a hole, the hole appears to move to the spot previously occupied by the electron.

As stated previously, both holes and electrons are involved in conduction. In N-type material the electrons are the majority carriers and holes are the minority carriers. In P-type material the holes are the majority carriers and the electrons are the minority carriers.

Current flow through an N-type material is illustrated in Figure 5-2. Conduction in this type of semiconductor is similar to conduction in a copper conductor. That is, an application of voltage across the material will cause the loosely bound electron to be released from the impurity atom and move toward the positive potential point.

Current flow through a P-type material is illustrated in Figure 5-3. Conduction in this material is by positive carrier (holes) from the positive to the negative terminal. Electrons from the negative terminal cancel holes in the vicinity of the terminal, while, at the positive terminal, electrons are being removed from the crystal lattice, thus creating new holes. The new holes then move toward the negative terminal (the electrons shifting to the positive terminal) and are canceled by more electrons emitted into the material from the negative terminal. This process continues as a steady stream of holes (hole current) move toward the negative terminal.

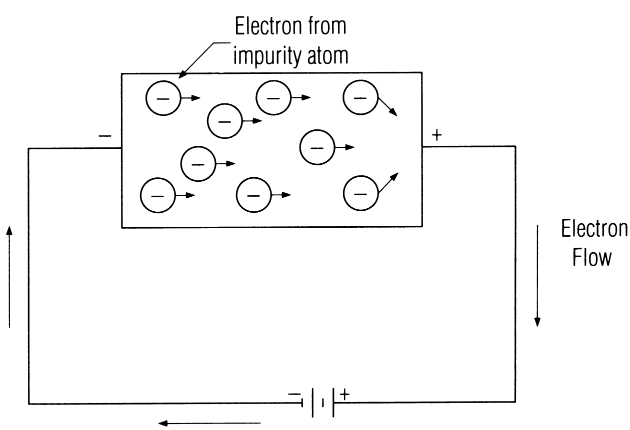


Figure 5-2. Electron Flow N-Type Material.

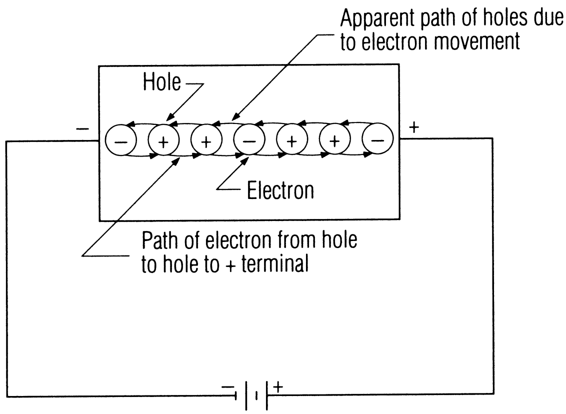


Figure 5-3. Electron Flow in P-Type Material.

P-N JUNCTION

Both N-type and P-type semiconductor materials are electrically neutral. However, a block of semiconductor material may be doped with impurities so as to make half the crystals N-type material and the other half P-type material. A force will then exist across the thin junction of the N-type and P-type material. The force is an electro-chemical attraction by the P-type material for electrons in the N-type material. Due to this force, electrons will be caused to leave the N-type material and enter the P-type material. This will make the N-type material near to the junction positive with respect to the remainder of the N-type material. Also the P-type material near to the junction will be negative with respect to the remaining P-type material.

After the initial movement of charges, further migration of electrons ceases due to the equalization of electron concentration in the immediate vicinity of the junction. The charged areas on either side of the junction constitute a potential barrier, or junction barrier, which prevents further current flow. This area is also called a depletion region. The device thus formed is called a semiconductor diode.

SEMICONDUCTOR DIODE

The schematic symbol for the semiconductor diode is illustrated in Figure 5-4. The N-type material section, of the device is called the cathode and the P-type material section the anode. The device permits electron current flow from cathode to anode and restricts electron current flow from anode to cathode.

Consider the case where a potential is placed externally across the diode, positive on the anode with respect to the cathode as depicted in Figure 5-5. This polarity of voltage (anode positive with respect to the cathode) is called forward bias since it decreases the junction barrier and causes the device to conduct appreciable current. Next, consider the case where the anode is made negative with respect to the cathode. Figure 5-6 illustrates this reverse bias condition.

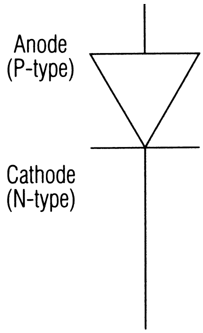


Figure 5-4. Semiconductor Diode Symbol.

Theoretically, no current flow should be possible with reverse bias applied across the junction due to the increase in the junction barrier.

However, since the block of semiconductor material is not a perfect insulator, a very small reverse or leakage current will flow. At normal operating temperatures this current may be neglected. It is noteworthy, however, that leakage current increases with an increase in temperature. The characteristic curve of the typical diode is shown in Figure 5-7. Excessive forward bias results in a rapid increase of forward current and could destroy the diode. By the same token, excess reverse bias could cause a breakdown in the junction due to the stress of the electric field. The reverse bias point at which breakdown occurs is called the breakdown or avalanche voltage.

Some semiconductor diodes are made to operate in the breakdown or avalanche region, the most common being the zener diode which is discussed later.

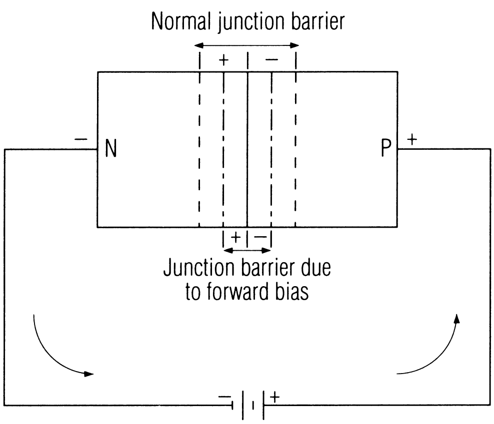


Figure 5-5. Semiconductor Diode with Forward Bias.

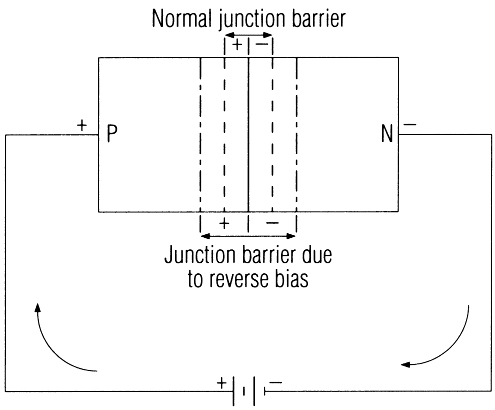


Figure 5-6. Semiconductor Diode with Reverse Bias.

TRANSISTORS

By connecting two P-N junctions, either at their N sides or their P sides, and appropriately applying forward bias to one junction while reverse biasing the other junction, an interesting phenomenon occurs. The thin connecting section of material is the base, and the sections on either end of the junction are the emitter and collector respectively. This device is shown in Figure 5-8. Reverse bias applied to the base-collector junction causes a small reverse current as shown in Figure 5-7 for a typical P-N junction. By forward biasing the emitter-base junction, the base-collector junction is driven further into the breakdown, or avalanche region, resulting in a much larger collector current. What, then, is the difference between the simple junction diode and the transistor? If a small, varying signal is applied between the emitter and base, the bias across the base-emitter junction can be used to control the large current flow in the collector circuit, and if the bias is reversed, current flow ceases. This is the means for controlling a large current by varying a smaller one, which is the basis for amplification.

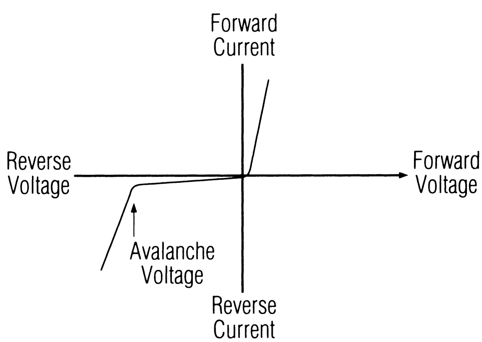


Figure 5-7. Semiconductor Diode Characteristic Curve.

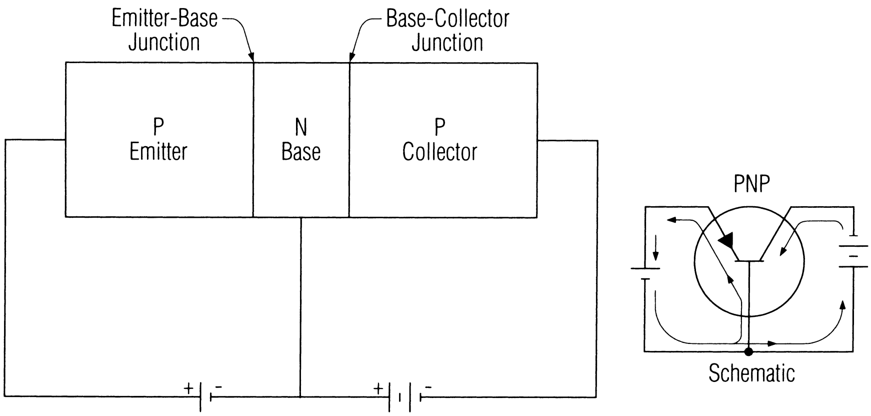


Figure 5-8. Basic PNP Transistor Circuit.

DIGITAL ELECTRONICS

While analog circuits operate on a continuous range of signals, digital electronic circuits have only two states: on and off. Digital circuits use electronic components which can be controlled to operate in either of two electrical conditions, for example, conducting and non-conducting. These two conditions represent the on and off states.

NUMBER SYSTEMS

Decimal Numbers

The decimal number system is comprised of ten digits, zero through nine. It is based on units of ten, and is called a base-ten system. For example, 4,732 is immediately recognized as four thousand, seven hundred, thirty-two. What the digits 4732 actually mean is the sum of four thousands, seven hundreds, three tens, and two ones. In the decimal number system, the digit in the one's place is multiplied by 10^0, the next digit by 10^1, the next digit by 10^2, and so on, for as many digits as there are in the number.

$$\begin{array}{rcrcrcrcr}
4 & \times & 1{,}000 & = & 4 & \times & 10^3 & = & 4{,}000 \\
7 & \times & 100 & = & 7 & \times & 10^2 & = & 700 \\
3 & \times & 10 & = & 3 & \times & 10^1 & = & 30 \\
2 & \times & 1 & = & 2 & \times & 10^0 & = & \underline{2} \\
 & & & & & & & & 4{,}732
\end{array}$$

Binary Numbers

The binary number system uses two digits, one and zero. It is called a base-two system. The binary system fits well with the way digital circuits operate. For example, a transistor can be controlled either to conduct or not conduct current, and can quickly switch from one state to the other. Whether the transistor is conducting or not controls whether its output is high or low, signifying a one or a zero.

The two-state digit is called a bit, a contraction of the words "binary digit." An example of a binary number is 100101 (read as one-zero-zero-one-zero-one). This number is the sum of six binary values which totals 37 in the decimal number system. In the binary number system, the digit in the one's place is multiplied by 2^0, the next digit by 2^1, the next digit by 2^2, and so on, for as many digits as there are in the number.

$$\begin{array}{ccccccccr}
1 & \times & 32 & = & 1 & \times & 2^5 & = & 32 \\
0 & \times & 16 & = & 0 & \times & 2^4 & = & 0 \\
0 & \times & 8 & = & 0 & \times & 2^3 & = & 0 \\
1 & \times & 4 & = & 1 & \times & 2^2 & = & 4 \\
0 & \times & 2 & = & 0 & \times & 2^1 & = & 0 \\
1 & \times & 1 & = & 1 & \times & 2^0 & = & \underline{1} \\
 & & & & & & & & 37
\end{array}$$

In computers, a combination of several bits is used to represent standard characters. Most computer products handle information in bytes, where a byte is a combination of eight bits. One byte can represent a number, a letter, or a special character.

Hexadecimal Numbers

Hexadecimal numbers are sometimes easier to manage when working with large numbers. Since it takes a long string of 1's and 0's to represent a number of any size, it might be convenient to group together binary numbers to form another value with the same meaning. Since computers operate mostly with 4-, 8-, and 16-bit numbers, a grouping of four bits is useful. The hexadecimal system, the base-16 system, is useful because 4 bits can be arranged 16 different ways, and 4 is a common factor of 4, 8, and 16. When working with bytes, two hexadecimal digits define one byte rather than the eight 1's and 0's which would be necessary in the binary number system.

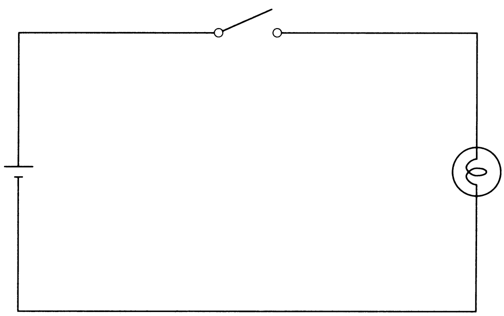
The relationship among the decimal, binary, and hexadecimal number systems, for the first 16 numbers, is as follows:

Decimal	Binary	Hexadecimal
0	0	0
1	1	1
2	10	2
3	11	3
4	100	4
5	101	5
6	110	6
7	111	7
8	1000	8
9	1001	9
10	1010	A
11	1011	B
12	1100	C
13	1101	D
14	1110	E
15	1111	F

Binary Digital Logic Circuits

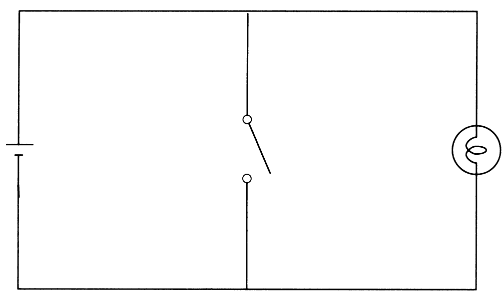
Figure 5-9 shows a schematic diagram of a circuit with a battery, a light bulb, and a switch. When the switch is closed, the light bulb is on. When the switch is open, the light bulb is off. In the truth table, the binary numbers 1 and 0 are used to represent on and off, or that the switch is open and closed.

The NOT function is illustrated in Figure 5-10. The light is on when the switch is not closed, and off when the switch is not open. The NOT function is an inverting function, and the circuit element is called an inverter. If the input is $\bar{A}$, the output is, which is read: "A bar" or "Not A."



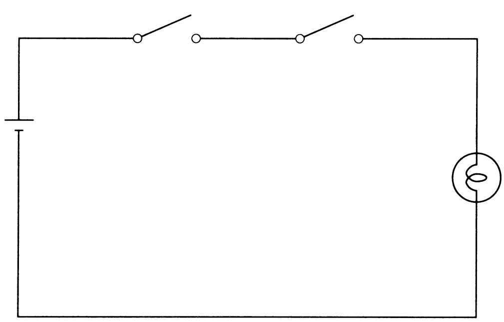
Switch	Light
0	0
1	1

Figure 5-9. Logic Circuit and Truth Table.



Switch	Light
0	1
1	0

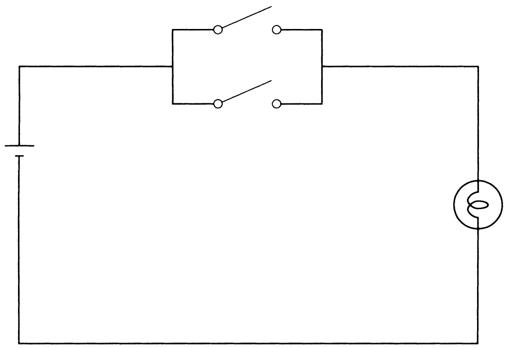
Figure 5-10. NOT Function.



S_1	S_2	Light
0	0	0
0	1	0
1	0	0
1	1	1

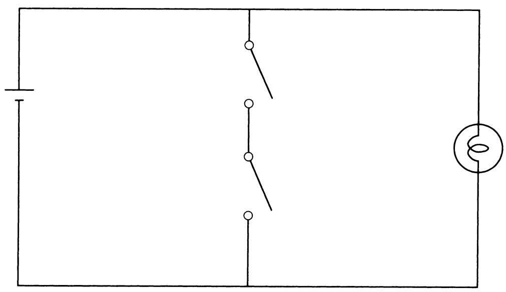
Figure 5-11. AND Function.

Certain digital circuits are called logic circuits because they perform like the logic functions AND, OR, NAND, and NOR. Figure 5-11 shows the AND function: the light is on only when both switches are closed. Figure 5-12 shows the OR function: the light is on when one switch or the other is closed. Figure 5-13 shows the NAND function: the light is not on only when both switches are closed. Figure 5-14 shows the NOR function: the light is not on when either switch is closed.



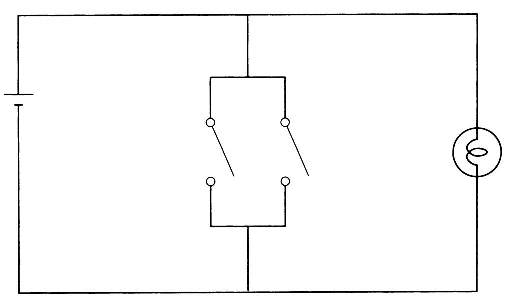
S_1	S_2	Light
0	0	0
0	1	1
1	0	1
1	1	1

Figure 5-12. OR Function.



S_1	S_2	Light
0	0	1
0	1	1
1	0	1
1	1	0

Figure 5-13. NAND Function.



S_1	S_2	Light
0	0	1
0	1	0
1	0	0
1	1	0

Figure 5-14. NOR Function.

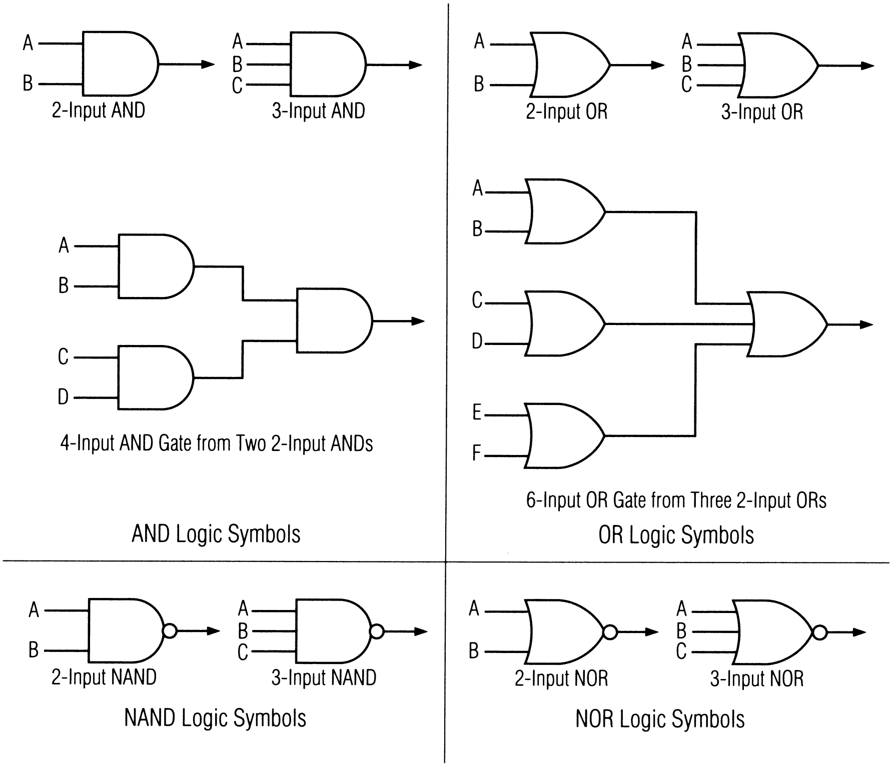


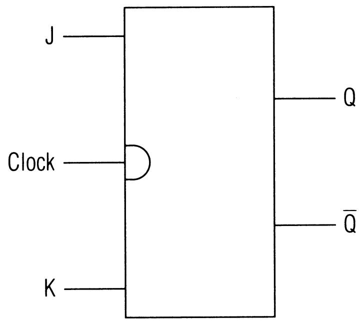
Figure 5-15. Logic Symbols.

Memory Circuits

In digital electronics, logic elements are used to make decisions. The decisions are then stored in memory elements whose basic building block is the flip-flop. A flip-flop is a one-bit circuit which remembers 1's and 0's.

The logic diagram for a J-K flip-flop is shown in Figure 5-16. The truth table lists possible values for the inputs J and K and the output Q, which will appear after the next clock pulse. The value of Q only changes each time a clock pulse appears. The new value of Q depends on the inputs J and K. If J and K are both 0, the output Q keeps the same value (0 or 1) it had before the new clock pulse. If J and K are both 1's, the output Q changes to the opposite of the value it had before the clock pulse. If J and K are 0 and 1, the output Q is set to 0; if J and K are 1 and 0, the output Q is set to 1. The other output $\bar{Q}$ is always the inverse of Q.

With AND, OR, NAND, and NOR circuits the outputs change immediately when inputs change. Flip-flop outputs change only when a clock pulse arrives. So a flip-flop is a memory circuit which remembers the input status from the last clock pulse.



J	K	$Q_{(n+1)}$
0	0	1
0	1	0
1	0	0
1	1	0

Figure 5-16. J-K Flip-Flop.

Most digital systems and all computers need to remember thousands of bits of information. Large memories are made by integrating thousands of flip-flops onto a single piece of silicon, forming a single integrated circuit. Since most computers operate with 8-bit bytes integrated circuits are designed to store bytes by the thousands.

Several construction techniques exist for memory circuits to satisfy different needs. The most popular electronic memory types are Random Access Memory (RAM), Read Only Memory (ROM), and Programmable Read Only Memory (PROM). All forms of memory can be read over and over again without changing the contents.

Random Access Memory is used for the temporary storage of data. It is used for applications where information is stored and retrieved quickly and frequently. A disadvantage of RAM is that all data is lost when power is removed from the circuit. This memory is also called volatile memory and can be supported with batteries (called battery back-up) to power the RAM in the event the main power supply fails.

Read Only Memory is made at an integrated circuit factory to a set of specifications called a mask. This memory can be programmed to perform like many individual gates or to store data which can be accessed as needed. When making a masked ROM, permanent changes are made to the silicon inside the integrated circuit (IC) package. Once a ROM is programmed at the factory, the contents of its memory can never be re-written. This memory is permanent and remains intact even when power is removed. It is called non-volatile memory.

Programmable Read Only Memory stores information which cannot be re-written. Therefore PROMs can be programmed by the user at the laboratory or manufacturing facility and installed in the electronics. Another form of PROM can be erased and programmed by exposing the silicon through a glass window in the package to intense ultra-violet light while entering new data. This is called Erasable Programmable Read Only Memory (EPROM). Electrically Erasable Programmable Read Only Memory (EEPROMS) are erased and written electrically. Another form of PROM is FLASH memory which is faster and permits more erase/write cycles than EEPROM. This type is generally used when there is a requirement for a large amount of non-volatile memory. Programmable Read

Only Memories are useful for prototyping, for low volume requirements, and for applications where the data stored might be changed periodically. The software programs stored in PROMs are sometimes called firmware.

MICROPROCESSORS

Microprocessors get instructions and data from memory, perform arithmetic and logical functions on the data, and store the results. The instructions are in a specific sequence, specifically written for each application by a programmer. Microprocessors typically operate on data organized in groups of 8 or 16 bits. Usually the data path used by the microprocessor defines the data path of the memory chips in the circuit. For example, 8-bit microprocessors use memory circuits with 8-bit data paths. A microprocessor has an input-output system to control communications between itself and external devices. Microprocessors are packaged as integrated circuits.

Analog to Digital Conversion Circuits

These circuits convert an analog signal to a digital representation. The digital output is represented as a word ranging from 8-bits to 20-bits. These words can be in a signed or unsigned format. Successive approximation and sigma delta are examples of different techniques used to perform this conversion.

Digital Signal Processor

Digital signal processors (DSP) are used to execute repetitive math-intensive algorithms. Multiply and accumulate is a fundamental math function in a DSP that is used in higher-level calculations such as watthours and VARhours. A DSP coupled with an Analog to Digital Conversion circuit can be used in a digital meter for calculation of energy and power.

CHAPTER 6
INSTRUMENTS

ELECTRICAL MEASURING INSTRUMENTS are necessary because the nature of most electrical phenomena is beyond the reach of our physical senses. Measurement of electrical quantities makes possible the design, manufacture, and maintenance of the innumerable electrical devices now in use.

The main purpose of any electrical instrument is to measure and indicate the value of an electrical quantity. The measurement may be indicated by a digital numeric value or by a pointer positioned on a scale. Some instruments provide additional functionality by recording measured values over time. This recording may be in the form of a physical indication on a moving chart, as maximum and minimum values during a time frame, or as periodic data stored in electronic memory. The devices commonly used for such measurements are voltmeters, ammeters, and wattmeters.

The field of instrumentation is extensive and includes many classifications of instruments according to portability, type of indication or record, accuracy, design features, etc. We shall briefly discuss only those instruments commonly used in meter departments. These include displaying, indicating, electronic digital, and recording measuring devices.

We will review digital, moving-coil, moving-iron, electrodynamometer, and thermal measuring technologies. Though digital is the most common technology offered today, many instruments utilizing the older technologies remain in use.

ELECTRONIC DIGITAL INSTRUMENTS

A digital instrument is an electronic device that measures voltage, current, and/or resistance by converting the measured analog input signal into a digital representation that is then displayed as a digital readout.

Advances in technology have led to digital instruments that are capable of high degrees of accuracy in the measurement of voltages, currents, and resistances over a wide range of values. Analog instruments indicate measured quantities by the deflection of a pointer on a scale, requiring the user to “eye up” the reading.

Today's digital instruments display measured results as discrete numbers (digits), removing much of the interpretation error from the act of reading an instrument. Typical display technologies include liquid crystal display (LCD), light emitting diode (LED), and gas discharge.

Some instruments offer the ability to send readings to other devices such as printers or computers or to be controlled by external computers. Interfaces built into the instruments, such as RS-232-C serial communications or the IEEE-488 bus standard, provide the data transmittal and external control capabilities.

The central component of a digital instrument is the digital DC voltmeter that uses electronic circuits to sense, process, and display the measured quantities. Input quantities other than DC voltages are converted to DC by transducers. Examples of transducers include internal shunts used to measure current and AC-to-DC converters to measure AC quantities. The transformed analog quantity (now in the form of an equivalent DC voltage) is then converted to a digital signal. Active electronic components, such as transistors, operational amplifiers, and integrated circuit modules perform this analog-to-digital (A/D) conversion.

Analog-to-Digital Conversion

Electronic instruments employ several different A/D conversion processes. These include dual-slope integration, ramp-and-counter, successive approximation, and voltage-to-frequency conversion. Each of these techniques produces a digital output equivalent to the measured analog input.

Figure 6-1 shows a simple version of an A/D converter. In this example, a binary counter increments one count with each clock pulse, until V_{out} equals V_{in}. This type of A/D converter is called a "digital ramp and counter" because the waveform at V_{out} ramps up step-by-step, like a staircase. It operates as follows:

1. A positive Start pulse is applied resetting the counter to zero. It also inhibits the AND gate so no clock pulses get through to the counter while the Start pulse is High.
2. With the counter at zero, $V_{out} = 0$, so the comparator output is High.
3. When the Start pulse goes Low, the AND gate is enabled, allowing pulses to enter the counter.

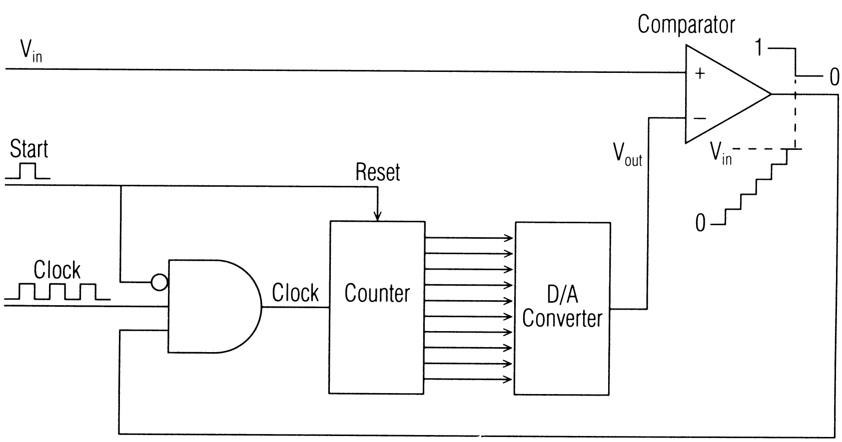


Figure 6-1. Analog-to-Digital Converter.

4. As the counter advances, the digital-to-analog (D/A) output (V_{out}) increases one step at a time, with the size of each step equal to its resolution (see below).
5. Stepping continues until V_{out} reaches a step that exceeds V_{in}. At this point, the comparator output goes Low, stopping the pulses to the counter, and stopping the counter at the digital equivalent of the analog input of V_{in}. The A/D process is now complete.

Resolution

The following example illustrates the resolution and accuracy of the digital-ramp A/D converter.

Assume the following values for the A/D converter of Figure 6-1: D/A converter has a 10-bit input and a full scale analog output of 10.23 volts; the comparator can detect a voltage difference of 1 millivolt or greater; V_{in} is 3.728 volts.

Since the D/A converter has a 10-bit input, the maximum number of steps possible is $(2^{10} - 1) = 1023$. With a full-scale output of 10.23 volts reached in 1023 steps, the step size is 10 millivolts. This means V_{out} increases in steps of 10 mV as the counter counts up from zero. Since $V_{in} = 3.728$ volts and the comparator threshold is 1 mV, then V_{out} has to reach 3.729 volts or greater before the comparator switches Low. At 10 mV per step, this requires 373 steps.

At the end of the conversion, the counter holds the binary equivalent of 373, which is 0101110101. This is the digital equivalent of the analog input of $V_{in} =$ 3.728 volts. The resolution of this A/D converter is equal to the step size of the D/A converter which is 10 mV, or approximately 0.1% ($.010/10.23 \times 100 = 0.1\%$).

The resolution of an A/D converter is equal to the resolution of the D/A converter that it contains. The D/A output voltage V_{out} is a staircase waveform (digital ramp) that goes up in discrete steps until it exceeds V_{in}. Thus, V_{out} approximates V_{in}. When the resolution (step size) is 10 mV, the accuracy we can expect is that V_{out} is within 10 mV of V_{in}. The resolution of the D/A converter is an inherent error, often referred to as a quantizing error. This quantizing error can be reduced by increasing the number of bits in the counter and in the D/A converter. It is specified as an error ± 1 least significant bit (LSB), indicating that the result can vary by that much due to the step size.

From another point of view, the input voltage V_{in} can take on an infinite number of values, from 0 to full scale. However, the output voltage V_{out} has only a finite number of discrete values. This means that similar values of V_{in} within a small range could have the same digital representation. For example, if the counter goes through 1,000 steps from zero to full scale, any value of V_{in} from 3.720 to 3.729 will require 373 steps, thus resulting in the same digital representation. In other words, V_{in} must change by 10 millivolts (the resolution) to produce a change in the digital output.

Accuracy

The D/A converter accuracy is not related to the resolution. It is related to the accuracy of the components in its circuit such as the resistors in the D/A network, comparator, level amplifiers, and the reference power supply. If a D/A has an accuracy of 0.01% full scale, the A/D converter may be off by 0.01% full scale owing to non-perfect components. This error is in addition to the quantizing error due to resolution. These two sources of error are usually specified separately, and for a given A/D converter are usually of the same order of magnitude.

In addition to the inherent errors noted above, the accuracy of an electronic instrument depends on proper selection of the meter range. Normally, the uncertainty of measurements is expressed as a percent of the reading plus the number of counts of the least significant digit (LSD) displayed for that range. If the 1,000 volt DC range is selected to measure a 2 volt signal for a three-and-a-half digit digital multimeter with a nameplate accuracy of ±0.5% of input voltage ±1 LSD, this setup would result in a meter accuracy of ±50.5%, as shown below.

Given: Meter Range Accuracy (MRA) is ±0.5% of input voltage ±1 LSD
Meter range set to 1,000 volts DC
Input voltage is 2 volts DC

Then: Meter Accuracy

$$\begin{aligned} &= \pm\ [(\text{MRA} \times \text{input V} + \text{LSD})/\text{Input Voltage}] \times 100 \\ &= \pm\ [(0.5\% \times 2 + 1)/2] \times 100 \\ &= \pm\ 50.5\% \end{aligned}$$

However, selecting a meter range of 2 volts DC on the same digital multimeter would result in an accuracy of 0.60%, nearly 100 times better, as shown below.

Given: Meter Range Accuracy is ±0.5% of input ±1 LSD
Meter range set to 2 volts DC
Input voltage is 2 volts DC

Then: Meter Accuracy

$$\begin{aligned} &= \pm\ [(\text{MRA} \times \text{input V} + \text{LSD})/\text{Input Voltage}] \times 100 \\ &= \pm\ [(0.5\% \times 2 + 0.002)/2] \times 100 \\ &= \pm\ 0.6\% \end{aligned}$$

Digital Display Resolution and Accuracy

Typical handheld digital instruments display from 3 to 5 digits. Laboratory digital instruments often offer 7 or 8 digits. The number of digits directly affects the available resolution of the reading. For example, a full 4-digit display is capable of presenting numbers from 0 to 9999 (with a decimal point somewhere in the display depending on the range setting of the instrument). This display can provide 10000 different readings for a particular range setting, so its resolution is limited to 1 part in 10000, or 0.01%. You may see this display referred to as a 10000-count display. A 6-digit display can present numbers from 0 to 999999. This display resolution would be 1 part in 1,000,000 or 0.0001%. It may be called a 1,000,000-count display. Examples in the previous section used LSD, Least Significant Digit, to adjust accuracy calculations to the characteristics of the display.

The design of a digital instrument often further limits the display. A 4-digit display, by design, may display numbers from 0 to 3999, rather than to 9999. That is, the left-most digit is programmed such that it only displays the numbers 0 to 3. This display is described as a 3½-digit display or as a 4000-count display. This design does not further affect the accuracy of calculations. The value of the LSD is the same for a 3½-digit display as for a 4-digit display.

Summary

Digital instruments offer a high degree of accuracy, precision, sensitivity, low cost, and designs ranging from laboratory grade to rugged field grade. The selection of a digital versus analog instrument depends on several considerations including accuracy, resolution, speed of measurement and reading, size and portability, environmental considerations, and cost. The majority of instruments available today are digital.

PERMANENT-MAGNET, MOVING-COIL INSTRUMENT

Figure 6-2 represents the mechanism of a permanent-magnet, moving-coil instrument. Here, the field produced by the direct current in the moving coil reacts with the field of the permanent magnet to produce torque.

Essentially, the permanent-magnet, moving-coil instrument, often called a d'Arsonval instrument, consists of a very lightweight, rigid coil of fine wire suspended in the field of a permanent magnet. The moving coil in most instruments consists of a very lightweight frame of aluminum, flanged for strength and to retain the windings. The windings consist of several layers of fine enameled wire. Pivot bases are cemented to the ends of the coil frame. These bases carry the hardened steel pivots on which the coil turns as well as the inner ends of the control and current-carrying springs. In addition, the upper pivot base mounts the pointer and the balance cross. Threaded balance weights, or their equivalents, are adjusted on the balance cross to balance the moving element in its bearing system. The pivots ride in jewel bearings to keep friction at a minimum. A taut band suspension may be used in place of the pivot and jewel-bearing system. Here the moving coil is supported by two metal ribbons under tension sustained by springs. Either bearing system allows a properly balanced instrument to be used in any position with little error.

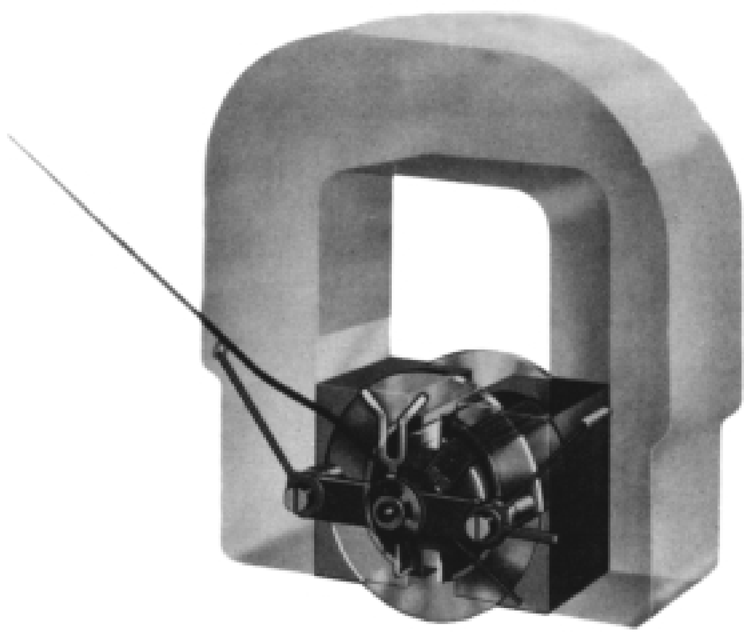


Figure 6-2. Mechanism of Permanent-Magnet, Moving-Coil Instrument.

Current is carried to the coil by two springs. These control and current-carrying springs oppose the torque of the moving coil and serve as the calibrating means of the instrument. The springs are generally made of carefully selected phosphor bronze or beryllium copper specially manufactured to provide stability so that the instrument accuracy will not be affected by time and use.

The torque developed by current flowing through the moving coil is a function of the field strength of the permanent magnet and of the current in the moving coil, as well as the dimensional factors of both magnet and coil. The torque T, in dyne-centimeters, is given by this equation:

$$T = \frac{B \times A \times I \times N}{10}$$

where:

B = flux density in lines per square centimeter in the air gap
A = coil area in square centimeters
I = moving-coil current in amperes
N = turns of wire in moving coil

The characteristics of the moving-coil instrument are very desirable. It has a high degree of accuracy, high sensitivity, low cost, and a uniform scale. It can measure extremely small currents because of the fine wire in the moving coil. The instrument is unique in the variety of accessories that can be used in conjunction with it. The four most commonly used are the series resistor, the shunt, the thermocouple, and the rectifier.

There are two inherent shortcomings of the permanent-magnet, moving-coil mechanism: except in a specially scaled instrument with rectifiers or thermocouples, it cannot measure AC quantities, and without auxiliary shunts or multipliers it can measure only small electrical quantities.

Rectifier-Type Instruments

Rectifier-type instruments may be used to measure AC milliamperes or AC volts. Since the DC mechanism is available by disconnecting the rectifier, this type is widely used in compact test sets where, by suitable switching, the same instrument can indicate both alternating and direct current. When used on alternating current, the rectifier-type instrument can provide an audio-frequency current measurement. It is subject to error due to waveform distortion if used on waveforms differing substantially from that with which the instrument was calibrated. See Figure 6-3.

Clamp Volt-Ammeter

A commonly used development of the rectifier-type instrument is the clamp volt-ammeter. The principal use of this instrument is the measurement of AC current without interrupting the circuit. Provision is also made for AC voltage measurements. The circuit arrangement of the instrument is shown in Figure 6-3.

The line current is measured using a hinged-core current transformer, the secondary current of which is suitably divided by a multiple-range series shunt for several ranges of line current. The secondary current is then rectified and applied to the permanent-magnet instrument mechanism. Voltage is measured by short-circuiting the transformer secondary and making direct connection to the rectifier with sufficient resistance added in series to produce the desired range.

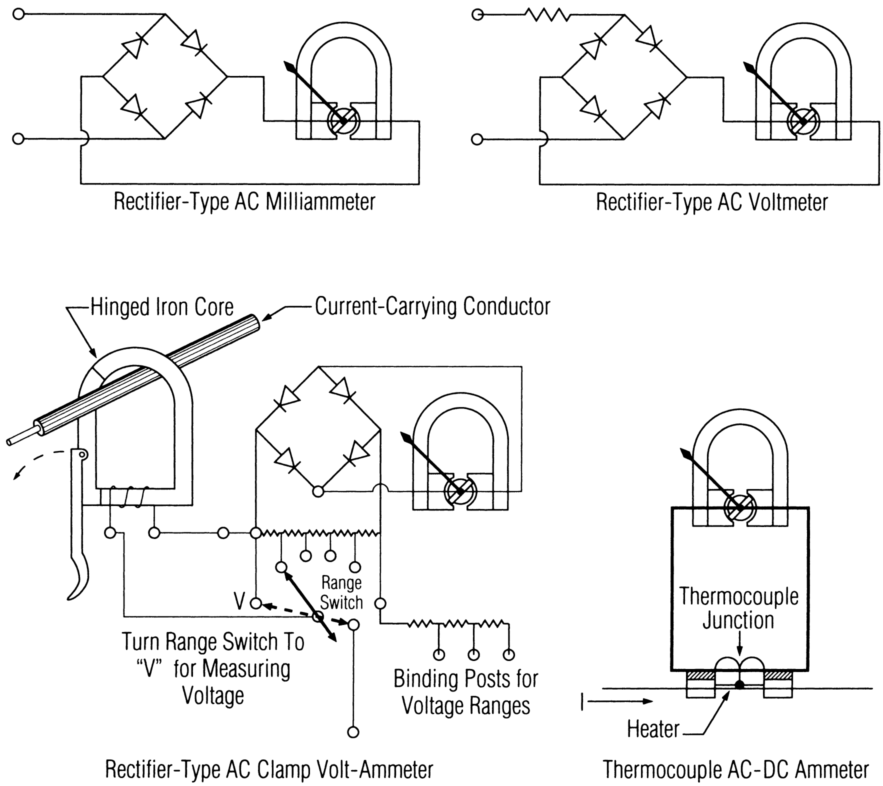


Figure 6-3. Circuits of Permanent-Magnet Instrument for AC Measurements.

This instrument is subject to the waveform and frequency errors which are characteristic of rectifier-type instruments.

THERMOCOUPLE INSTRUMENT

This instrument is a combination of a permanent-magnet, moving-coil mechanism and a thermocouple or thermal converter. The latter consists of a heater, which is a short wire or tube of platinum alloy, to the center of which is welded the junction of a thermocouple of constantan and platinum or other non-corroding alloy. The cold ends of the thermocouple are soldered to copper strips thermally in contact with, but insulated from, the heavy end terminals. This construction is necessary to reduce temperature errors. The copper strips in turn are connected to a sensitive moving-coil instrument.

The current to be measured passes through the heater causing a temperature rise of the thermocouple junction over the cold ends, and the resultant voltage is proportional to the temperature differential. Since the temperature rise of the hot junction is proportional to the square of the heater current, the instrument reading is also proportional to the square of the heater current.

With suitable conversion and circuit components, the thermocouple instrument may be used as a millivoltmeter, ammeter, milliammeter, or voltmeter. It indicates true root-mean-square (RMS) values on all waveforms and shows little error over a frequency range from direct-current to 20 kHz or more. Its disadvantages are its low overload capacity, its scale distribution, and its relatively slow response.

Figure 6-3 shows some representative circuits of the permanent-magnet, moving-coil mechanism for AC measurements.

THE MOVING-IRON INSTRUMENT

The measurement of alternating current (or voltage) is the measurement of a quantity that is continuously reversing direction. The permanent-magnet, moving-coil instrument movement cannot be used since the AC field of the moving coil reacting with the unidirectional permanent-magnet field will produce a torque reversing in direction at line frequency. Because of its inertia, the moving element will be unable to respond to this rapidly reversing torque and the pointer will only vibrate at zero. A different type of meter movement is therefore required.

The moving-iron instrument is specifically designed to operate on AC circuits. This instrument is called the moving-iron type because its moving member is a piece of soft iron in which magnetism induced from a field coil interacts with the magnetic field of a fixed piece of soft iron to produce torque.

The mechanism of this instrument, shown in Figure 6-4, essentially consists of a stationary field coil, with two soft iron pieces in the magnetic field. One is fixed while the other, commonly called the moving vane, is attached to a pivoted shaft provided with a pointer which is free to rotate. When current flows through the field coil the two pieces are magnetized with the same polarity, since they are both under the influence of the same field and, hence, repel each other, causing the pivoted member to rotate. The angular deflection of the moving unit stops at the point of equilibrium between the actuating torque and the counter torque of the spiral control spring.

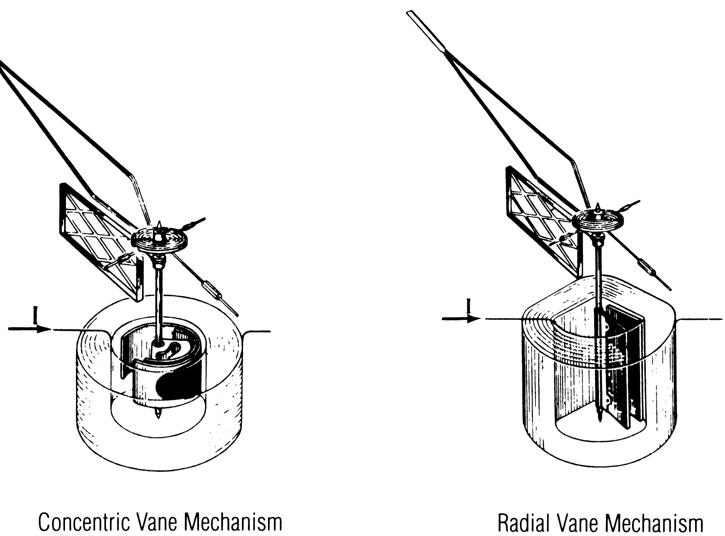


Figure 6-4. Mechanism of Moving-Iron Instrument.

The illustration shows that the operating current flows through a stationary winding. Depending upon the use for which it is designed, the coil may be wound with fine or heavy wire, giving this type of instrument a wide range of capacities. The instrument will tolerate overloads with less damage to springs and pointer than will most other types of instruments, since, with excess current, the iron vanes tend to become saturated and limit the torque. Damping is provided by either a light aluminum vane fixed to the shaft and moving in a closed air chamber, or by a segment of an aluminum disc moving between poles of small permanent magnets.

The bearing system may consist of a pivoted shaft turning in jeweled bearings or may be of the taut-band suspension type where the moving element is supported by two metal ribbons under tension sustained by springs.

Application of Moving-Iron Instrument

Measurement of Current

Since the actuating coil may be wound with a choice of many wire sizes, the instrument may be constructed to measure current from a few milliamperes up to 100 or 200 amperes in self-contained ratings. For measuring currents beyond this range, a 5-ampere instrument may be used with a current transformer.

Current Transformer Field Test Set

A special application of the moving-iron ammeter is the current transformer field test set.

The circuit of this instrument is shown in Figure 6-5. It is used to check current transformer installations in service on the secondary side, for possible defects such as short-circuited primary or secondary turns, high-resistance connections in the secondary circuit, or inadvertent grounds, any of which could cause incorrect metering.

It is essentially a multi-range, moving-iron-type ammeter with a built-in burden which is normally shunted out, but which can be put in series with the meter by the push button.

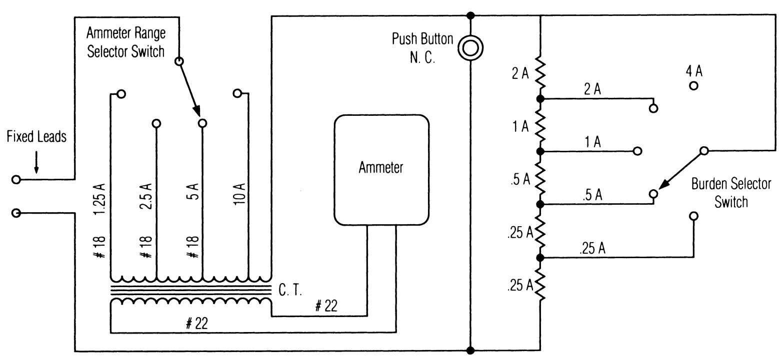


Figure 6-5. Circuit of Current Transformer Field Test Set.

In the typical instrument illustrated here, ammeter current ranges of 1.25, 2.5, 5, and 10 amperes are obtained from the tapped primary winding of a small internal current transformer, the secondary winding of which is connected to the ammeter which has corresponding multiple scales. It is thus possible to obtain a reading well up-scale on the ammeter for most load conditions under which the current transformer is operating. The rotary burden switch permits the addition of 0.25, 0.5, 1, 2, or 4 ohms to the secondary circuit as desired.

The imposition of an additional secondary burden on a current transformer having the defects previously mentioned will result in an abnormal decrease in the secondary current. The extent of this decrease and the ohms burden required to effect it depend on the characteristics of the transformer under test. The check on the current transformer consists of inserting the field test set in series with the current transformer secondary circuit and comparing the ammeter readings under normal operating conditions with the readings after the additional field test set burden is added.

The use of this device under field conditions is discussed in Chapter 10, “Instrument Transformers.”

Measurement of Voltage

By the use of an actuating coil of many turns of fine wire in series with a resistor, the moving-iron instrument may be used to measure voltage. Such a voltmeter may have an operating current of around 15 milliamperes with a range up to 750 volts. External multipliers may be used to extend this range. These voltmeters are used in applications where sensitivities lower than those of the rectifier d’Arsonval instrument are satisfactory. The moving-iron voltmeter may be used on DC with some loss in accuracy. The best accuracy is obtained by using the average of the readings taken before and after reversal of the leads to the instrument terminals. This instrument will not indicate the polarity of DC.

ELECTRODYNAMOMETER INSTRUMENTS

The electrodynamometer-type mechanism, shown in Figure 6-6, is adaptable to a wider variety of measurements than any of the instruments previously described and is especially useful in AC measurement and as a DC-to-AC transfer instrument.

In this instrument, both stator and rotor are coils. Current flowing through the stationary or field coil winding produces a field in proportion to the current. As current is applied to the moving coil, the coil moves because of the reaction on a current-carrying conductor in a magnetic field. The torque actuating the moving element is a function of the product of the two magnetic fields and their angular displacement.

This instrument can be used for measurement of volts, amperes, watts, either alternating or direct current, as well as power factor and frequency. Figure 6-7 shows the coil arrangements for various applications.

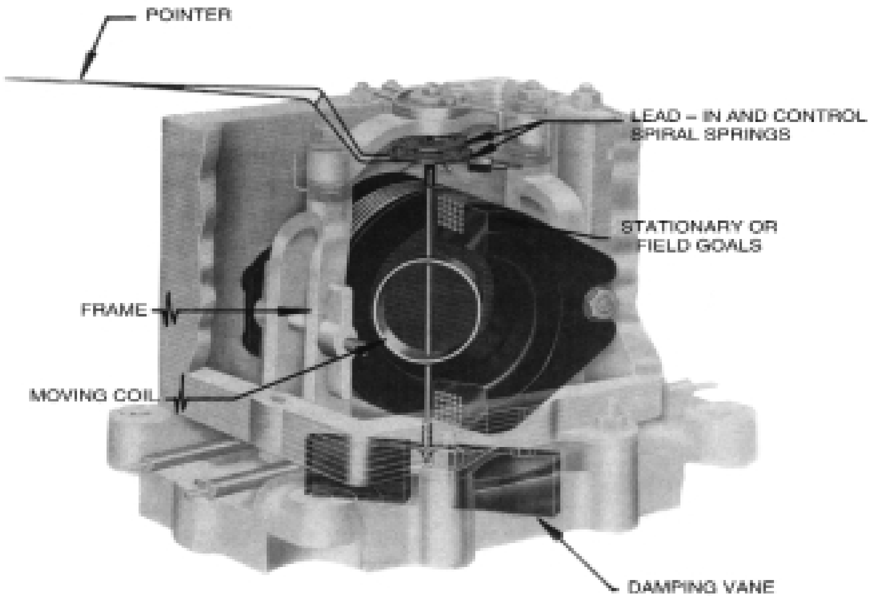


Figure 6-6. Mechanism of Electrodynamometer Instrument.

Application of Electrodynamometer Instrument

Measurement of Power

The most important use of the electrodynamometer mechanism is as a wattmeter. In this construction the moving coil is in series with a resistance and is connected across the circuit as a voltmeter, while the field coil is connected in series with the load as an ammeter coil. The torque between these coils is proportional for DC to the product of volts and amperes, or watts. For AC, the instrument recognizes the phase difference between volts and amperes, which is the power factor. Its readings then are proportional to the product of volts, amperes, and power factor.

When used as a wattmeter, the moving coil is wound with fine wire, while the field coil may be wound with large-size wire, the nominal rating of the latter being usually 5 amperes.

By superimposing two complete wattmeter elements with the two moving coils on the same shaft, power in a three-wire circuit may be measured by one instrument. The torques developed by the two elements add algebraically to give an indication of total power. By using phasing transformers to shift the voltages to the moving coils 90°, a three-phase VARmeter is obtained.

Measurement of Current

Electrodynamometer ammeters have the field and moving coils connected in series. Since the moving coil is connected to the circuit by rather fragile lead-in spirals, it is evident that the current-carrying capacity of that part of

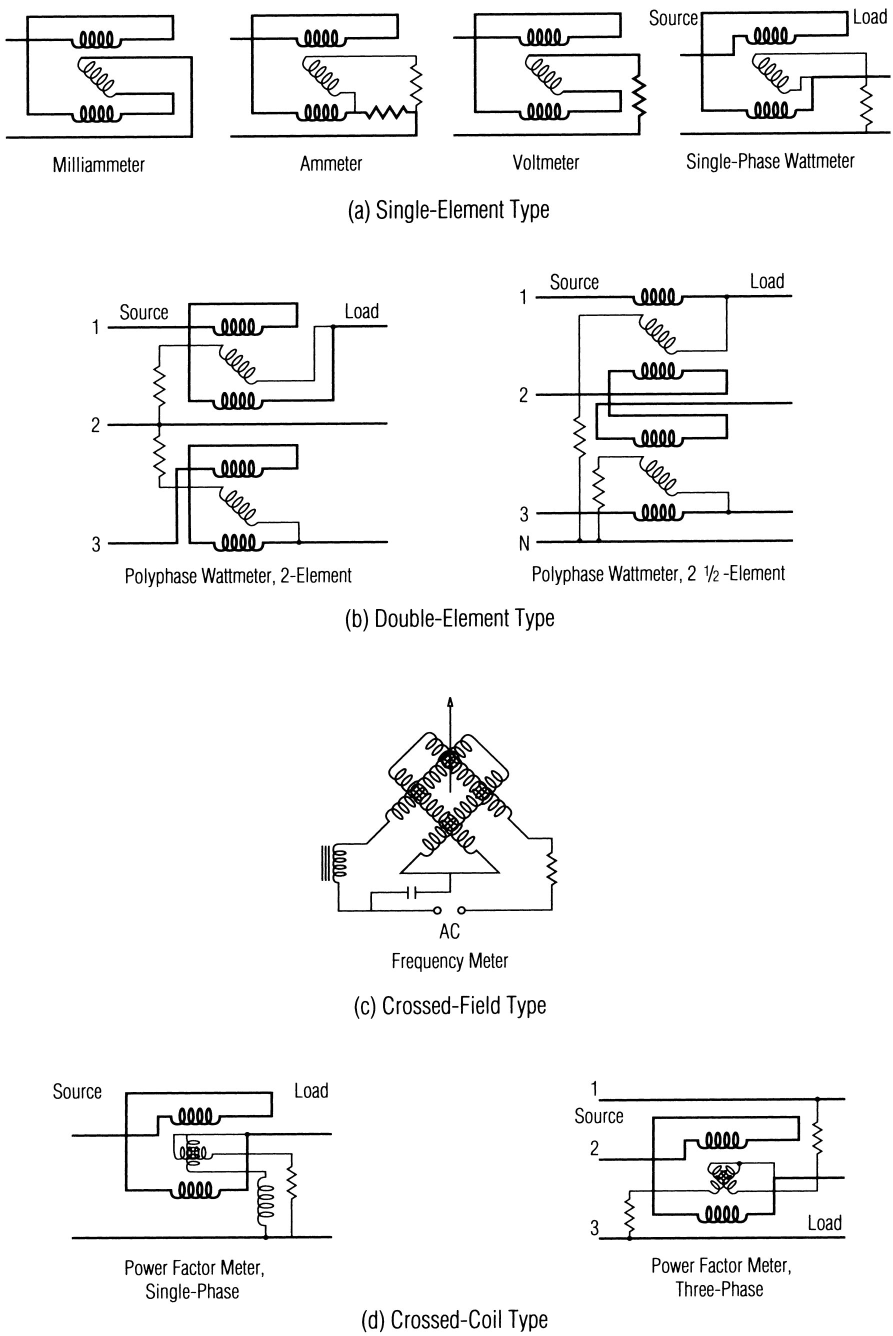


Figure 6-7. Circuits of Electrodynamometer Instruments.

the instrument is limited. For this reason the moving coil is shunted in instruments above l00 milliamperes capacity. The full line current passes through the field coil and the shunt.

Measurement of Voltage

In the electrodynamometer voltmeter, the field coil is connected in series with the moving coil and a resistance across the line. The sensitivity of this instrument is less than that of a DC voltmeter because of the greater current required by the dynamometer mechanism. It is, however, more accurate than the moving-iron voltmeter and is better adapted to precise voltage measurements.

Measurement of Power Factor and Phase Angle

A variation of the fundamental electrodynamometer instrument is used to measure power factor or the phase angle, and is called the crossed-coil type. See Figure 6-7. In this design the moving element consists of two separate coils, instead of one which are mounted on the same shaft and set at an angle to each other. The lead-in springs or spirals to the crossed coils are made as light or weak as possible so as to exert practically no torque. In the single-phase instrument, one of the crossed moving coils is connected in series with a resistor across the line while the other is connected in series with a reactor across the line. The current flowing through the reactor-connected coil is approximately 90 degrees out of phase with the line voltage. The field coil is connected in series with the line as an ammeter coil.

In operation, the moving system assumes a position dependent upon the phase relationship between the line current and the line voltage. If the line current is in phase with the line voltage, the reactor-connected moving coil will exert no torque and the resistor-connected coil will align its polarities with those of the fixed-coil field. If the line current is out of phase with the line voltage, the reactor-connected moving coil will exert a restraining or counter torque and the moving element will assume a position in the field of the fixed coil where the two torques are in balance.

This instrument may be calibrated to indicate either power factor or the phase angle between the line voltage and current.

In the three-phase power factor instrument, the crossed moving coils are connected to opposite legs of a three-phase system. The fixed coils are connected in series with the line used as a common for the moving-coil connection. This instrument will give correct indication on balanced load only.

When these instruments are not energized, the pointer has no definite zero or rest position as do instruments whose restraining torque is a spring. They are therefore known as free-balance instruments.

Power factor meters may also be of the induction type. In one such type for single-phase use, the fixed element consists of three stationary coils and the moving element comprises an indicator shaft bearing an iron armature. As in the electrodynamometer type, operation is based on the interaction of a rotating and an alternating magnetic field.

Measurement of Frequency

Another variation of the electrodynamometer instrument, the crossed-field type, is used to measure frequency. Crossed field or stationary coils are connected to the line through inductive and capacitive circuit elements so that the relative strengths of the fields become a function of the frequency. See Figure 6-7. An iron vane attached to a freely rotatable pointer shaft will align itself with the direction of the resultant field and the instrument will indicate the frequency. This frequency meter is also a free-balance instrument.

THERMAL AMPERE DEMAND METERS

Thermal ampere demand meters differ from instruments previously discussed in that the moving element deflection does not result from the electromagnetic interaction between fixed and moving instrument components, but is due entirely to the mechanical torque exerted on a shaft by the heat distortion of a bimetallic strip or coil. These instruments are generally not designed for precise measurements. They are simple, inexpensive, and rugged measuring units which are easily adapted to a variety of applications.

Lincoln Ampere Demand Meter

The moving element of a Lincoln ampere demand meter consists of a horizontal shaft mounted in bearings to which are attached an indicating pointer and two bimetallic coils which are temperature sensitive. The inner ends of both bimetallic coils are attached to the shaft while the outer ends are attached to the instrument frame. These two bimetallic coils are carefully matched and are wound in opposite directions.

One bimetallic coil is placed in an enclosure of heat-insulating material with, and adjacent to, a non-inductive nichrome or manganin resistor used as a heater. See Figure 6-8. When a current I passes through the heater R, the heater and its enclosure are heated at a rate proportional to I^2R, producing a temperature difference between the bimetallic coils which results in motion of the shaft and pointer. The motion is proportional to the current squared. This heater current may be either line current or a smaller current from the secondary of an internal current transformer.

When both coils are at the same temperature, the instrument pointer reads zero. Changes in external temperature affect both bimetallic coils equally and therefore cause no change in pointer position. Since this arrangement is equivalent to a differential thermometer, the shaft motion is proportional to the temperature difference between the two coils.

The restraining torque is largely supplied by the bimetallic coil that is not heated. Additional restraining torque is supplied by a coiled spring and a third weak spiral spring. The former aids in improving scale distribution while the latter provides for a slight zero adjustment.

Thermal capacity of the system is large and so the pointer responds very slowly, reaching 90% of the current value in approximately 15 minutes under steady current, 99% in 30 minutes, and 99.9% in 45 minutes.

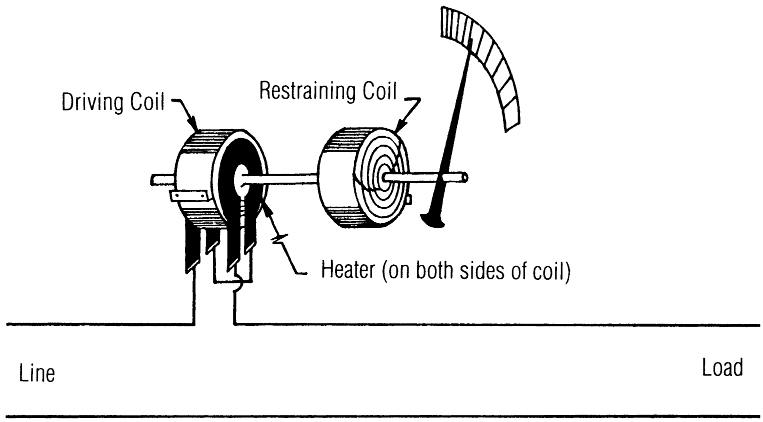


Figure 6-8. Mechanism of Thermal Demand Ammeter.

To obtain maximum indication over a long period of time, the regular pointer pushes a second pointer which is not attached to the shaft. This second pointer has sufficient friction so that it stays at the maximum point to which it is pushed. Provision is made for setting the free pointer to the pusher pointer when desired.

Typical movements of this type require 3 to 6 amperes through the heater resistor for full-scale deflection.

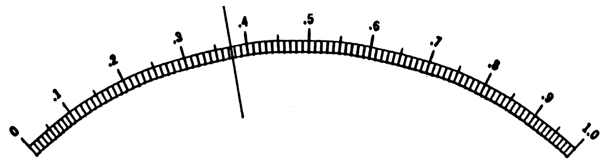
INSTRUMENT SCALES

Figure 6-9a shows a sample instrument scale of the kind easiest to read. This type of scale is characteristic of DC, permanent-magnet, moving-coil instruments in that the divisions are of equal size from zero to full scale. Since each major division is equal to 0.1 and each minor division to 0.01 of full scale, reading errors are minimized and rather precise readings may be made.

Figure 6-9b shows a more complicated scale of a three-range voltmeter. Note that the divisions are not uniform and are smaller and cramped near the zero end of the scale. This scale is characteristic of moving-iron instruments. Since the values of each major and minor division are different for each of the three ranges, it is important to know the range to which the meter is connected in order to determine the correct reading.

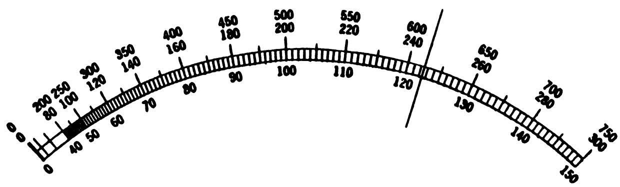
Figure 6-9c shows a scale often used in high-accuracy instruments, such as secondary standards in the meter laboratory. The diagonals connecting each minor division and the additional lines parallel to the arc of the scale permit close readings to a fraction of a division. Where four intermediate arcs are drawn, each intersection of a diagonal with an arc line is 0.2 of the marked division.

When reading instrument indications, one must be careful to have one's eye directly above the knife edge of the pointer to avoid errors due to parallax. In many instruments and especially those of high accuracy, the scale is equipped with a mirror so that the pointer may be lined up with its reflection. This alignment aid assures that the eye is in the proper position for accurately reading the scale.



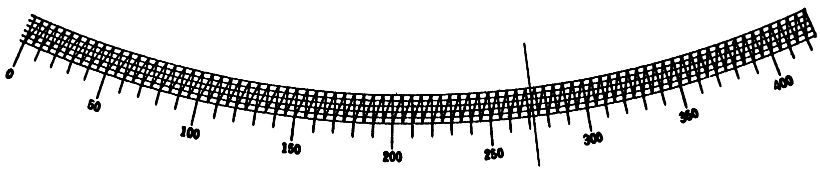
(a) Linear Instrument Scale

Instrument Reads 0.374



(b) Scale of Triple Range Voltmeter

On 300 Volt Scale, Instrument Reads 245



(c) Scale of Precision Wattmeter

Instrument Reads 272.5

Figure 6-9. Typical Instrument Scales.

MEASUREMENT OF RESISTANCE

Voltmeter-Ammeter Method

The simplest approach to resistance measurement is simultaneous measurement of the current through a circuit or component and the voltage across it. This method is shown in Figure 6-10. From the current and voltage readings the resistance can be calculate by the application of Ohm's Law:

$$R = \frac{E}{I}$$

For accurate results in measuring resistance by this method, use the relative resistances of the voltmeter and ammeter themselves. For low values of resistance R, the resistance of the ammeter must be subtracted from the value of the circuit resistance determined by the preceding equation. For relatively high values of R (compared to the resistance of the ammeter), the value of the ammeter resistance may be neglected.

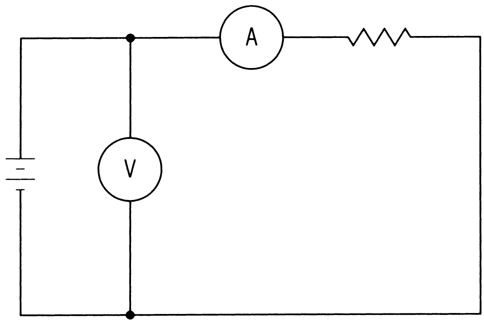


Figure 6-10. Circuit for Measurement of Resistance by Voltmeter-Ammeter Method.

Ohmmeters

These are self-contained instruments with a source of low DC voltage that measure within reasonable limits of accuracy the resistances of a circuit or component and indicate the value of resistance on a meter scale calibrated in ohms.

In application, the ohmmeter is one of the most useful test instruments. It can locate open circuits and check circuit continuity. This instrument should not be used on energized circuits. Figure 6-11 shows the circuit arrangement of a typical ohmmeter.

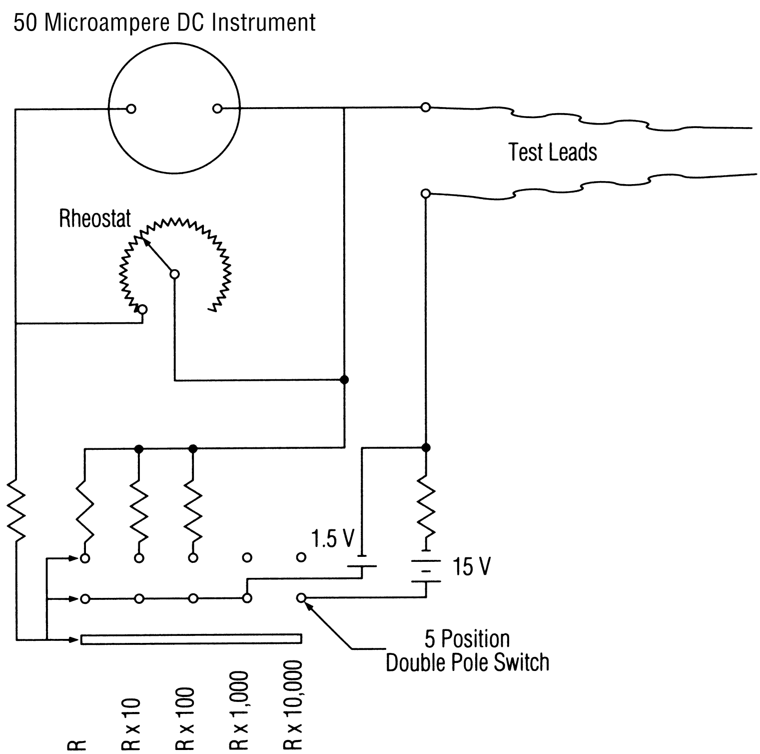


Figure 6-11. Circuit of Ohmmeter.

The megger is a special variety of ohmmeter. It is a portable test set for measuring extremely high values of resistance—100,000 megohms or more. These levels are encountered when testing resistances in cable insulation; the resistance between conductors in multiple cables and between windings or from windings to ground in transformers, motors, and other forms of electrical equipment. These instruments have built-in, hand-driven or electronic DC generators to supply 500 volts or more so that measurable currents can be produced through the high resistances encountered. Figure 6-12 shows a typical megger for measuring insulation resistance.

Ground-resistance ohmmeters are used for measuring resistance to earth of ground connections, such as substation or transmission tower and lightning arrester grounds. These instruments have built-in AC generators instead of DC units. They also differ from the type used for insulation resistance measurements by their range and that the resistance of the leads is electrically removed from the indicated reading by the nature of the test connections. Where the former has a full-scale range of 100,000 megohms or more, the ground-resistance megger shown in Figure 6-13 has the capability of measuring ground-resistance values from fractions of an ohm to several thousand ohms. A single instrument may have several measurement ranges.

Figure 6-12. Megger Insulation Tester.

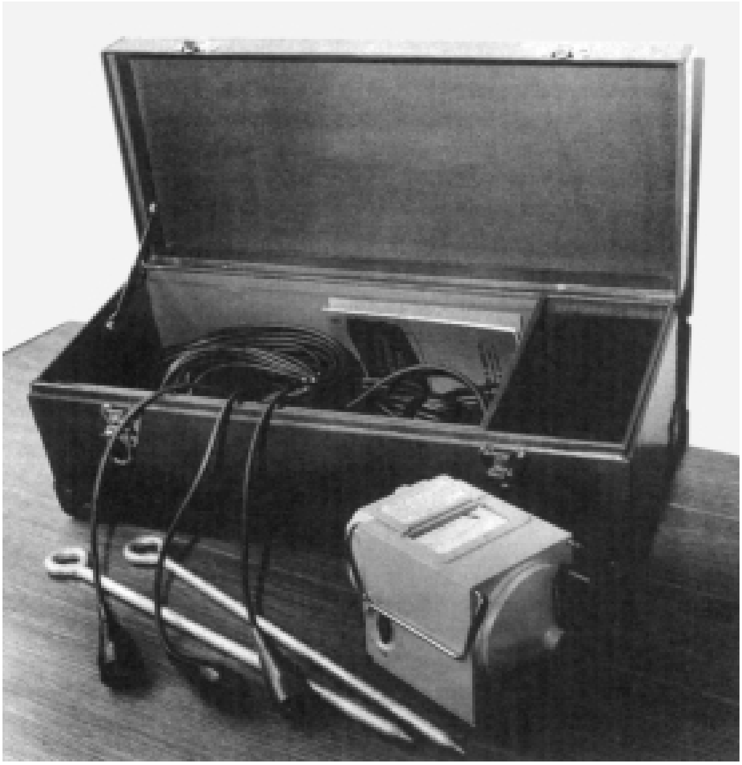


Figure 6-13. Megger Ground Tester.

SELECTION OF INSTRUMENTS

The selection of instruments and related equipment best adapted to meet the requirements of a particular use is very important and should receive careful consideration. The most suitable types and ranges must be determined by the nature of the work for which they are to be used and the degree of accuracy required.

Consideration must be given to the choice between ruggedness and accuracy in an instrument. This choice is usually determined by service and economic requirements. The majority of all field test work is done with instruments of the general-purpose type. These are rugged, moderately priced instruments with accuracies in the range of 0.1 to 2.0%. AC voltage and current measurements tend toward the upper end of this accuracy range, while DC voltage and current measurements tend to the lower. On field tests or investigations where high accuracy is required, handheld instruments, with accuracies in the range of 0.04 to 0.3%, are available. These instruments are more expensive, but offer rugged construction and portability. Bench instruments offer accuracies in the range of 0.001 to 0.5% but do not offer the same degree of ruggedness and portability as the handheld types.

Technically, a higher degree of accuracy is always desirable. The benefits of higher accuracy must be weighed against higher costs. The specifics of each application will determine the value of smaller size and portability versus larger size and ease of use in a laboratory environment.

All instruments should be as resistant as possible to the effects of temperature changes, stray fields, frequency variation, waveform, spring set, pivot roll, and vibration. Analog instruments should be equipped with accurate, legible scales having plainly marked divisions from which intermediate values can be easily determined.

CARE OF INSTRUMENTS

Instruments should be handled with great care. To avoid damage to internal mechanics or electronics, instruments should receive no shock or blow from contacts with a table, bench, or other instruments. Analog instruments should be transported in a vertical position so that the shafts of the moving elements maintain a horizontal position. Chances of damage to the bearing systems will be lessened, since shocks are taken on the sides of the pivots and jewels. Instruments should be carried in well padded shock-mounted cases for further protection. In placing an instrument in its case, the case should be laid flat and the instrument slowly slid into it. Digital electronic instruments are less susceptible to much of the physical damage that threatens analog instruments. However, digital instruments can still be damaged by careless or rough handling. In particular, the displays of digital devices are susceptible to physical damage.

Precaution should be taken to insure that the current or voltage to be measured is within the range of the instrument being used. If the range of quantities to be measured is not already known, a high-range instrument should be connected first to get an approximate indication of the value. Then an instrument with the proper range may be used.

Fuses can be used in current-measuring instruments to prevent burnout of instrument windings or electronics. However, fuses will not prevent the mechanical shock to the moving element when subject to sudden overloads, nor will they protect electronics against all transient damage. Fuses should not be used in instruments that might be connected in the secondary circuit of current transformers. An open fuse in the current circuit could damage the current transformers.

Precision analog instruments should be properly leveled before use. Zero should be adjusted before the instrument is energized. After the pointer has been deflected for a long time, a small zero shift may be noted. This shift is seldom permanent and should not be corrected until the instrument has been de-energized for some time. Zero shift caused by a bent pointer should be corrected by straightening the pointer rather than by the zero adjustment. In this connection, it should be emphasized that the case or cover should not be removed from the instrument for any reason except in the laboratory. Digital electronic instruments exhibit little if any sensitivity to physical orientation. In addition, they are generally self-zeroing.

INFLUENCE OF TEMPERATURE

Temperature affects all electrical instruments. Through care in design and the use of special materials, the effect of temperature on most modern instruments is minimized. Temperature errors may be caused by exposure of the instrument to an environment of temperature extremes or by self-heating during use. If the instrument has been subjected to unusual heat or cold for some time, it should be exposed to room temperature until the temperature of the instrument is approximately normal. If it is necessary to use an instrument under extreme conditions of temperature, make the test as quickly as possible while the temperature of the instrument is close to normal. If this is not practical and maximum accuracy is required, apply temperature-correction factors to the instrument readings.

Minimize temperature errors due to self-heating by leaving the instrument in the circuit for as short a time as possible. Most portable voltage-measuring instruments are designed for intermittent use only and should not be left in a circuit indefinitely.

Temperature errors may also result from exposing the instrument to localized hot spots or temperature inequalities such as may be caused by a lamp close to the instrument scale. Such heating may affect the instrument but not the temperature compensation circuit and cause errors. A cold light should be used.

INFLUENCE OF STRAY FIELDS

Stray fields may cause appreciable errors in instruments. Such stray fields may be produced by other instruments, conductors carrying heavy currents, generators or motors, and even non-magnetized masses of iron. Since it is often not known if strong stray fields are present in the test area, the instrument should be read, then rotated 180°, read again, and an average taken of the test readings. If an instrument is to be permanently used on magnetic panels (iron or steel), the instrument should be calibrated on location or with an equivalent panel.

MECHANICAL EFFECTS

Mechanical faults causing errors may include pivot friction, defective springs, imbalance of the moving coil, and, in some lower-grade instruments, incorrectly marked scales. Correction of the errors should be made only in the meter laboratory. These types of errors do not apply to digital instruments.

Another effect that may lead to serious errors in instrument readings is due to electrostatic action. In a cold dry atmosphere, rubbing the instrument scale window to clean it will often cause the pointer to move from its zero position due to the action of an electric charge produced on the glass. Generally, the static charge can be dissipated by breathing on the glass, the moisture in the breath causing the charge to leak away. In the laboratory, when calibrating wattmeters with separate sources of current and voltage, there may be an electrostatic force exerted between the fixed coil and the moving coil sufficient to introduce errors into the readings. The remedy is to arrange a common connection between the current and voltage circuits at some point.

The matter of good electrical contact is important in connection with the use of electric instruments. Contact surfaces must be clean and binding posts must be tightened. This is particularly important when using a millivoltmeter with shunt leads, since small voltage drops due to poor contact can have significant effects on accuracy.

INFLUENCE OF INSTRUMENTS ON CIRCUITS

All instruments of the types under discussion require energy to actuate them. This energy must come from the circuit under test. To some degree, the energy requirement of the measuring instrument will affect the circuit being measured. In general, the more sensitive the instrument the less it will affect circuit conditions. However, where measurements of a high degree of accuracy are desired, the effect of the energy requirements by the instrument must be considered. A voltmeter, for instance, connected to measure the voltage drop across a resistor, provides a parallel path for the current. The total resistance of the circuit and the total current is not the same with the voltmeter connected as it was before the connection. In order to keep such circuit changes to a minimum, it is necessary in certain applications to use a high-resistance instrument.

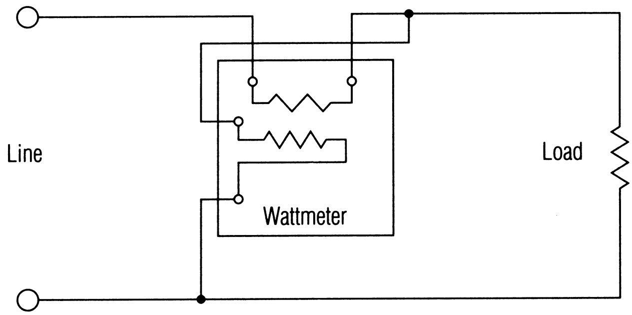
An ammeter also has some resistance and will, when inserted in series with a load, change the total resistance of the circuit. An ammeter should have the lowest possible resistance. Low-range ammeters of 1 ampere capacity or less may have resistances exceeding 1 ohm.

In the wattmeter there is an error (unless compensated for) due to the method of connecting the voltage element. See Figure 6-14.

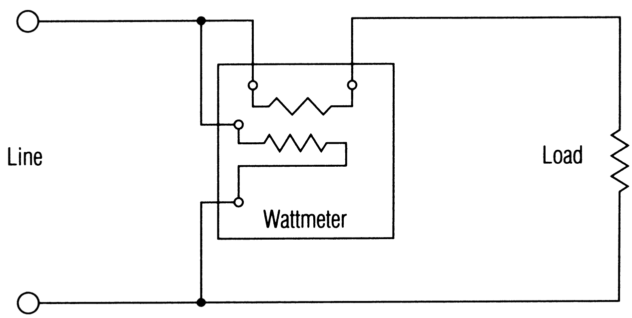
In the connection shown in Figure 6-14a, the current coil of the instrument measures not only the load current but also that taken by the voltage coil, since the latter is connected on the load side of the current coil. In the connection shown in Figure 6-14b, the voltage coil measures the drop across the load plus the drop across the current coil of this instrument. When precise measurements are needed, it is necessary to apply corrections. In such cases, the connections shown in Figure 6-14a should be used, since it is easy to calculate the comparatively constant loss in the voltage circuit and to subtract this value from the wattmeter reading. Where the error due to connections is not considered significant, the connections shown in Figure 6-14b may be used.

ACCURACY RATING OF INSTRUMENTS

The accuracy rating of an indicating instrument gives the maximum deviation from the true value of a measured quantity and is expressed as a percent of the full-scale rating of the instrument. Thus, an instrument of the 0.5% accuracy class, when new, will indicate the true value at any point on the scale with an error not more than 0.5% of the full-scale reading on the instrument. An AC voltmeter of 0.5% accuracy class and having a full-scale range of 150 V should be within 0.75 volts (0.5% of 150 volts) at any point on its scale. In general, the more accurate instruments are more fragile in construction, greater in cost, and require greater care in use. It is logical that the instrument should be selected with an accuracy rating no greater than that needed by the practical requirements of the measurement.



(a) Wattmeter reading includes voltage circuit loss.



(b) Wattmeter reading includes current coil loss.

Figure 6-14. Wattmeter Connections.

MAINTENANCE OF INSTRUMENTS

Most public utilities maintain a laboratory for calibration and minor repairs of instruments. Good practice directs that all instruments be returned to the laboratory for recalibration on a routinely scheduled basis. The length of time between laboratory inspections and calibrations generally depends on the accuracy class and the use of the instrument. When an instrument has been subjected to any accidental electrical or mechanical shock, even though no apparent damage may have resulted, return it to the laboratory for recalibration. Whenever there is any doubt concerning the accuracy of an instrument's indications, return it to the laboratory for testing.

CHAPTER 7

THE WATTHOUR METER

THE PREVIOUS CHAPTER explains that an indication of electric power may be obtained by use of a wattmeter. A wattmeter and a watthour meter have roughly the same relationship to each other as do the speedometer and the odometer of an automobile. A speedometer indicates miles per hour. An odometer shows the total number of miles traveled. A wattmeter indicates the instantaneous consumption of watts. A watthour meter measures the total watthours that have been used. Just as an odometer will indicate 60 miles, for example, after a car has traveled two hours at a speedometer indication of 30 miles per hour, a watthour meter will indicate 1000 watthours if connected for two hours in a circuit using 500 watts. Consumer loads may be constantly changing, so to accurately measure watthours, it is necessary to have a meter that will accumulate the instantaneous watts over time. In the United States, meters are typically read monthly and a bill produced. Historically, watthour meters start their accumulation at the time of installation and continue to accumulate up-scale throughout the remainder of their lives. Just as the miles traveled during a trip can be measured by noting the odometer readings at the beginning and end of a trip, the monthly energy consumed is determined by subtracting the watthour reading at the end of the previous billing period from the reading at the end of the current billing period.

THE GENERIC WATTHOUR METER

There are a number of ways to implement a watthour meter, but all approaches require power to be measured, accumulated, and the results stored and displayed. As such, voltage and current for each electrical phase must be sensed (or approximated), voltage and current for each electrical phase must be multiplied, the resultant power must be accumulated, and the accumulated watthours must be stored and displayed. For the electricity provider, the electricity meter (the watthour meter) is the cash register. As such, the meter must be very accurate and reliable over a variety of environmental conditions, and the meter performance must be certifiable to the energy provider, consumer, and any involved regulatory agencies. A major challenge for the watthour meter manufacturer is to perform these functions economically. Each watthour meter approach has tradeoffs that are balanced by the meter manufacturer to meet the perceived market needs. The best approach depends on how the user values the tradeoffs.

Because of the care taken in their design and manufacture, and because of the long-wearing qualities of the materials used in them, modern watthour meters normally remain accurate for extended periods of time without periodic maintenance or testing. Probably no commodity available for general use today is so accurately measured as electricity.

The Two-Wire Single-Phase Meter

The two-wire meter is the simplest watthour meter and forms the basis for all other meters. The service this meter is used to measure has one voltage supplying the load and one current being used by the load. As such, the meter has one voltage sensor and one current sensor. Because the voltage and current are changing with load conditions in real time, the voltage and current must be measured in real time. Regardless of DC, AC, or distorted waveforms, at each instant in time the following equation is true:

$$Watts_{\mathrm{i}} = V_{\mathrm{i}} \times I_{\mathrm{i}}$$

If all of these instances of watts are collected over time, watthours are computed. The equation for this is:

$$Watthours = \sum_{i=0}^{i=T} V_{\mathrm{i}} \times I_{\mathrm{i}}$$

The real quantities in the electrical system are current, voltage, and (real) power and can be defined for each instance in time. Most other quantities reflect some average effect or are a mathematical convenience to more easily understand what is happening on a macro scale. For example, it is common to speak of meters in terms of rms voltages, rms currents, and phase angles between these. However, in a real electrical system, the waveforms may be distorted and dynamically changing as loads are switched in and out of the service. At one extreme, consider an electricity meter on an oil pump. During the up stroke of the pump, significant power is drawn from the service, during the down stroke, the pump motor turns into a generator. In between, there are significant current distortions. If a revenue meter attempted to compute watts from the rms voltage, rms current, and phase angle between these, the meter would not be very accurate. Therefore, revenue meters measure watts in real-time and accumulate their effect to produce watthours. This can be accomplished with magnetic fluxes within an electromechanical meter disk or with electronic components.

The Three-Wire Single-Phase Meter

The three-wire meter has a voltage sensor, connected across the two line wires of a single-phase service, and two phase currents of the service usually passing through a single current sensor with a magnetic circuit. Each current passes through the magnetic circuit in such a way that the magnetic fluxes produced are additive. In an electromechanical meter, the number of turns in each of the two current coils is one half as many as used in the current coil of a two-wire meter. According to Blondel's theorem, which is defined and discussed in Part II of this chapter, two elements (stators) are required for accurate registration of energy flowing through a three-wire circuit. If the voltages between each line wire and the neutral are single phase and exactly equal, the single-stator, three-wire meter is accurate. An imbalance in the voltage will cause accuracy proportional to one half the difference between voltages. Because modern systems are normally very closely balanced, any errors, usually less than 0.2%, are considered negligible.

With the improved voltage compensation on modern meters, some utilities use the standard three-wire, 240-volt, single-stator meter on two-wire, 120-volt services in place of the standard two-wire meter or the two- or three-wire convertible meters previously described. By connecting the meter's two current inputs in series, the meter Kh constant and registration are not changed on the two-wire service and the voltage compensation provides good performance at the 50% voltage operation.

MULTI-ELEMENT (MULTI-STATOR) METERS

This section on multi-stator watthour meters relies on single-stator meter data for its basic meter theory because a multi-stator meter is essentially a combination of single-stator meters on a common base. The differences are in a few special features and in the various applications to polyphase power circuits.

THE EVOLUTION OF THE POLYPHASE METER

History

The first American polyphase power systems were all two-phase. Knowledge of three-phase systems was limited at that time and their advantages were not fully understood. There was also some difference of opinion as to their merits compared with the two-phase system.

It was a simple matter to use separate single-stator watthour meters for metering the two-phase circuits and this was the general practice in America from 1894 to 1898. Even the early three-phase systems were metered by combinations of two single-stator meters. The first commercially available, true polyphase meters were produced in the United States in 1898. They consisted of the two element (two-stator) polyphase types for three-wire, three-phase, and two-phase services.

The multi-element (multi-stator) polyphase meter is generally a combination of single-phase elements (stators). In a modern electromechanical meter, the watthour-meter stators drive a common shaft at a speed proportional to the total power in the circuit. The older types of electromechanical meters were multi-rotor meters with a rotor for each stator. One way of accomplishing this was to mount the stators side by side in a common case with the two rotor shafts recording on one dial through a differentially geared register. In such a meter the stators did not need to be identical in current and voltage rating, but, if not identical, they need to be geared to the register so that an equal number of watthours as determined by the watthour constants of each stator, would produce the same registration on the dial. A second method of combining meter stators was to locate the stators one above the other in a common case, with the disks mounted on a common spindle to form a rotor which was geared to a single register. With this combination of stators, the stators did not need to be identical but the watthour disk constant needed to be the same for each stator.

About 1935, polyphase meters were modified to reduce cost, weight, and space requirements and resulted in a radical change in design. In this design, the magnetic fluxes from the two stators were made to operate on one rotor disk. In 1939 one manufacturer went a step further and provided a meter with three stators operating on one rotor disk. These developments decreased the size of polyphase meters close to that of the single-stator meter.

In the early to mid-1980s, commercial electronic polyphase meters began to appear. These meters evolved similarly to their electromechanical counterparts. The first electronic meters had separate voltage and current sensors for each phase element and usually had separate multiplication circuits for each phase. The result of each multiplication was then combined into a single mechanical or electronic register that stored and displayed the result. Later designs combined the multiplication function for each phase into a single electronic circuit, such as a custom integrated circuit, digital signal processor (DSP), or microcontroller.

Polyphase Metering Today

Most U.S. meter manufacturers supply meters with maximum currents (meter Classes) of 100, 200 and 320 amperes for direct connection to the electrical services. These meters are referred to as self-contained or whole-current meters. Most manufacturers also supply meters with maximum currents of 10 and 20 amperes for use with instrument transformers. These meters are referred to as transformer-rated meters. Most polyphase meter manufacturers can furnish their meters with potential indicators that indicate the reduction of a phase voltage below some threshold. In electromechnanical meters, voltage indicating lamps or LEDs are used. Typically, these are installed on transformer-rated meters to indicate if the transformer has failed, however there is growing interest in this function to assure all lines are connected to the meter. In electronic meters, LEDs or indicators on the meter's display are typically used to indicate the voltage is present on each phase. In addition, many electronic meters now provide a number of additional measurement, security, instrumentation and power quality functions.

Multi-element (multi-stator) meters are made in both "A", (bottom-connected), and "S", (socket) type bases. Type "A" are normally connected to the Line and Load by means of a test block installed at the site. One disadvantage of the "A" base is that full Class 200 capacity is difficult to obtain due to the limitation placed on the size of the terminal connections defined by standardization of meter base dimensions. The use of the Class 200 "S" meter has increased rapidly. Its advantages include quick and easy insertion and removal of the meter in a compact meter socket and full Class 200 and 320 capacity. To test the meter, a socket test jack can be used or the meter can be removed, although most of the newer electronic meters provide numerous meter and installation diagnostics, often eliminating the need for this jack. The socket can be furnished with a manual or an automatic bypass to short the secondary of the any external current transformers, or allow removing or changing the meter without interrupting the customer's service.

Multi-stator Classes 10 and 20 meters are also furnished for switchboard use in semi-flush or surface-mounted cases, with or without draw-out features. Draw-out cases provide a means to test the meter in place, or to withdraw it safely from the case without danger of opening the current-transformer secondary circuits.

Blondel's Theorem

The theory of polyphase watthour metering was first set forth on a scientific basis in 1893 by Andre E. Blondel, engineer and mathematician. His theorem applies to the measurement of real power in a polyphase system of any number of wires. The theorem is as follows:

> If energy is supplied to any system of conductors through N wires, the total power in the system is given by the algebraic sum of the readings of N wattmeters, so arranged that each of the N wires contains one current coil, the corresponding voltage coil being connected between that wire and some common point. If this common point is on one of the N wires, the measurement may be made by the use of N-1 wattmeters.

The receiving and generating circuits may be arranged in any desired manner and there are no restrictions as to balance among the voltages, currents, or power-factor values.

From this theorem it follows that basically a meter containing two elements or stators is necessary for a three-wire, two- or three-phase circuit and a meter with three stators for a four-wire, three-phase circuit. Some deviations from this rule are commercially possible, but resultant metering accuracy, which may be decreased, is dependent upon circuit conditions that are not under the control of the meter technician. An example of such a deviation is the three-wire, single-stator meter previously described.

The circuit shown in Figure 7-1 may be used to prove Blondel's Theorem. Three watthour meters, or wattmeters, have their voltage sensors connected to a common point D, which may differ in voltage from the neutral point N of the load, by an amount equal to E_N. The true instantaneous load power is:

$$Watts_{\text{Load}} = E_A I_A + E_B I_B + E_C I_C$$

Inspection of the circuit shows:

$$E_A = E'_A + E_N$$
$$E_B = E'_B + E_N$$
$$E_C = E'_C + E_N$$

Substituting in the equation for total load power:

$$Watts_{\text{Load}} = (E'_A + E_N)I_A + (E'_B + E_N)I_B + (E'_C + E_N)I_C$$

$$Watts_{\text{Load}} = E'_A I_A + E'_B I_B + E'_C I_C + E_N(I_A + I_B + I_C)$$

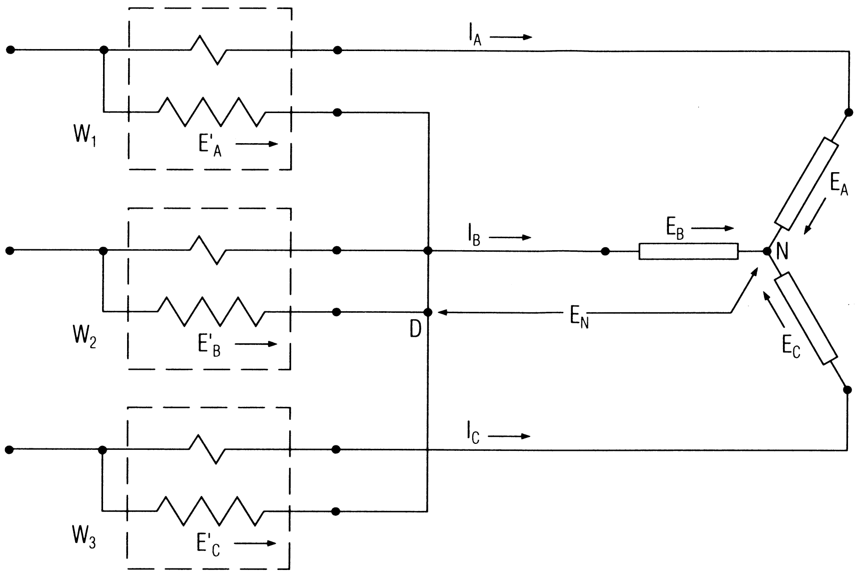


Figure 7-1. Diagram Used in Proof of Blondel's Theorem.

Since from Kirchhoff's Law, $I_A + I_B + I_C = 0$, the last term in the preceding equation becomes zero, leaving

$$Watts_{\text{Load}} = E'_A I_A + E'_B I_B + E'_C I_C = W_1 + W_2 + W_3$$

Thus, the three watthour meters correctly measure the true load power. If, instead of connecting the three voltage coils at a common point removed from the supply system, the common point is placed on any one line, the voltage becomes zero on the meter connected in that line. If, for example, the common point is on line C, E'_C becomes zero and the preceding formula simplifies to:

$$Watts_{\text{Load}} = E'_A I_A + E'_B I_B = W_1 + W_2$$

proving that one less metering unit than the number of lines will provide correct metering regardless of load conditions.

THREE-WIRE NETWORK SERVICE

Two-Stator Meter

Three-wire network service is obtained from two of the phase wires and the neutral of a three-phase, four-wire wye system, as shown in Figure 7-2. It is, in reality, two two-wire, single-phase circuits with a common return circuit and it has voltages that have a phase difference of 120 electrical degrees between them. The voltage is commonly 120 volts line-to-neutral/208 volts line-to-line.

The normal method of metering a network service is with a two-element (two-stator) meter connected as shown in Figure 7-2. With this connection, which follows Blondel's Theorem, each stator sees the voltage of one phase of the load. The phasors representing the load phase currents, I_{AN} and I_{BN}, are shown in the diagram lagging their respective phase voltages. The meter current conductors carry the line currents, I_{AN} and I_{BN}, and inspection of the circuit shows that these currents are identical to the load phase currents. Hence, the meter correctly measures the total load power. Any loads connected line-to-line, between A and B in Figure 7-2, will also be metered properly. With this type of meter there are no metering errors with imbalanced load voltages or varying load currents and power factors.

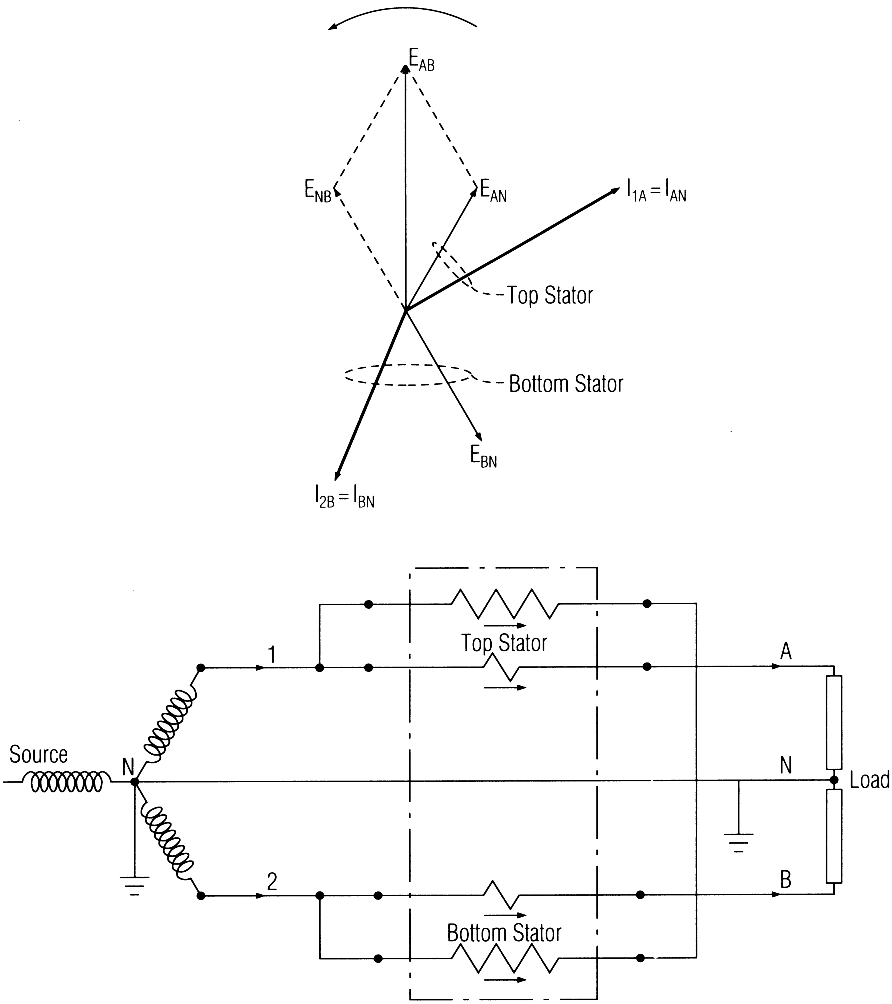


Figure 7-2. Two-Stator Meter on Three-Wire Network Service.

As such, the watt metering formula for any instance in time is:

$$Watts = (V_{AN} \times I_A) + (V_{BN} \times I_B)$$

Accumulating the watts over time allows the metering of watthours.

Single-element (single-stator) meters for measuring network loads have been developed and may be used with reasonable accuracy under particular load conditions. These meters are described under “Special Meters” in this chapter.

The conventional three-wire, single-element (single-stator), single-phase meter cannot be used for network metering. It will, of course, measure the 208-volt load correctly; but the two 120-volt loads are metered at 104-volts rather than at 120 volts and at a phase angle which is 30 degrees different from the actual. Therefore, for 120-volt balanced loads, meter registration will be close to 75 percent of the true value; but with imbalanced loads, the resulting meter error varies, rendering such metering useless.

Single-Stator Meters for Three-Wire Network Service

Single-stator meters have been developed for use on three-wire network services. These meters do not conform to Blondel’s Theorem and are subject to metering errors under certain conditions noted in the following paragraphs.

The schematic connections for the two types of meters now in use are shown in Figure 7-3. Each meter has one voltage coil and two current coils. In one case, Figure 7-3a, the meter is designed to use line-to-line voltage (208 V) on the voltage coil and the other, Figure 7-3b, uses one line-to-neutral voltage (120 V) on its voltage coil. The currents in the meter current coils are shifted in phase to provide correct metering. Obviously, any imbalance in line-to-neutral voltages will cause metering errors and, where imbalanced voltages exist, a two-stator meter should be used for accurate results.

In electromechanical meters, the current phase shifting is accomplished by impedance networks of resistors and inductors along with the current coils to split the total line currents and shift the phase position of the meter-current-coil current the desired amount. The number of turns and the impedance of the current coil may also be varied in design to obtain a usable meter. The current-impedance networks are shown in Figure 7-3. Electronic meters can accomplish the phase shifting using a variety of techniques.

Phase sequence of voltages applied to these meters is extremely important since such meters can usually only be designed to provide the correct phase shift of meter-coil current for only one phase sequence. If they are installed on the wrong phase sequence their energy registration is useless. All meters of this type have a built-in phase-sequence indicator.

THREE-WIRE, THREE-PHASE DELTA SERVICE

Two-Element (Two-Stator) Meter

The three-wire, three-phase delta service is usually metered with a two-stator meter in accordance with Blondel’s Theorem. The meter used has internal components identical to those of network meters, but may differ slightly in base construction. Typical meter connections are shown in Figure 7-4. In the top element (stator) of the meter the current sensor carries the current in line lA and the voltage sensor has load voltage AB impressed on it. The bottom element (stator) current sensor carries line current 3C and its corresponding voltage sensor has load voltage CB impressed. Line 2B is used as the common line for the common voltage-sensor connections.

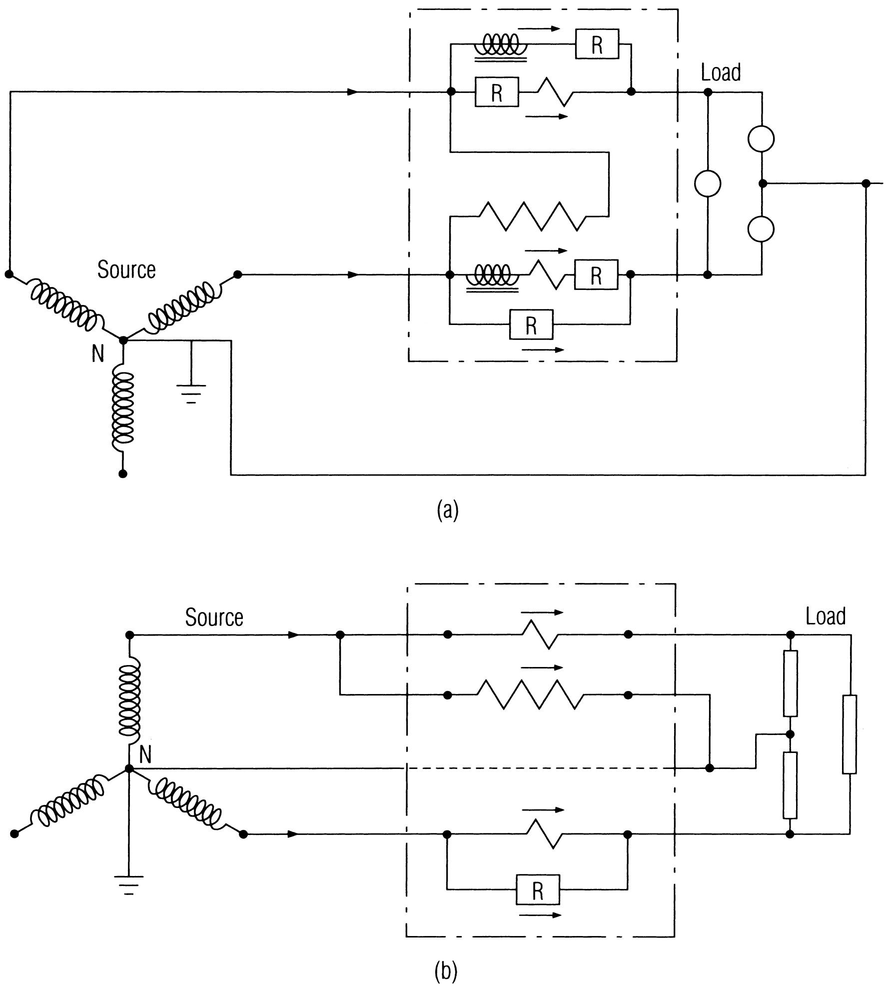


Figure 7-3. Single-Stator, Three-Wire Network Meters.

The phasor diagram of Figure 7-4 is drawn for balanced load conditions. The phasors representing the load phase currents I_{AB}, I_{BC}, and I_{CA} are shown in the diagram lagging their respective phase voltages by a small angle θ. By definition, this is the load power-factor angle. The meter current coils have line currents flowing through them, as previously stated, which differ from the phase currents. To determine line currents, Kirchhoff's Current Law is used at junction points A and C in the circuit diagram. Applying this law, the following two equations are obtained for the required line currents:

$$\dot{I}_{1A} = \dot{I}_{AB} - \dot{I}_{CA}$$

$$\dot{I}_{3C} = \dot{I}_{CA} - \dot{I}_{BC}$$

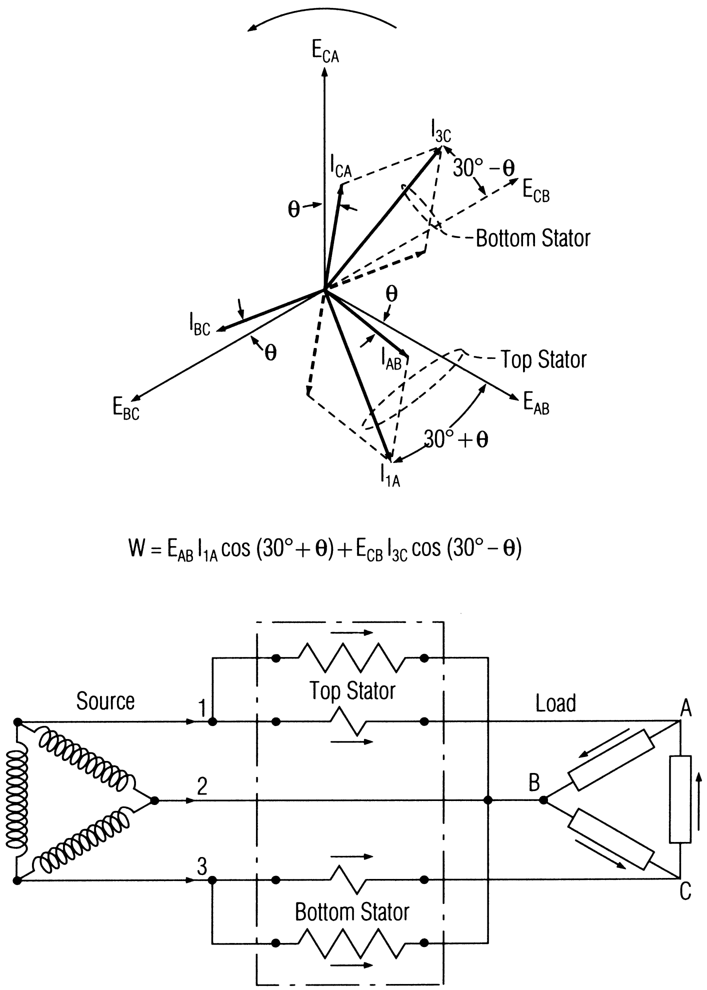


Figure 7-4. Two-Stator Meter on Three-Phase, Three-Wire Delta Service.

The operations indicated in these equations have been performed in the phasor diagrams to obtain I_{1A} and I_{3C}. Examination of the phasor diagram shows that for balanced loads the magnitude of the line currents is equal to the magnitude of the phase currents times the $\sqrt{3}$.

The top element (stator) in Figure 7-4 has voltage E_{AB} impressed and carries current I_{1A}. These two quantities have been circled in the phasor diagram and inspection of the diagram shows that for the general case the angle between them is equal to $30° + \theta$. Therefore, the power measured by the top element (stator) is $E_{AB}I_{1A}\cos(30° + \theta)$ for any balanced-load power factor. Similarly, the bottom element (stator) uses voltage E_{CB} and current I_{3C}. These phasors have also been circled on the diagram and in this case the angle between them is $30° - \theta$. The bottom element (stator) power is then $E_{CB}I_{3C}\cos(30° - \theta)$ for balanced loads. The sum of these two expressions is the total metered power.

Examination of the two expressions for power shows that even with a unity power factor load the meter currents are not in phase with their respective voltages. With a balanced unity power factor load the current lags by 30° in the top element (stator) and leads by 30° in the bottom element (stator). However, this is correct metering. To illustrate this more cleanly, consider an actual load of 15 amperes at the unity power factor in each phase with a 240-volt delta supply. The total power in this load is:

$$3 \times E_{\text{Phase}} \times I_{\text{Phase}} \times \cos\theta = 3 \times 240 \times 15 \times 1 = 10{,}800 \text{ watts}$$

Each element (stator) of the meter measures:

$$\begin{aligned}
\text{Top Element} &= E_{AB} I_{1A} \cos(30° + \theta) \\
\text{Since } I_{1A} &= \sqrt{3}\, I_{\text{Phase}} \\
\text{Top Element} &= 240 \times \sqrt{3} \times 15 \times \cos(30° + 0°) \\
&= 240 \times \sqrt{3} \times 15 \times 0.866 = 5{,}400 \text{ watts} \\
\text{Bottom Element} &= E_{CB} I_{3C} \cos(30° - \theta°) \\
\text{Since } I_{3C} &= \sqrt{3}\, I_{\text{Phase}} \\
\text{Bottom Element} &= 240 \times \sqrt{3} \times 15 \times \cos(30° - 0°) \\
&= 240 \times \sqrt{3} \times 15 \times 0.866 = 5{,}400 \text{ watts}
\end{aligned}$$

$$\text{Total Meter Power} = \text{Top Element} + \text{Bottom Element} = 5{,}400 + 5{,}400$$
$$= 10{,}800 \text{ watts} = \text{Total Load Power}$$

When the balanced load power factor lags, the phase angles in the meter vary in accordance with the $30° \pm \theta$ expressions. When the load power factor reaches 50%, the magnitude of θ is 60°. The top stator phase angle becomes $30° + \theta = 90°$ and, since the cosine of 90° is zero, the torque from this stator becomes zero at this load power factor. To illustrate this with an example, assume the same load current and voltage used in the preceding example with 50% load power factor.

$$\begin{aligned}
\text{Total Load Power} &= 3 \times 240 \times 15 \times 0.5 = 5{,}400 \text{ watts} \\
\text{Top Element} &= 240 \times \sqrt{3} \times 15 \times \cos(30° + 60°) \\
&= 240 \times \sqrt{3} \times 15 \times 0 = 0 \text{ watts} \\
\text{Bottom Element} &= 240 \times \sqrt{3} \times 15 \times \cos(30° - 60°) \\
&= 240 \times \sqrt{3} \times 15 \times 0.866 = 5{,}400 \text{ watts}
\end{aligned}$$

$$\text{Total Meter Power} = 0 + 5{,}400 = 5{,}400 \text{ watts} = \text{Total Load Power.}$$

With lagging load power factors below 50%, the top element power reverses direction and the resultant action of the two elements (stators) becomes a differential one, such that the power direction is that of the stronger element (stator). Since the bottom element (stator) power is always larger than that of the top element (stator), the meter power is always in the forward direction, but with proportionately lower power at power factors under 50%. Actually on a balanced load, the two elements (stators) operate over the following ranges of power factor angles when the system power factor varies from unity to zero: the leading element (stator) from 30° lead to 60° lag, the lagging element (stator) from 30° lag to 120° lag.

As such, the watt metering formula for any instant in time is:

$$Watts = (V_{ab} \times I_a) + (V_{cb} \times I_c)$$

Accumulating the watts over time allows the metering of watthours.

FOUR-WIRE, THREE-PHASE WYE SERVICE

Three-Element (Three-Stator) Meter

Figure 7-5 shows the usual meter connections for a three-stator meter on a four-wire wye service in accordance with Blondel's Theorem. The neutral conductor is used for the common meter voltage connection.

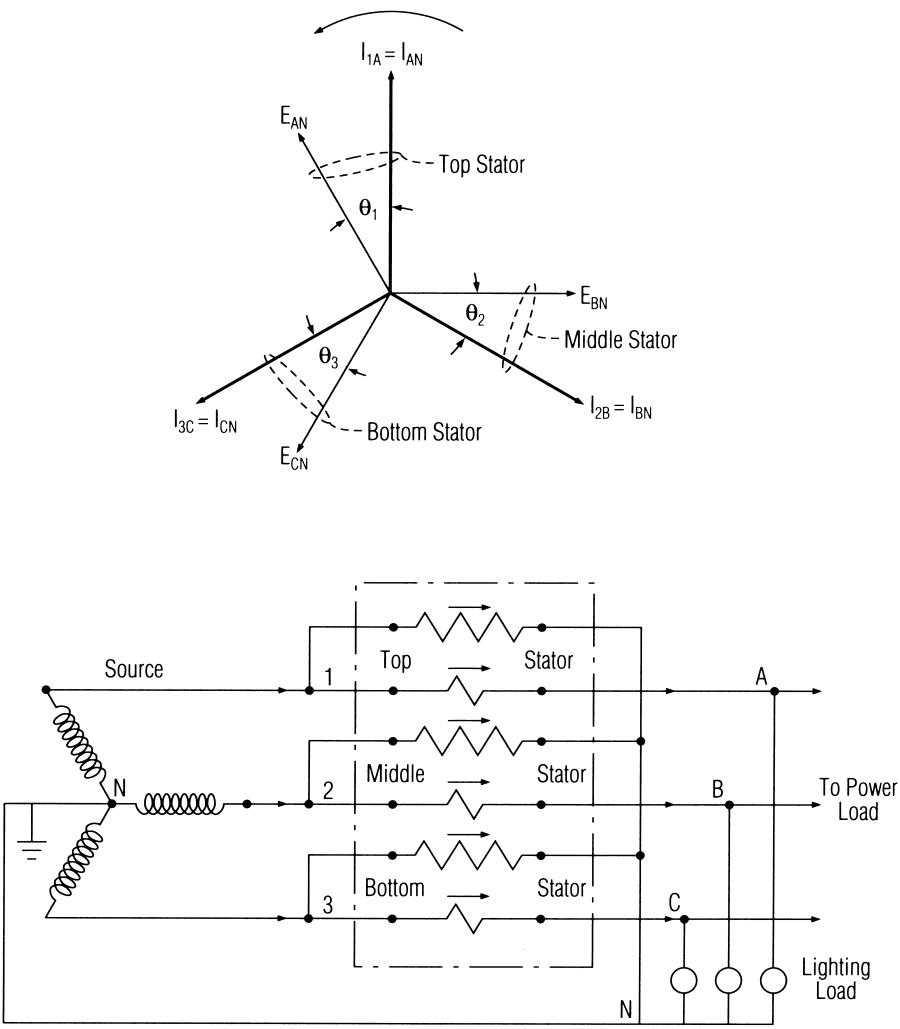


Figure 7-5. Three-Stator Meter on a Three-Phase, Four-Wire Wye Service.

The connection diagram shows three line-to-neutral loads and the phasor diagram shows the metering quantities. The diagram is drawn for balanced line-to-neutral loads, which have a lagging power factor angle.

The expression for total meter power can be written as follows by inspection of the phasor diagram:

$$\text{Total Meter Power} = E_{AN}I_{AN}\cos\theta_1 + E_{BN}I_{BN}\cos\theta_2 + E_{CN}I_{CN}\cos\theta_3$$

which is the total power developed by the load.

If the loads are connected line-to-line, instead of line-to-neutral, the total load power will still be the same as the total meter power, because it can be proven that any delta-connected load may be replaced by an equivalent wye-connected load.

Hence, there are no metering errors with imbalanced load voltages of varying load currents or power factors.

As such, the watt metering formula for any instant in time is:

$$\textit{Watts} = (V_{an} \times I_a) + (V_{bn} \times I_b) + (V_{cn} \times I_c)$$

Accumulating the watts over time allows the metering of watthours.

TWO-ELEMENT (TWO-STATOR), THREE-CURRENT SENSOR METER

For years, metering personnel have struggled with the cost of metering. Trade-offs can be made among the accuracy of the metering, the assumptions about the service voltages and currents, and the cost of the meter or the number of instrument transformers required. The two-element (two-stator), three current sensor meter is an example of a trade-off that many metering engineers have found acceptable. This meter employs two elements (stators) with two voltage sensors and three current sensors. Historically, an electromechanical meter of this type was less expensive than one with three voltage sensors. In addition, in a service requiring external voltage instrument transformers, two voltage transformers could be used instead of three. This could represent a significant equipment cost savings.

The metering is accomplished by recognizing that if the voltages of a four-wire wye system are truly 120° apart and balanced, one voltage can be accurately approximated by inverting the other two phase voltages and summing them together, as shown in Figure 7-6.

As such, the watt metering formula for any instant in time is:

$$\textit{Watts} = [V_{an} \times I_a] + [(-V_{an} - V_{cn}) \times I_b] + [V_{cn} \times I_c]$$

Accumulating the watts over time allows the metering of watthours. The above equation can be rewritten as follows:

$$\begin{aligned}\textit{Watts} &= [V_{an} \times I_a] + [(V_{an} + V_{cn}) \times (-I_b)] + [V_{cn} \times I_c] \\ &= [V_{an} \times (I_a - I_b] + [V_{cn} \times (I_c - I_b)].\end{aligned}$$

Note that this meter does not fulfill Blondel's Theorem, resulting in possible metering errors that will be discussed in following paragraphs. Because this meter has three current circuits and only two voltage circuits, it is often called a 2 1/2-element (2 1/2-stator) meter, although this is technically incorrect.

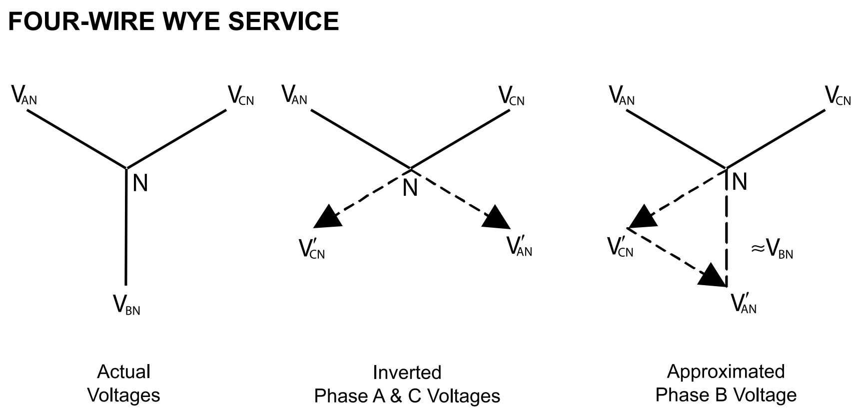


Figure 7-6. Approximation of V_{BN} in 2½-Element Meters.

In electronic meters, any of the above equations can be implemented. However, electronic meters that support quantities other than real energy often implement the first equation.

In electromechanical meters, the last equation is implemented. Two of the current circuits consist of separate current coils with the normal number of turns on each of the two stators. In addition, on each stator there is a second current coil with an equal number of turns. These two coils are connected in series internally to form the third meter current circuit, which is commonly called the Z-coil circuit.

Circuit connections are shown in Figure 7-7 for the two-element (two-stator), three-current-sensor meter on a four-wire wye service. The two voltage sensors are connected to measure the line-to-neutral voltages of the lines to which the associated current sensors are connected. The Z coil is connected in the line which does not have a voltage coil associated with it. For correct metering, the internal meter connections of this coil are reversed so that reverse direction is obtained in each element (stator) as shown in the circuit diagram.

The Z coil current reacts within the meter with the other two line-to-neutral voltages since it flows through both elements (stators). This reaction is equivalent to the current acting with the phasor sum of the two line-to-neutral voltages as shown in the above equations. The assumption is made for this meter that the phasor sum of the two line-to-neutral voltages is exactly equal and opposite in phase to the third line-to-neutral voltage. When this condition exists the metering is correct regardless of current or power-factor imbalance. The assumption is correct only if the phase voltages are balanced. If the voltages are not balanced, metering errors are present, and the magnitudes depend on the degree of voltage imbalance.

The phasor diagram of Figure 7-7 shows the metering quantities. The diagram is drawn for balanced line-to-neutral loads which have a lagging power factor angle. The current sensor without an associated voltage sensor (Z coil) carries line current I_{2B}, but because its connections are reversed within the meter, the phasor current which reacts with the meter voltages is actually $-I_{2B}$, or I_{B2}. Thus, as shown

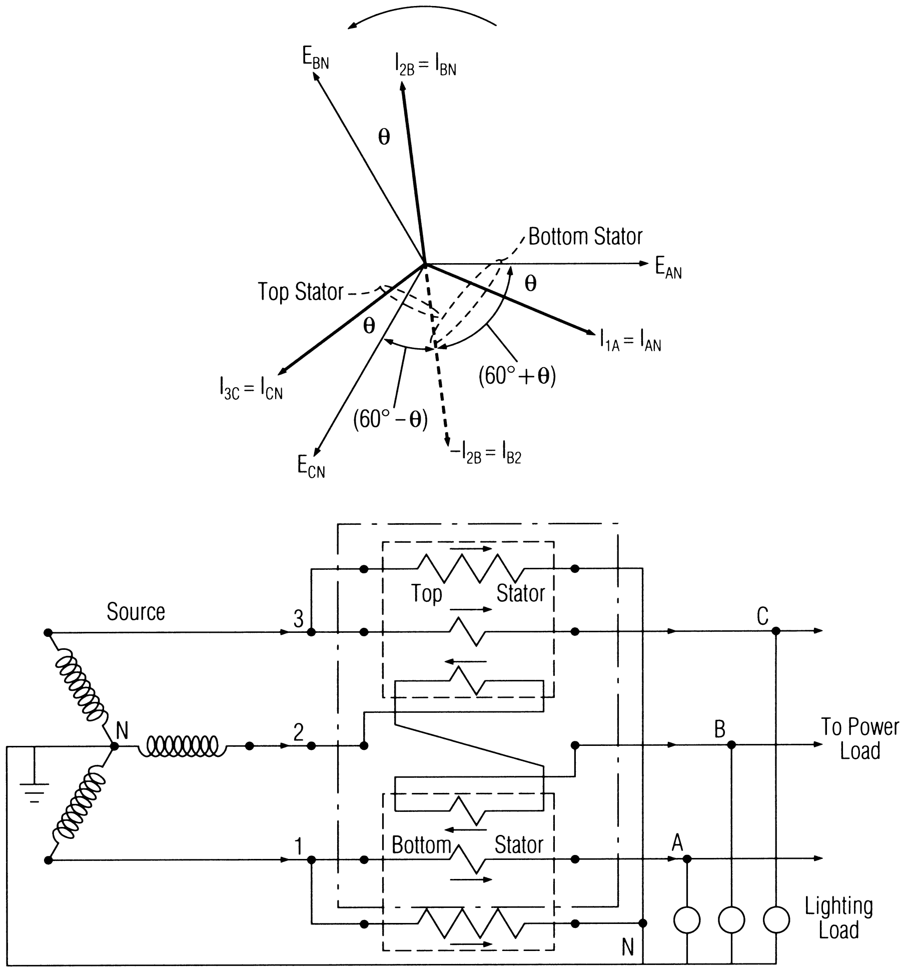


Figure 7-7. Two-Stator, Three-Current-Coil Meter on Three-Phase, Four-Wire Wye Service.

in the phasor diagram, in the top element (stator), I_{B2} and I_{3C} react with E_{CN} while in the bottom element (stator), I_{B2} and I_{1A} react with E_{AN}. In both cases the angles between the voltage and current phasors are less than 90°, so forward power is measured. For the general case with a balanced load, the angle between I_{B2} and E_{AN} is $60° + \theta$ while the angle between I_{B2} and E_{CN} is $60° - \theta$.

The expression for total meter power can be written as follows by inspection of the phasor diagram:

$$\text{Total Meter Power} = E_{AN}I_{1A}\cos[\theta] + E_{CN}I_{3C}\cos[\theta] + E_{AN}I_{B2}\cos(60° + [\theta]) + E_{CN}I_{B2}\cos(60° - [\theta])$$

As an example, with a balanced line-to-neutral load from each of 15 amperes at 120 volts with a lagging power factor of 86.6% the true load power is:

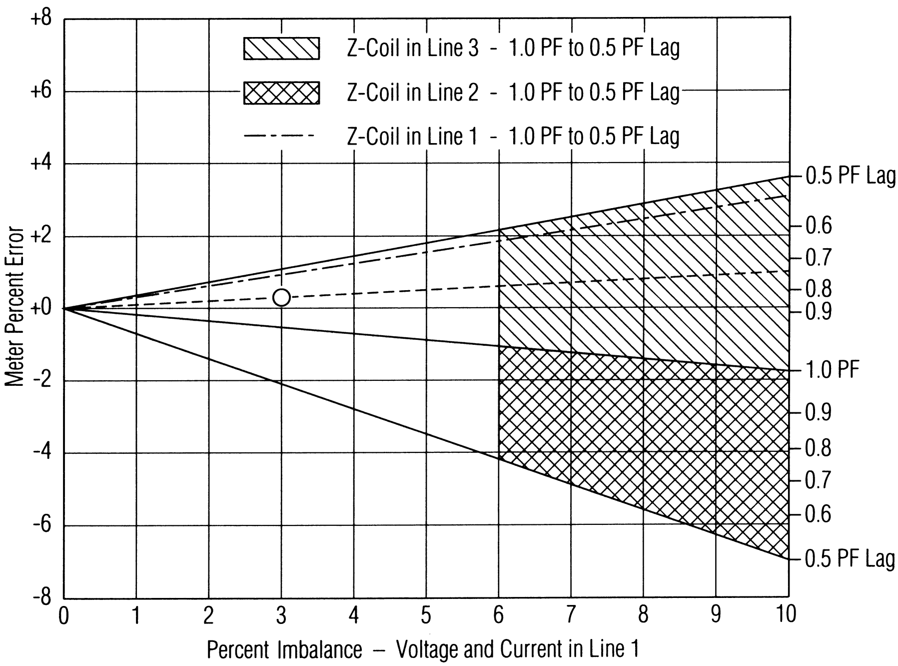
$$\text{True Power} = 3\ E_{Phase}I_{Phase}\cos[\theta] = 3 \times 120 \times 15 \times 0.866 = 4676.4 \text{ watts}$$

For 86.6% power factor the phase angle θ is 30°.

$$\begin{aligned}\text{Metered Power} &= 120 \times 15 \times 0.866 + 120 \times 15 \times 0.866 + 120 \times 15 \times \cos(60° + 30°) + 120 \times 15\cos(60° - 30°) \\ &= 2 \times 120 \times 15 \times 0.866 + 120 \times 15\cos 90° + 120 \times 15\cos 30° \\ &= 2 \times 120 \times 15 \times 0.866 + 120 \times 15 \times 0 + 120 \times 15 \times 0.866 \\ &= 3 \times 120 \times 15 \times 0.866 \\ &= 4676.4 \text{ watts}\end{aligned}$$

A similar proof of correct metering may be developed for a polyphase power load connected to lines A, B, and C.

As previously stated, a 2½-element (2½-stator) meter is in error when the voltages are not balanced in magnitude or phase position. With imbalanced voltages the amounts of any current imbalance and power-factor values also have a bearing on the amount of metering error as well as where the voltage imbalance occurs relative to the connection of the Z coil. The curves of Figure 7-8 are drawn



To use error chart, place a straight edge through the zero point on the Meter Percent Error scale and through the desired PF in the selected Z coil location. Then select Percent Imbalance, and read percent error on the Meter Percent Error scale. For example, with the Z coil in Line 3 and a 0.75 PF lag, a 3 percent voltage and current imbalance in Line 1 will result in a 0.35% error. See point O.

$$\text{Percent Imbalance} = \frac{\text{Maximum Deviation from Average}}{\text{Average}} \times 100$$

Figure 7-8. Error Curves for Equal Voltage and Current Imbalance in One Phase and for Three Possible Locations of Z Coil.

for an assumed equal voltage and current imbalance in one load phase and for the three possible locations of the Z coil. Using the curves for an assumed voltage and current imbalance of 2% in Phase 1, the following tabulation shows the variations in metering errors as the Z coil is moved.

It must be remembered, however, that if the voltages remain balanced, the 2½-element (2½-stator) meter will meter correctly with current and power factor imbalance.

While this method of metering does not follow Blondel's Theorem and is less accurate than a three-element meter in cases of imbalanced voltages, many users find it acceptable for energy measurement.

Two-Element (Two-Stator) Meter Used with Three Current Transformers or Two Window Current Transformers

This method of metering a four-wire wye service uses a conventional two-element (two-stator), two-current sensor meter with three-current transformers in the circuit. The circuit connections are shown in Figure 7-9.

The component currents in each current sensor are indicated by the arrows on the circuit diagram of Figure 7-9. Note that in both elements (stators) the third line transformer current, I_{2B}, is in opposition to the other line transformer current. The phasor diagram shows how these components add to produce the total current in each current sensor, I_X and I_Y.

Before the component currents are added, the phasor diagram for this connection is similar to that shown in Figure 7-7 for the 2½-element meter, showing that this method is electrically equivalent to the 2½-element meter. The difference is that the third line current flows through an external transformer and its current is combined in the meter's two-current sensors rather than processing the third line current in the meter directly.

As such, the watt metering formula for any instant in time is:

$$Watts = [V_{an} \times (I_a - I_b)] + [V_{cn} \times (I_c - I_b)]$$

Accumulating the watts over time allows the metering of watthours.

An alternate to this approach is to use two current transformers with window openings through the transformer cores. The window current transformers allow the line currents to be combined in these external transformers rather than in the meter current sensors. In this approach, one service line passes through one current transformer window and the second service line passes through the second current transformer window. The third service line passes through each of the current transformer windows in the opposite direction from the first two service lines.

These methods have the same accuracy limitations and errors as the 2½-element meter.

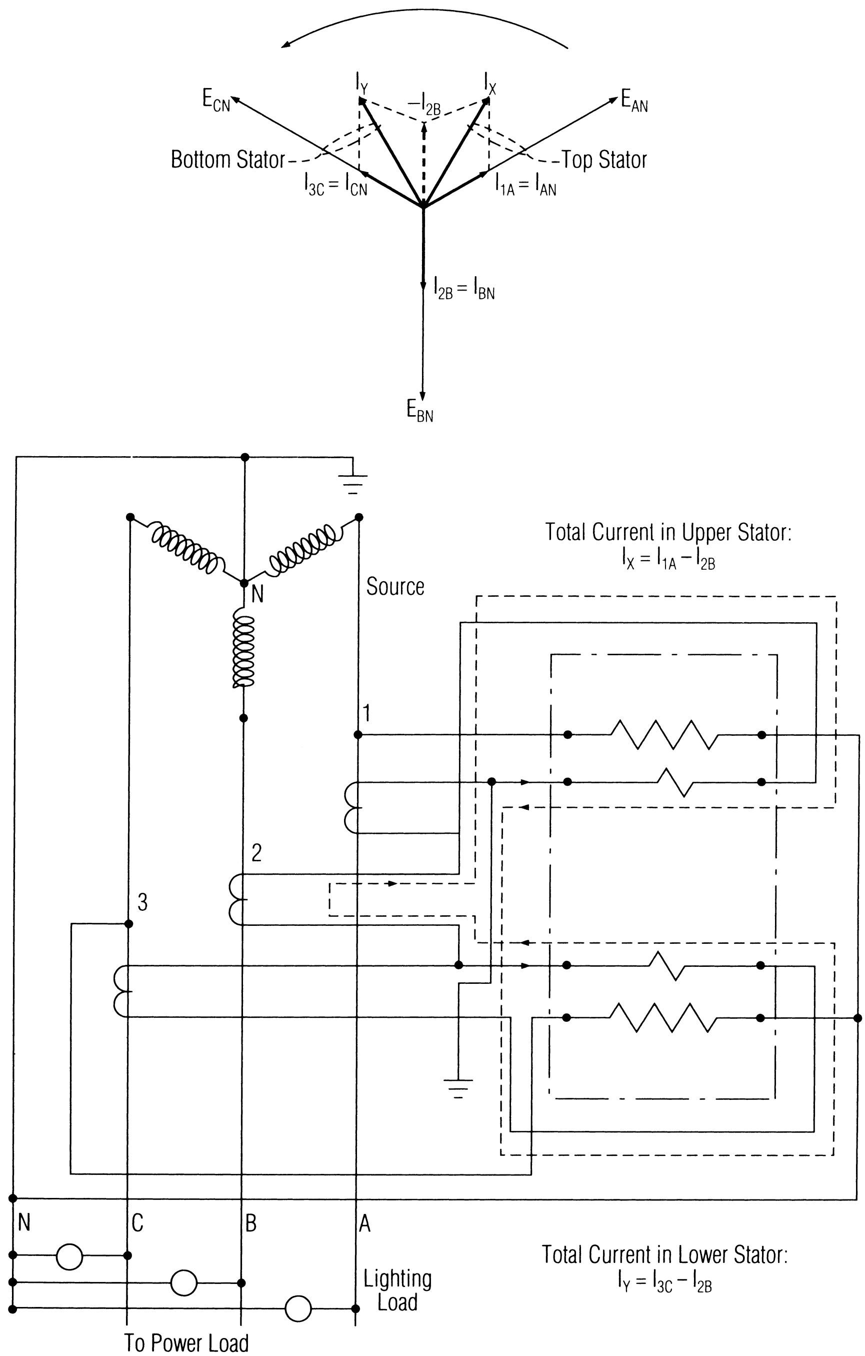


Figure 7-9. Two-Stator Meter Used with Three-Current Transformers on a Three-Phase, Four-Wire Wye Service.

FOUR-WIRE, THREE-PHASE DELTA SERVICE

Three-Element (Three-Stator) Meter

The four-wire delta service is used to supply both power and lighting loads from a delta source. The lighting supply is obtained by taking a fourth line from the center-tap of one of the transformers in the delta source. Correct metering according to Blondel's Theorem requires a three-element (three-stator) meter. Figure 7-10 shows the circuit and metering connections. Since the mid-tap neutral wire is usually grounded, this line is used for the common meter voltage connection. The diagram shows the nominal voltage impressed on each voltage sensor in the meter for a 240-volt delta source. As such, the watt metering formula for any instant in time is:

$$Watts = (V_{an} \times I_a) + (V_{bn} \times I_b) + (V_{cn} \times I_c)$$

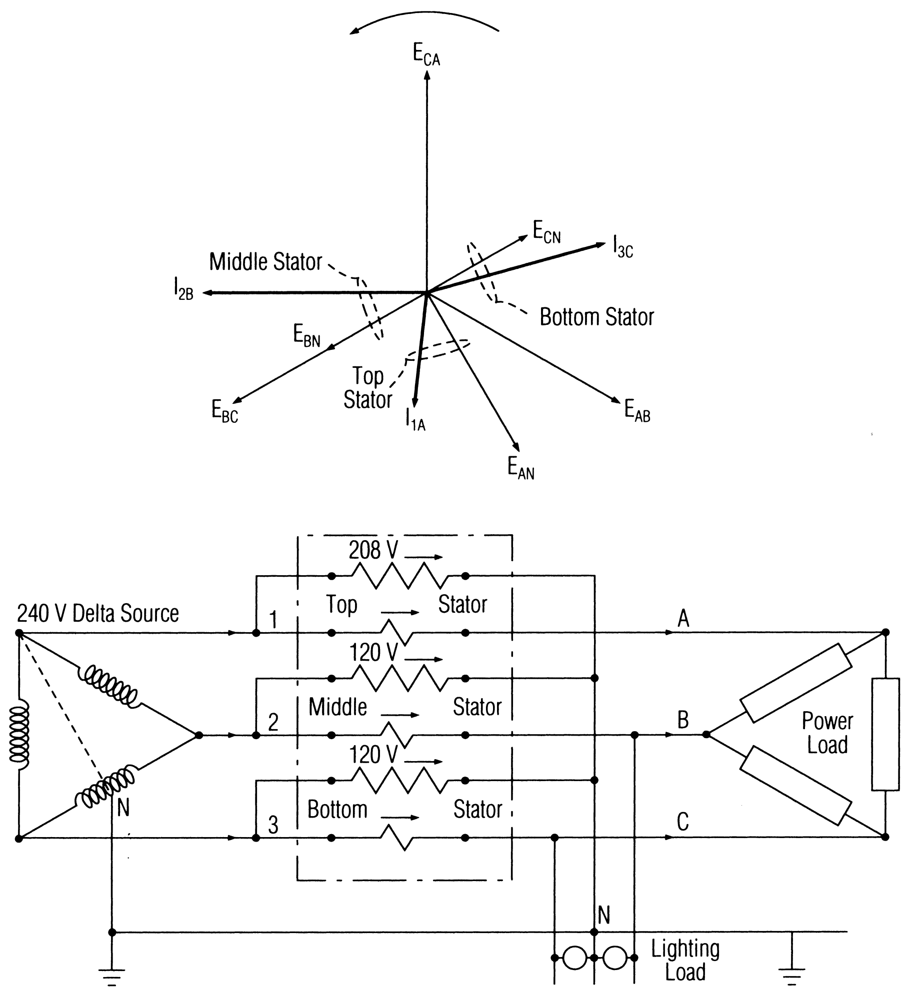


Figure 7-10. Three-Stator Meter on a Three-Phase, Four-Wire Delta Service.

where V_{AN} and V_{BN} are nominally 120 VAC, and V_{CN} is nominally 208 VAC. Accumulating the watts over time allows the metering of watthours.

Today's wide-voltage-range, three-element electronic meters are ideally suited for this service since a mixture of line voltages must be metered. In an electromechanical meter, the top stator voltage sensor is commonly rated at 240 volts, although in service it operates at 208 volts. Because the torque of each stator must be equal for the same measured watts, it is necessary that the calibrating watts, or test constant, be the same for each stator. This necessitates that the current coils in the 120-volt stators have double the rating of the current coil in the 240-volt stator.

The phasor diagram of Figure 7-10 is drawn for a combined power and lighting load. To simplify the diagram, the current phasors for the individual loads are not shown. Since this method follows Blondel's Theorem, it provides correct metering under any condition of voltage or load imbalance.

The advantages of using a three-element (three-stator) meter for this application are: (1) correct registration under all conditions of voltage; and (2) increased meter capacity in lighting phases, an important advantage when the load in these phases greatly exceeds that in the power phase. A disadvantage of this metering is that to verify a meter's accuracy in this service, polyphase test stations that can apply different voltages to different elements are required. These were not readily available in the past, and still may not be the common test station within today's meter shop. Another disadvantage is that electromechanical meters for this metering are difficult to produce. However, with today's three-element electronic meters and polyphase test stations, there really are no disadvantages to providing three-element electronic meters for this service. Most wide-voltage-range, three-element, electronic meter designs can be qualified to work on this service using a polyphase test station, and then individual meter calibration can be verified with 120 volts applied to all elements with no concern that the meter will not perform accurately when the third element is powered at 208 volts.

TWO-ELEMENT (TWO-STATOR), THREE-CURRENT SENSOR METER

It is possible, as with the four-wire wye service, to meter a four-wire delta service with a two-element (two-stator), three current sensor meter. Although it is a compromise with Blondel's Theorem which allows possible metering errors, historically, it has been the preferred electromechanical metering approach. This was because of the difficulty of producing and testing a three-stator meter for this service. Because this service can be more accurately metered with a wide-voltage-range, electronic, three-element meter, today's electronic meter manufacturers sometimes do not feel the need to offer this type of meter.

The meter connections are shown in Figure 7-11. The bottom element (stator), which has two independent current sensors, has its voltage sensor connected across the two lines that supply the lighting load. The top element (stator), is connected the same as in the three-element (three-stator) meter of Figure 7-10. It is now possible for both voltage sensors to have the same voltage rating.

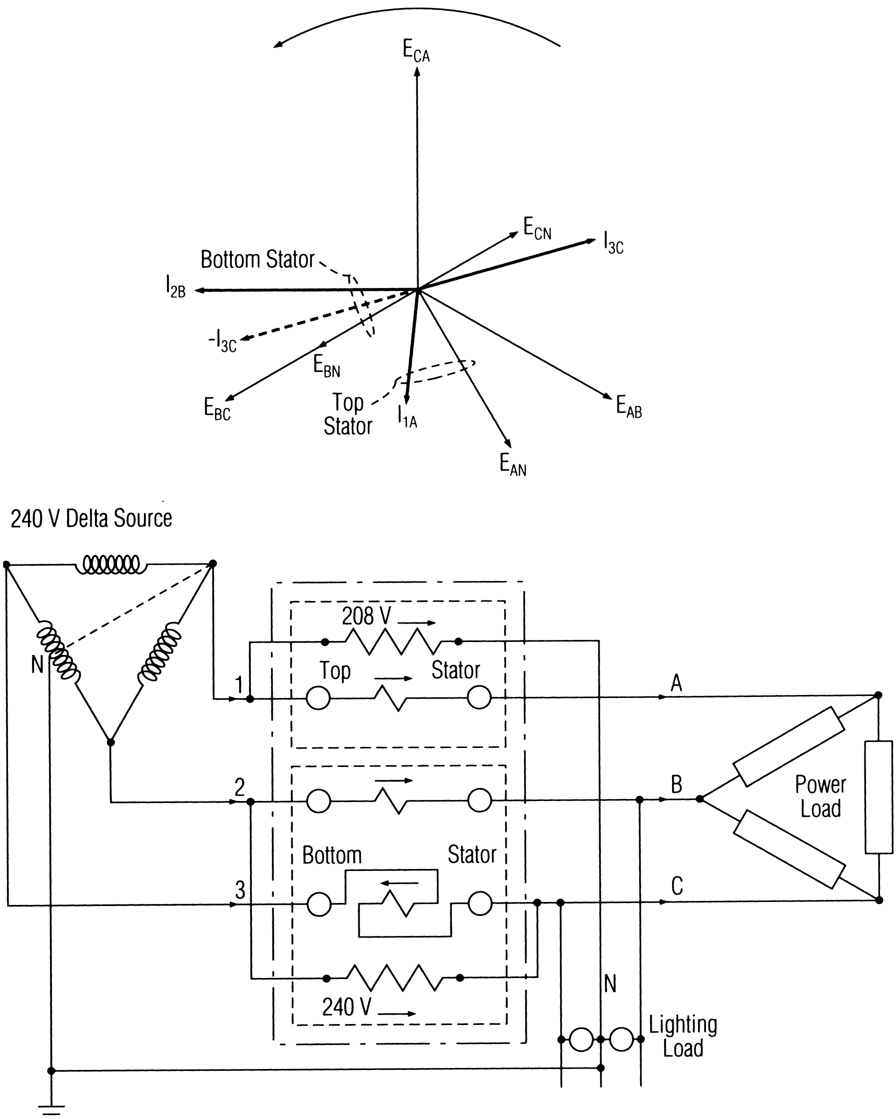


Figure 7-11. Two-Stator, Three-Current-Coil meter on a Four-Wire Delta Service.

The phasor diagram of Figure 7-11 is drawn for the identical load conditions used in Figure 7-10 for the three-element (three-stator) delta meter. However, the metering conditions here are different. The bottom element (stator) now uses voltage E_{BC}. If the phasor current in the bottom service current, I_{3C}, were to act with this voltage, the developed power would be negative since the angle between them is greater than 90°. Therefore, to measure power in the forward direction, the bottom current sensor connections are reversed internally within the meter, the current phasor, which is used by the meter, is $-I_{3C}$ as shown on the phasor diagram. The bottom element (stator) operates on the same principle previously described for the three-wire, single-phase meter with one current conductor reversed.

Comparing this meter with the three-element (three-stator) delta meter of Figure 7-10, it can be seen that the middle and bottom current sensors are now acting with a voltage of twice the rating that they do in the three-element (three-stator) meter. In electromechanical metering, the current flux must be cut in half to offset the voltage flux which is doubled. Since the current is not changed, it is necessary to reduce the turns of each of the two current coils by half. Again, the same principle applies as in the three-wire, single-phase meter. In electronic meters, this can be adjusted in the weighting (or measurement) of either the voltage or the current sensors. It is normal to match the operation of the electromechanical meter and make the adjustments in the current measurement.

As such, the watt metering formula for any instant in time is:

$$Watts = [V_{ab} \times {}^{1}\!/_{2}(I_a - I_b)] + [V_{cn} \times I_c]$$

Accumulating the watts over time allows the metering of watthours. One advantage of using this meter over the three-element (three-stator) meter in four-wire delta applications is that the same test procedure as the three-wire, three-phase meter can be used. One disadvantage is the possibility of errors under certain voltage and current conditions in the three-wire lighting circuit. On small loads, this may be of little concern as the errors are similar to those that exist wherever a standard single-stator, three-wire meter is used.

MULTI-ELEMENT (MULTI-STATOR) METER APPLICATIONS WITH VOLTAGE INSTRUMENT TRANSFORMERS

The usual customer metering of polyphase services does not normally present major problems. With metering at the higher distribution voltages (either of distribution lines or customers at these voltages), voltage instrument transformers are required and new issues must be considered. In many cases the actual circuit conditions are hard to determine, which in itself presents a metering problem. Required ground connections may not be present or of sufficiently low impedence, or there may be unintended ground connections. These considerations are of particular concern with wye circuits.

Wye-Circuit Metering with Voltage Instrument Tranformers

Consider the circuit shown in Figure 7-12a. Here a four-wire wye circuit is derived from a delta-wye transformer bank. With this circuit there is no question that a three-stator meter, or its equivalent, is required to correctly meter any connected load. Three voltage transformers would be connected wye-wye as shown, with their primary neutral connected to the circuit neutral. When voltage transformers are connected in wye-wye there is a third-harmonic voltage generated in each primary winding. The neutral connection between voltage transformer neutral

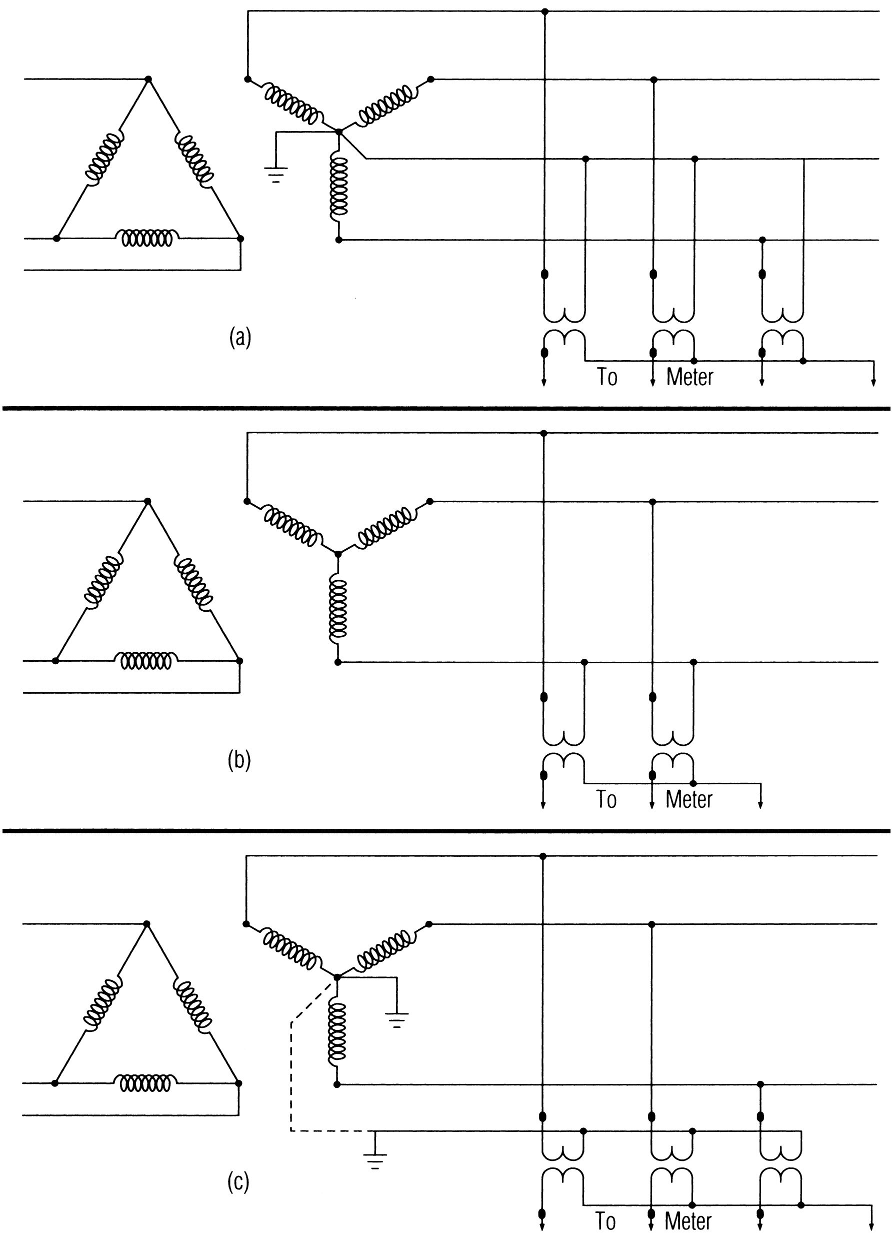


Figure 7-12. Wye-Circuit Voltage Transformer Connections.

and system neutral provides a path for a third-harmonic current flow, thereby keeping the third-harmonic voltages at low values. If this path were not present, the transformer voltages would be highly distorted by the excessive third-harmonic voltages, potentially causing metering errors. Also, serious hazards to voltage transformer insulation exist because of large increases in exciting current due to harmonic voltages. The four-wire wye circuit may also be derived from a wye-wye distribution bank, wye auto-transformer, wye grounding bank, or zig-zag transformer connections. Regardless of its source, the metering connections previously discussed are correct.

The circuit of Figure 7-12b is a delta-wye transformer bank with a three-wire secondary without ground. If it is known that there is no possibility of an actual or unintended phantom ground in the secondary circuit, it may be metered (as in any three-wire circuit) by a two-stator meter. Two voltage transformers would be connected as shown using one of the lines for the common connection.

The three-wire wye secondary circuit with neutral grounded as shown in Figure 7-12c, presents a major metering problem. Since the secondary circuit is three-wire, it is possible to use a two-stator meter. However, it is possible that this may not be correct metering, since loads may be connected from the unmetered line to ground and thereby fail to be metered. Also, loads connected from metered lines to ground will not be measured correctly. For correct metering under all load conditions, a three-stator meter or equivalent must be used. In this case three voltage transformers connected wye-wye would be used as shown. To limit third-harmonic effects, the neutral of the voltage transformers must be connected to the neutral of the distribution bank by a low-impedance connection. If the meter is located at the same substation as the distribution bank, a ground connection to the station grounding grid may be sufficient or the two neutrals may be directly connected. If the metering location is at a considerable distance from the distribution bank, it may not be possible to establish a firm common ground. When the metering transformer neutral is left floating, the harmonic problem is again very serious. Harmonic voltages as large as 30% have been found in some instances. If the voltage transformer neutral is grounded at the metering location to an isolated ground, other problems exist. Differences in ground voltage under certain conditions can cause extremely hazardous conditions at the meter and a high-resistance ground may not eliminate the harmonic errors. Because of these conditions, many companies require that a neutral conductor be run between the distribution and instrument voltage transformers.

Many other problems can arise in wye-circuit metering, but they are too numerous to discuss here. In any such problem, the presence of harmonics and their potential effects on the metering should always be considered. In metering transmission and distribution circuits, a thorough understanding of circuit connections is necessary. For example, the three-wire wye connection with neutral ground is frequently encountered. With voltages in the order of 24,000 volts the designer is reasonably certain that customer loads will not be connected line-to-ground and two-stator metering will be correct. However, this may not always be the case. Further details on transformer connections will be found in Chapter 11, “Instrument Transformers.”

ELECTROMECHANICAL METERING

Basically, the electromechanical watthour meter consists of a motor whose torque is proportional to the power flowing through it, a magnetic brake to retard the speed of the motor in such a way that it is proportional to power (by making the braking effect proportional to the speed of the rotor), and a register to count the number of revolutions the motor makes and convert, store, and display these revolutions as watthours. Figure 7-13 shows these parts. If the speed of the motor is proportional to the power, the number of revolutions will be proportional to the energy.

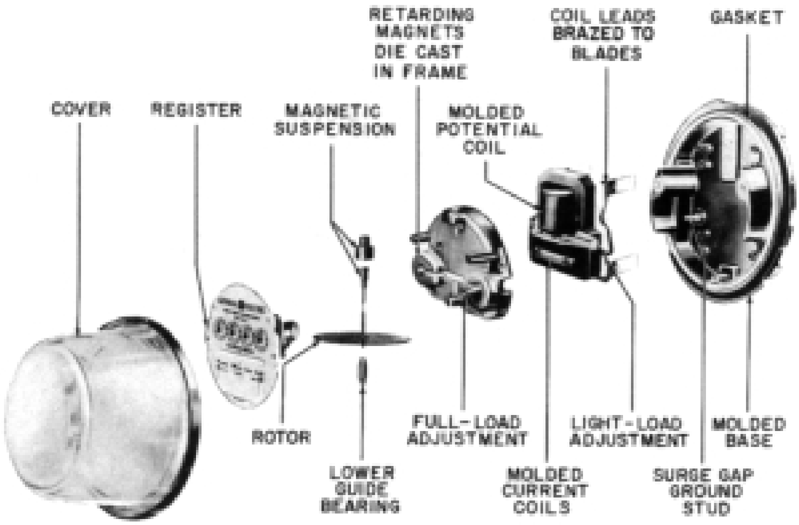


Figure 7-13. Basic Parts of a Watthour Meter.

THE MOTOR IN AN ELECTROMECHANICAL SINGLE-STATOR AC METER

The motor is made up of a stator sensing the phase voltage and current with electrical connections, as shown in Figure 7-14, and a rotor, which provides the function of multiplication. The stator is an electromagnet energized by the line voltage and load current. The portion of the stator energized by the line voltage is known as the voltage coil and serves the function of voltage sensor. For meters built since 1960, the voltage coil consists of approximately 2,400 turns of No. 29 AWG wire for a 120 volt coil to more than 9,600 turns of No. 35 AWG wire for a 480 volt coil. These coils are so compensated that the meter can be used within the range of 50 to 120% of nominal voltage, as explained later in this chapter. Because of the large number of turns, the voltage coil is highly reactive.

The portion of the stator energized by the load current is known as the current coil and serves the function of current sensor. For a Class 200 meter, the current coil usually consists of two or four turns of wire equivalent to approximately 30,000 circular mils in size. The current coils are wound in reverse directions on the two current poles for correct meter operation.

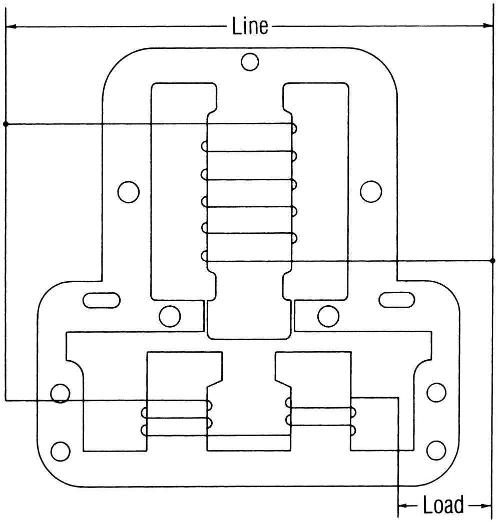


Figure 7-14. Basic Electromagnet (for Two-Wire Meter).

Dr. Ferraris, in 1884, proved that torque could be produced electromagnetically by two alternating-current fluxes, which have a time displacement and a space displacement in the direction of proposed motion. The voltage coil is highly inductive, as mentioned before, so the current through the voltage coil (and hence the flux from it) lags almost 90° behind the line voltage. In modern meters, this angle is between 80° and 85°. Although the current coil has very few turns, it is wound on iron, so it is inductive. However, it is not as inductive as the voltage coil. The power factor of a modern meter current coil may be 0.5 to 0.7 or an angle of lag between 60° and 45°. It is important to remember that the meter current coils have negligible effect on the phase angle of the current flowing through them. This is true because the current coil impedance is extremely small in comparison to the load impedance, which is connected in series. The load voltage and load impedance determine the phase position of the current through the meter. With a unity-power-factor load, the meter current will be in phase with the meter voltage. Since current through the voltage coil lags behind current through the current coil, flux from the voltage coil reaches the rotor after flux from the current coil and a time displacement of fluxes exists. The stator is designed so that the current and voltage windings supply fluxes that are displaced in space. These two features combine to give the time and space displacement that Dr. Ferraris showed could be used to produce torque.

In order to understand why torque is produced, certain fundamental laws must be remembered. They are:

1. Around a current-carrying conductor there exists a magnetic field;
2. Like magnetic poles repel each other; unlike poles attract each other;
3. An electromotive force (EMF) is induced in a conductor by electromagnetic action. This EMF is proportional to the rate at which the conductor cuts magnetic lines of force. The induced EMF lags 90° behind the flux that produces it;

4. If a conducting material lies in an alternating-current magnetic field, the constantly changing or alternating magnetic lines of force induce EMFs in this material. Because of these EMFs, eddy currents circulate through the material and produce magnetic fields of their own;
5. When a current is caused to flow through a conductor lying within a magnetic field, a mechanical force is set up which tends to move the current-carrying conductor out of the magnetic field.

The reason for this effect can be seen from Figure 7-15. In Figure 7-15a, a conductor is indicated as carrying current from above into the plane of the paper, which establishes a magnetic field that is clockwise in direction. Figure 7-15b indicates an external magnetic field. When the current-carrying conductor is moved into the external field, as in Figure 7-15c, it reacts with the external field and causes a crowding of the flux lines on the left where the two fields are additive. On the right, where the fields are in opposition, the flux lines move apart. The flux lines may be considered as elastic bands acting on the conductor, causing a force that tends to move the conductor to the right.

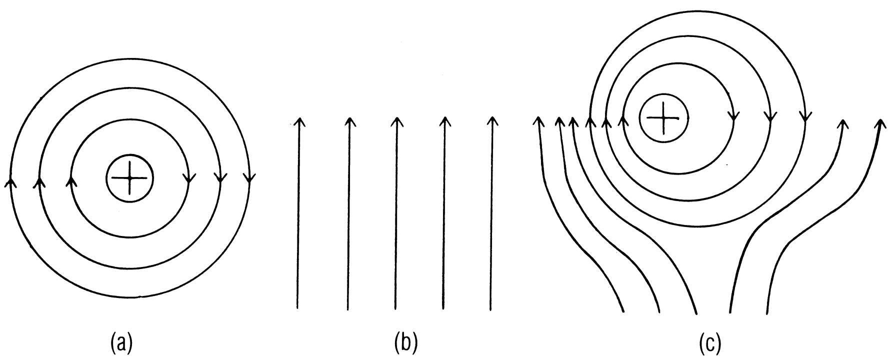


Figure 7-15. Effect of a Current-Carrying Conductor in an External Magnetic Field.

The rotor of the meter is an electrical conductor in the form of a disk that is placed between the pole faces of the stator as indicated in Figure 7-16. The magnetic fluxes from the stator pass through a portion of the disk and, as the magnetic fields alternately build up and collapse, induced EMFs in the disk cause eddy currents that react with the alternating magnetic field, causing torque on the disk. The disk is free to turn, so it rotates.

Figure 7-17 shows the flux relationships and disk eddy currents in a meter at various instants of time during one cycle of supply voltage. It also indicates the space displacement that exists between the magnetic poles of the current coils and the voltage coil. The four conditions in Figure 7-17 correspond to the similarly marked time points on the voltage and current flux waveforms of Figure 7-18. This illustration also shows the time displacement existing between current and voltage coil fluxes. In relating the fluxes and eddy currents shown in Figure 7-17 to the waveforms of Figure 7-18, it must be remembered that when the flux waveforms cross the zero axis there is no magnetic field generated at this instant in time. However, it is at this particular instant that the rate of change of

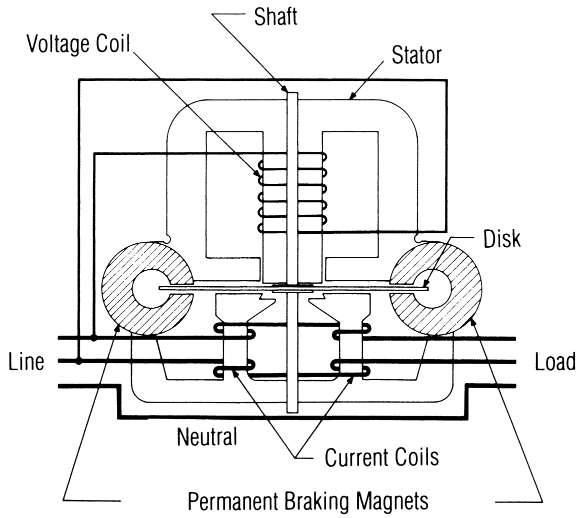


Figure 7-16. Schematic Diagram of a Three-Wire, Single-Phase Induction Watthour Meter.

flux is greatest, giving the maximum induced voltage in the disk and maximum resulting disk eddy currents. Thus, at Time 1, the voltage flux is at its maximum (negative) value as shown, but it causes no disk eddy currents because at this instant its rate of change is zero. At the same time the current flux is zero, but its rate of change is at maximum, giving the greatest disk eddy currents. Consideration in Figure 7-17 of the directions of the fluxes created by the disk eddy currents and the air-gap fluxes from the voltage and current coils shows that, in accordance with Figure 7-15, a force is developed with direction of the resultant torque as shown to the left.

In Figure 7-18, below the flux waveforms, are enlarged views of the current and voltage poles and disk, which show more clearly the flux interactions that produce disk torque. It is assumed that an exact 90° phase relationship has been obtained between the two fluxes. Let us analyze each time condition separately:

1. The current coils are at the zero point of their flux curve; hence the rate of change of current flux is maximum, giving disk eddy currents as shown for the two current poles. The voltage-coil flux curve lags that of the current coil by 90°. Since this curve is below the zero line, the voltage coil develops a south magnetic pole. Interaction of the disk eddy-current flux (in the central portion of the disk) and the voltage-coil flux develops a force to the left in the disk according to the principle shown in Figure 7-15. The return paths of the disk eddy currents shown in the outer portions of the disk are too far removed from the voltage flux to have an appreciable effect on disk force.
2. At this time, 90° after Time 1, the voltage-coil flux has reached zero. Its rate of change is maximum, causing disk eddy currents as shown. The current-coil flux has reached its maximum. North and south current poles are produced as indicated because the current coils are wound in reverse directions on the two poles. Again, the interaction of flux produced by the disk eddy currents with the current-coil flux creates disk force to the left.

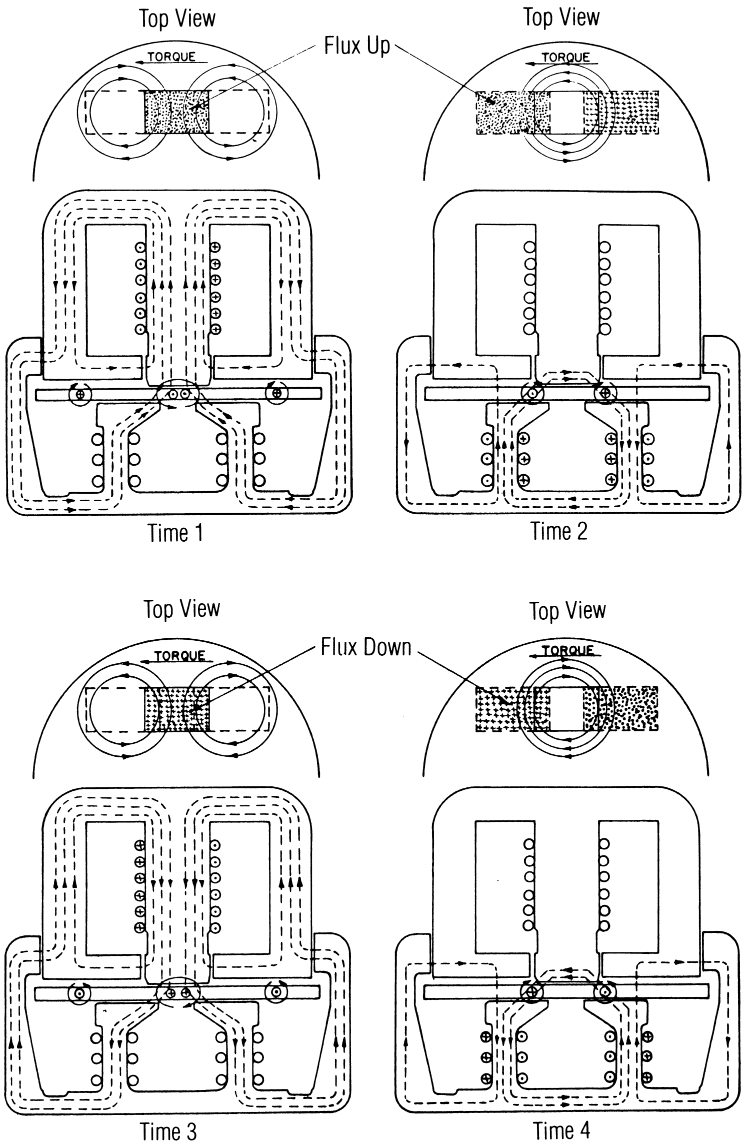


Figure 7-17. Flux Relationships and Disk Eddy Currents.

3. This point is similar to that at Time 1 and occurs 180° later. Here, the voltage flux curve is above the zero line, producing a north pole. The current-coil flux has again reached zero, but its rate of change is in the opposite direction so that the direction of disk eddy-current flow is reversed from that shown at Time 2. Since both the voltage flux and disk eddy-current flux are reversed in direction, the resultant disk force is still to the left.

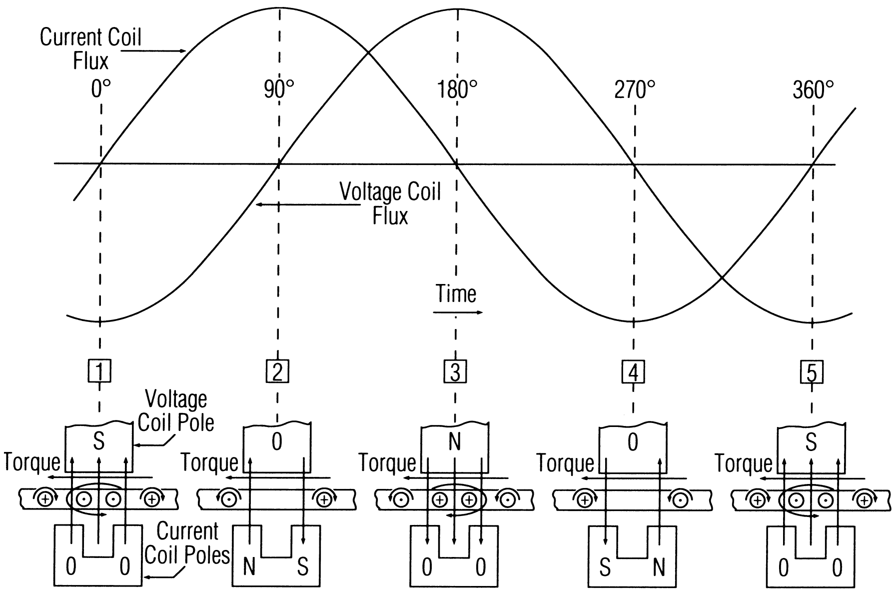


Figure 7-18. Voltage and Current Flux Wave Forms.

4. This point, 270° after Time 1, is similar to that at Time 2. Again the direction of both current-coil flux and disk eddy-current flux are reversed, giving resultant disk force to the left.
5. At this time the cycle of change is completed, producing the identical conditions of Time 1 360° later.

Summarizing the results, it is found that first a south pole, then a north pole, and then a south pole moves across the disk. At any position, the torque which causes the disk to turn is caused by interaction between flux from current in one coil and disk eddy currents caused by the changing flux from current through the other coil.

Because we want to measure watts, or active power, the force driving the disk must be proportional not only to the voltage and current, but also to the power factor of the load being metered. This means that, for a given voltage and current, the torque must be maximum when the load being metered is non-inductive and that it will be less as the power factor decreases.

When the successive values of the flux of a magnetic field follow a sine curve, the rate of flux change is greatest, as previously stated, at the instant of crossing the zero line and the induced electromotive force is greatest at this instant. The magnetic field is greatest at the maximum point in the curve, but at this peak the rate of change is zero, so the induced EMF is zero. With two fields differing in phase relation, in order for one field to be at zero value while the other is at maximum, the phase difference must be 90°. The curves of Figure 7-18 were shown this way. Since the torque on the disk depends on the interaction between the magnetic field and the disk eddy currents, the greatest torque occurs when the phase difference between the fields is 90°. This is true at any instant throughout the cycle. When the two fields are in phase with each other, the disk eddy current produced by one field will be in a definite direction, which will not change while the field changes from a maximum negative to a maximum positive value. The other field, in changing during the same period from a negative to a positive value and reacting with the disk eddy currents, tends to change the direction of rotation because direction of the torque changes. The change occurs every one-fourth cycle and the resultant average torque is zero. This is also true if the fields are 180° apart.

It is apparent from previous discussion that if one field is proportional to the current in a power circuit and the other to the voltage across the circuit, the torque produced will be proportional to the product of these values. If an initial phase difference between the two fields is exactly 90° when the line current and voltage are in phase, the torque produced on the rotating element when the current and voltage are not in phase will be proportional to the cosine of the angle of phase difference, which is the power factor. When the correct phase difference is obtained between the current and voltage flux (when the meter is properly lagged), the meter can be used to measure the active power in the circuit since the power is equal to the product of the voltage, current, and power factor.

THE PERMANENT MAGNET OR MAGNETIC BRAKE

Another essential part of the electromechanical meter is a magnetic brake. Torque on the disk caused by interaction of fluxes tends to cause constant acceleration. Without a brake, the speed of rotation would only be limited by the supply frequency, friction, and certain counter torques at higher speeds (discussed in later paragraphs concerning overload compensations). Therefore, some method of limiting the rotor speed and making it proportional to power is needed. A permanent magnet performs these functions. As the disk moves through the field of the permanent magnet, eddy currents result in much the same manner as though the magnetic field were changing as previously described. These eddy currents remain fixed in space with respect to the magnet pole face as the rotor turns. Again, as in the case of eddy currents caused by fluxes from the voltage and current coils, the eddy currents are maximum when the rate of cutting flux lines is greatest. In this case the cutting of flux lines is caused by the motion of the disk, so the eddy currents are proportional to the rotational speed of the disk. They react with the permanent-magnet flux, causing a retarding torque which is also proportional to the speed of the disk. This balances the driving torque from the stator so that the speed of the disk is proportional to the driving torque, which in turn is proportional to the power flowing through the meter. The number of revolutions made by the disk in any given time is proportional to the total energy flowing through the meter during that time interval. The strength of the permanent magnet is chosen so that the retarding torque will balance the driving torque at a certain speed. In this way the number of watthours represented by each revolution of the disk is established. This is known as the watthour constant (K_h) of the meter.

ADJUSTMENTS

On modern electromechanical, single-stator watthour meters there are three adjustments available to make the speed of the rotor agree with the watthour constant of the meter. They are the “Full-Load” adjustment, the “Light-Load” adjustment, and the “Power-Factor” adjustment.

Full-Load Adjustment

The eddy currents in the disk caused by the permanent magnets produce a retarding force on the disk. In order to adjust the rotor speed to the proper number of revolutions per minute at a given (or "rated") voltage and current at unity power factor, the full-load adjustment is used.

Basically, there are two methods of making the full-load adjustment. One is to change the position of the permanent magnet. When the permanent magnet is moved, two effects result. As the magnet moves further away from the center of the disk, the "lever arm" becomes longer, which increases the retarding force. The rate at which the disk cuts the lines of flux from the permanent magnet increases and this also increases the retarding force.

The second method of making the full-load adjustment, by varying the amount of flux by means of a shunt, depends on the fact that flux tends to travel through the path of least reluctance. Reluctance in a magnetic circuit is resistance to magnetic lines of force, or flux. By changing the reluctance of the shunt, it is possible to vary the amount of flux that cuts the disk. One way of doing this is by means of a soft iron yoke used as a flux shunt, in which there is a movable iron screw. As the screw is moved into the yoke, the reluctance of this path decreases, more lines of flux from the permanent magnet flow through the yoke and less through the disk, so the disk is subject to less retarding force and turns faster.

In either case, the retarding force is varied by the full-load adjustment and, by means of this adjustment, the rotor speed is varied until it is correct. Normally the full-load adjustment is made at unity power factor, at the voltage and test current (TA) shown on the nameplate of the watthour meter, but the effect of adjustment is the same, in terms of percent, at all loads within the class range of the meter.

Light-Load Adjustment

With no current in the current coil, any lack of symmetry in the voltage coil flux could produce a torque that might be either forward or reverse. Because electrical steels are not perfect conductors of magnetic flux, the flux produced by the current coils is not exactly proportional to the current, so that when a meter is carrying a small portion of its rated load it tends to run slower. A certain amount of friction is caused by the bearings and the register, which also tends to make the disk rotate at a slower speed than it should with small load currents. To compensate for these tendencies, a controlled driving torque, which is dependent upon the voltage, is added to the disk. This is done by means of a plate (or shading pole loop) mounted close to the voltage pole in the path of the voltage flux. As this plate is moved circumferentially with respect to the disk, the net driving torque is varied and the disk rotation speed changes accordingly. The plate is so designed that it can be adjusted to provide the necessary additional driving torque to make the disk revolve at the correct speed at 10% of the TA current marked on the nameplate of the meter. This torque is present under all conditions of loading. Since it is constant as long as applied voltage does not change, a change in the light-load adjustment at 10% of test amperes will also change full-load registration, but will change it only one-tenth as much as light-load registration is changed.

Inductive-Load or Power-Factor Adjustment

In 1890, Shallenberger presented the theory behind the inductive load adjustment. The theory is that in order to have correct registration with varying load power factor, the voltage-coil flux must lag the current-coil flux exactly 90° when the load on the meter is at unity power factor. This 90° relationship is essential to maintain a driving force on the disk proportional to the power at any load power-factor value. One way of doing this is to make the voltage-coil flux lag the current-coil flux by more than 90° by means of a phasing band, or coil, around the core of the center leg of the voltage coil. It is then necessary to shift the current-coil flux toward the voltage-coil flux until the angle is exactly 90°.

Figure 7-19 shows this in a phasor representation, E is the voltage and ϕE is the flux caused by E. A voltage is induced by ϕE in the phasing band which causes a current to flow, creating the flux shown as ϕE_{PB}. This, added phasorially to ϕE, gives ϕE_T, which is the total resultant flux that acts on the disk and which lags E by more than 90°. Since this analysis is for unity-power-factor load, the current I and its flux ϕI are in phase with E. But the flux ϕI must be shifted toward ϕE_T until the angle is exactly 90°. A closed figure-8 circuit loop is inserted on the current magnet. The Flux, ϕI, induces a voltage in this loop, which causes current to flow, creating the flux field ϕI_{PF}. Varying the resistance of the power-factor loop can change this value. Adding ϕI and ϕI_{PF} gives ϕI_T which is adjusted by varying ϕI_{PF} until it is exactly 90° from ϕE_T. Any reactance in the current coil which would cause ϕI to be slightly out of phase with I is compensated for at the same time.

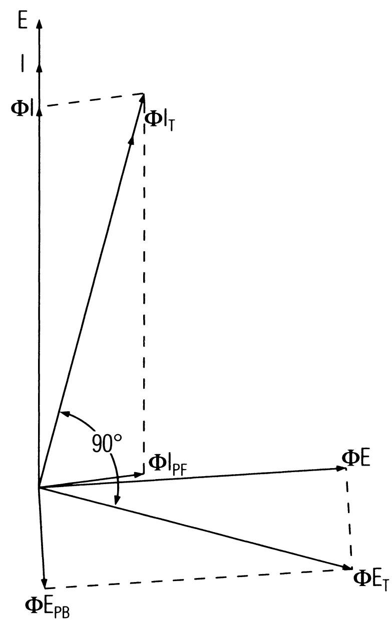


Figure 7-19. Phasor Diagram of Lag Adjustment.

As explained in the preceding discussion, the shift of resultant current-coil flux is done by means of a figure-8 conducting loop on the current electromagnet. The coil usually consists of several turns of wire. The ends of this lag coil are twisted together and soldered at the point necessary to provide the 90° angle. A change in the length of the wire varies the resistance of the coil and the amount of current flowing, which results in a variation in the amount of compensating flux.

The means of adjusting the flux angle may be located on the voltage-coil pole instead of the current poles, in which case it would vary ϕE_{PB} instead of ϕI_{PF}. The adjustment may be in the form of a lag plate or a coil with soldered ends, so that loop resistance may be varied. A lag plate would be movable under the voltage pole piece radially with respect to the disk. In this manner it would provide adjustable phase compensation with minimum effect on light-load characteristics.

Many modern meters use a fixed lag plate operating on voltage flux with the compensation permanently made by the manufacturer at the factory. Such plates may be located on the voltage coil pole or may form a single loop around both current poles.

For practical purposes, all modern meters leave the factories properly adjusted and, once calibrated, this lag or power-factor adjustment seldom requires change regardless of the method used.

Once the proper phase relationship between the load-current flux and the voltage flux is attained, there will be no appreciable error at any power factor. If this adjustment is improperly made, an error will be present at all power factors other than unity and it will increase as the power factor decreases. This is calculated as follows:

$$\% \text{ error} = 100 \left(1 - \frac{\text{Meter watts}}{\text{True watts}}\right)$$

Using the information supplied and the method explained in Chapter 3, this can be developed into a formula which may be resolved into the following:

$$\% \text{ error} = 100 \left(1 - \frac{\text{Meter watts}}{\text{True watts}}\right)$$

$$= 100 \left(\frac{\cos\theta - \cos(\theta \pm \phi)}{\cos\theta}\right)$$

where θ is the angle between the line current and voltage and ϕ is the angle of error between the line-current flux and the voltage flux due to improper relation within the meter. This error is computed without reference to errors of calibration at full load. Full-load errors are independent of those just calculated and add to or subtract from them dependent upon their relative signs. The errors indicated, while computed for lagging power factor, are also applicable for leading power factor. The sign of the effect will change when going from a lagging power factor to a leading power factor. In other words, an improper lag adjustment, which causes the meter to run slow on lagging power factor, will cause it to run fast on leading power factor.

COMPENSATIONS

Although the three adjustments mentioned in previous paragraphs are the usual adjustments for a single-stator electromechanical watthour meter, several other factors must be compensated to make the meter accurate for the variety of field conditions in which it must operate. These compensations are built into the meter and provide corrections needed to make the meter register accurately under conditions of overload, temperature variation, frequency error, and voltage fluctuation.

Overload Compensation

The meter may be adjusted to record correctly at its nominal load. However, the current sensing approach used in electromechanical meters is not perfect, and unless it is compensated, it will not record correctly as loads increase up to the maximum load of the meter (class current). Because electromagnetic steels are not perfect conductors of flux, the speed of rotation of the disk will tend to be proportionately less at higher loads. Also, as load currents increase, the damping caused by the interaction of the disk eddy currents with the fluxes that produce them also increases. This effect becomes more visible at the higher overload currents of the meter. For example, the voltage coil produces eddy currents which interact with the current-coil flux to drive the disk, but the interaction of the voltage-coil eddy currents with the voltage-coil flux retards the disk. The voltage-coil flux is practically constant regardless of load, so its retarding effect can be calibrated out of the meter. The fluxes produced by the current coil will act with the current-coil eddy currents to retard rotation of the disk. At rated load these self-damping effects are in the order of only 0.5% of the total damping. However, the retarding action increases as the square of the current flux. This is true because the retarding force is a function of the eddy currents multiplied by the flux, and in this case the eddy currents increase as the flux increases, so the retarding force increases as the flux multiplied by itself.

Figure 7-20 shows the factors of accuracy for a meter with the typical load curve (6) of a model compensated meter. To negate the retarding or dropping accuracy shown as curve 4, which would result without overload compensation, a magnetic shunt is placed between but not touching the poles of the current

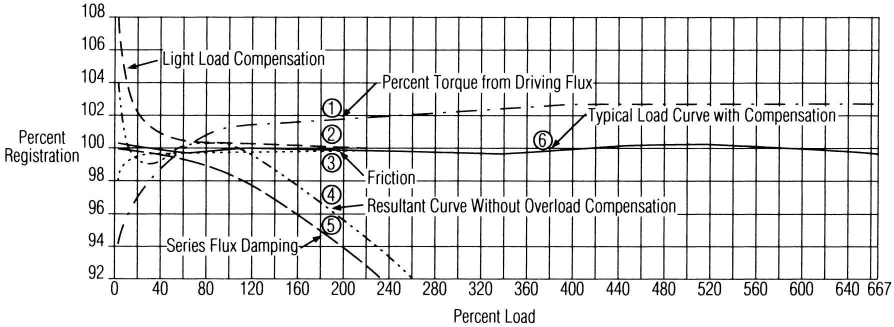


Figure 7-20. Factors of Accuracy.

electromagnet and is held in place by non-magnetic spacers. (See Figure 7-21.) This shunt has little effect below the point at which the accuracy curve of the meter would otherwise start to drop, but as the load increases the shunt approaches saturation causing the current flux which cuts the disk to increase at a greater ratio than the current. This causes an added increase in torque, which counteracts the drop in the accuracy curve up to the point at which the shunt is saturated. Beyond this point, which is usually beyond the maximum rated load of the meter, the accuracy curve drops very rapidly.

Figure 7-22 shows another diagram of the magnetic circuit for overload compensation on the current element. Other ways of minimizing the retarding effect are: (1) proper proportioning of the voltage and current fluxes, so that the effective voltage-coil flux (about 4% of the total damping flux) is proportionately higher than the effective current-coil flux; (2) by use of stronger permanent magnets and lower disk speed; and (3) a design which gives the greatest driving torque while getting the least damping effect from the electromagnets. Present-day meters will accurately register loads up to 667% of the meter's nominal rating. Figure 7-23 shows comparisons of the accuracy of modern meters with that of those manufactured in 1920, 1940, and 1955.

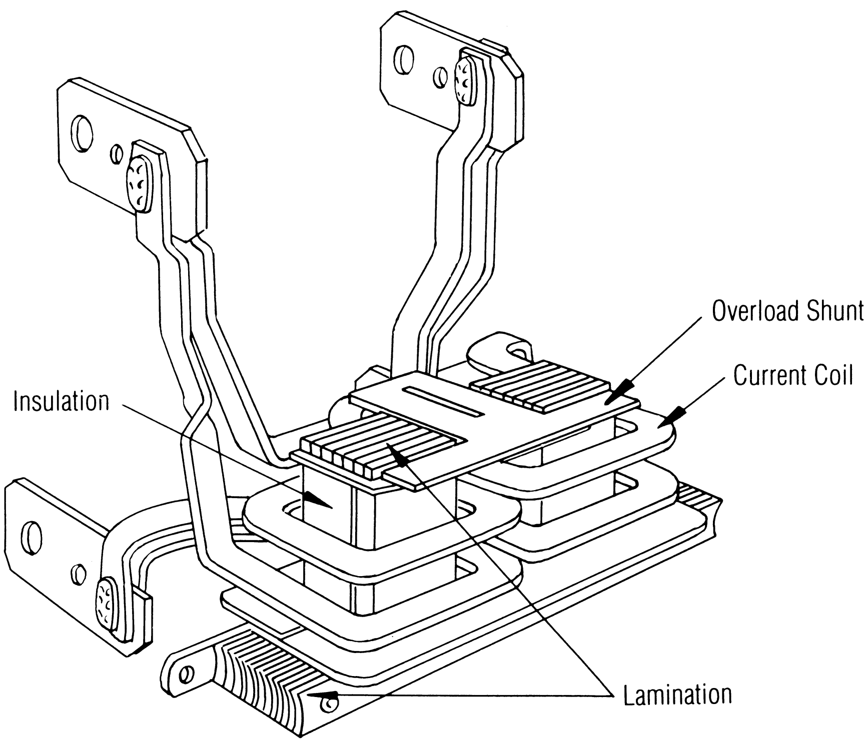


Figure 7-21. Simplified Diagram of Magnetic Circuit of Current Element for Overload Compensation.

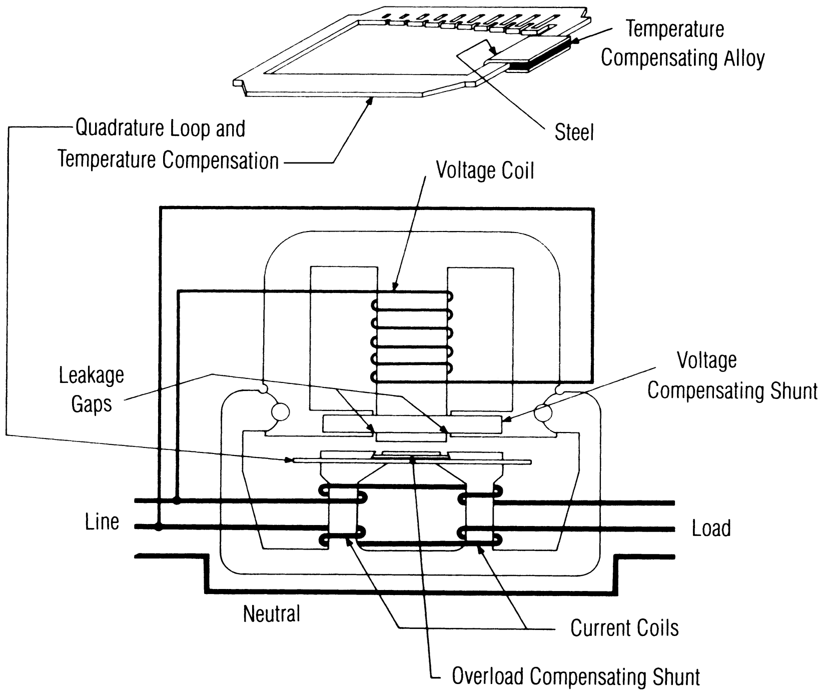


Figure 7-22. Overload, Voltage, and Class 2 Temperature Compensations.

At the same time that these improvements were being made, similar improvements were effected in light-load performance as can be seen from the curves in Figure 7-24.

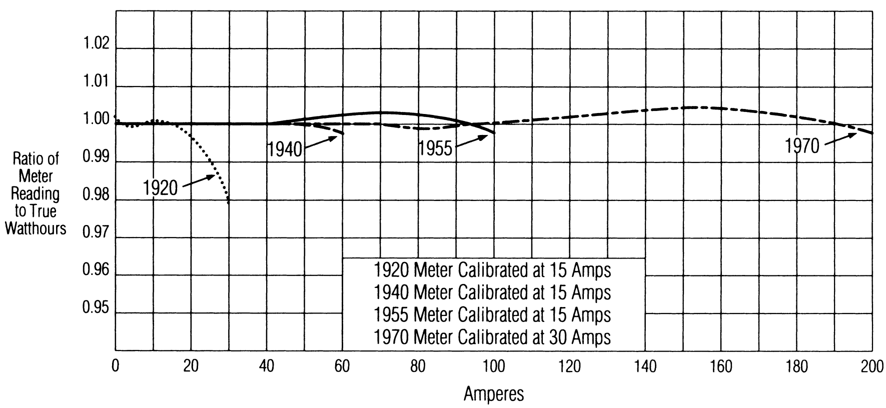


Figure 7-23. Heavy-Load Accuracy Curves.

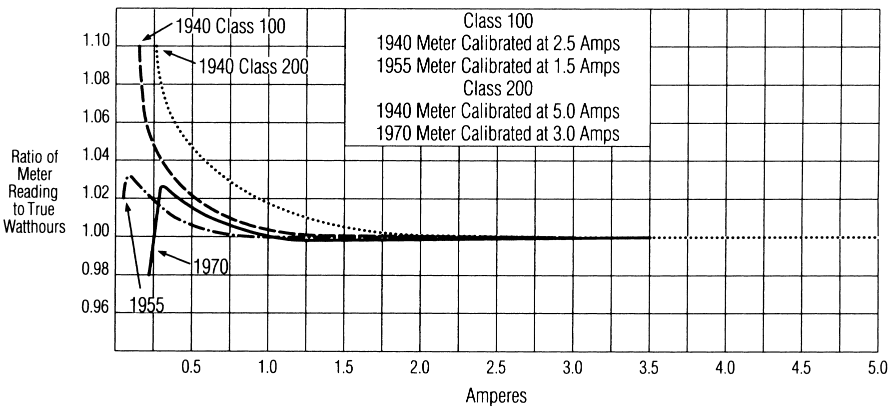


Figure 7-24. Light-Load Performance Curves.

Voltage Compensation

Inaccuracies of registration in modern electromechanical meters over the usual range of voltage variations are very small. In a meter with no voltage compensation, errors resulting from voltage change are caused by:

1. The damping effect of the voltage flux,
2. Changes in the electromagnet characteristics due to changes in voltage,
3. Changes in the effect of the light-load adjustment due to changes in voltage.

The damping effect of the voltage flux is similar to that of the current flux, with changes in effect being proportional to the square of the voltage.

The errors caused by the characteristics of electromagnets are due to the failure of the magnetic circuit to be linear under all conditions of flux density. In an electromagnet the effective flux is not equal to the total flux. The ratio between the effective and the total flux determines many of the characteristics of the electromagnet. Improvements in the metals used have permitted a much closer approach to the desired straightline properties of the magnetic circuit. Finally, by use of saturable magnetic shunts similar to those used in the current magnetic circuit, voltage flux is controlled and the errors due to normal voltage variations are reduced to a negligible amount.

Since the light-load compensation is dependent only on voltage, a voltage change varies the magnitude of this compensation and tends to cause error. Increasing voltage increases light-load driving torque so that a meter tends to over-register at light-load current under over-voltage conditions. Good meter design, which maintains a high ratio of driving torque to light-load compensating torque, reduces these errors to very small values.

The reduction of voltage errors in some electromechanical meters of recent manufacture is to a degree that such a meter designed for use on 240 volts may (in most cases) be used on 120-volt services without appreciable error. Figure 7-25 shows a voltage characteristic curve for one of the modern meters.

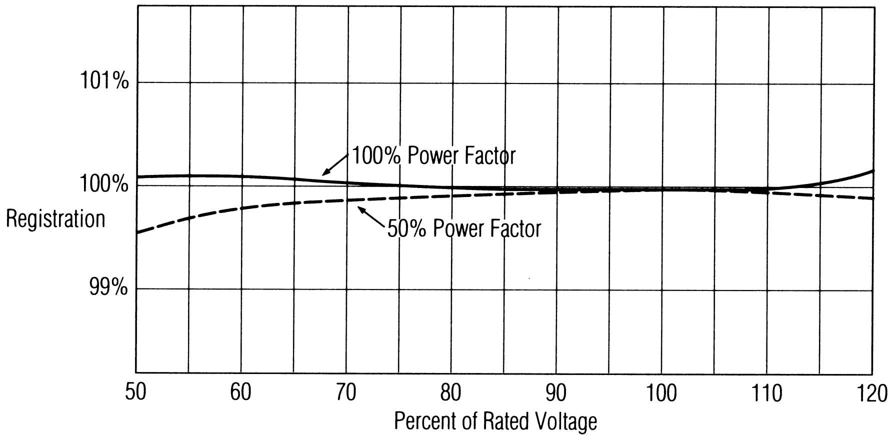


Figure 7-25. Voltage Characteristic Curves.

Temperature Compensation

Watthour meters are subjected to wide variations in ambient temperature. Such temperature changes can cause large errors in metering accuracy unless the meter design provides the necessary compensation. Temperature changes can affect the strength of the retarding magnets, the resistance of the voltage and lag coils, the characteristics of the steels, the disk resistance, and other quantities that have a bearing on accuracy. Temperature errors are usually divided into two classes. Class 1 errors are those temperature errors which are independent of the load power factor, while Class 2 errors are those which are negligible at unity power factor, but have large values at other test points.

Class 1 temperature errors are caused by a number of factors which produce a similar effect; namely, that the meter tends to run fast with increasing temperature. Since this is the effect caused by weakening the permanent magnet, the compensation for this class of error consists of placing a shunt between the poles of the permanent magnet to bypass part of the flux from the disk. This shunt is made of a magnetic alloy that exhibits increasing reluctance with increasing temperature. With proper design the shunt will bypass less flux from the disk with increasing temperature so that the braking flux increases in the proper amount to maintain high accuracy at unity power factor over the entire temperature range.

Class 2 temperature errors which increase rapidly with decreasing power factor, are due primarily to changes in the effective resistance of the voltage and lag circuits, which in turn, cause a shift in the phase position of the total voltage flux. Improved design has reduced these errors, and various forms of compensation have further minimized them. One compensation method consists of placing a small piece of material with a negative permeability temperature characteristic around one end of the lag plate (or a small amount of the alloy in the magnetic circuit of a lag coil) to vary the reactance of the lag circuit so that the lag compensation remains correct with temperature change. Another method consists of over-lagging the voltage flux with a low-temperature-coefficient resistor in the lag circuit and adjusting the current flux with a lag circuit that contains a high-temperature-coefficient resistor. With proper design, changes in one lag circuit due to temperature are counterbalanced by changes in the other lag circuit.

Some of the temperature effects tend to offset one another. An example of this is the change in disk resistance with temperature. An increase in disk resistance reduces electromagnet eddy-current flow, which reduces driving torque. However, the same effect occurs with the eddy currents set up by the braking magnets, so braking torque decreases with driving torque and disk speed tends to remain constant.

Figure 7-22 shows methods of compensating for overload, voltage variation, and temperature. Figure 7-22 shows the Class 2 temperature compensation of a three-wire meter and Figure 7-26 shows the temperature characteristic curves of modern watthour meters, indicating the high degree of temperature compensation which has been secured by the methods previously outlined.

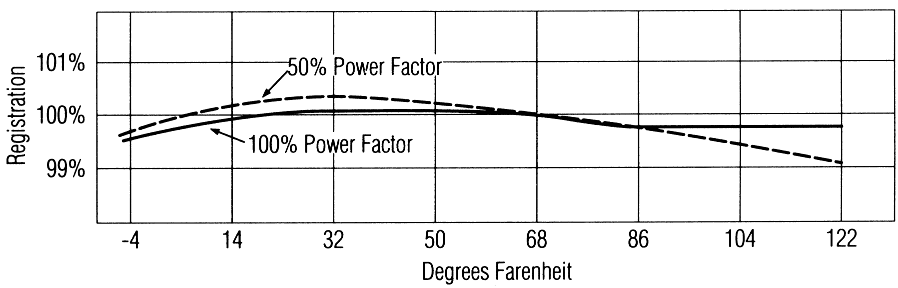


Figure 7-26. Temperature Characteristic Curves.

ANTI-CREEP HOLES

Without anti-creep holes, the interaction of the voltage coil and the light-load adjustment might provide enough torque to cause the disk to rotate very slowly when the meter was energized, but no current flowing. This creep would generally be in a forward direction, because the light-load adjustment is so designed that it helps overcome the effects of friction and compensates for imperfections of the electromagnet steels. In order to prevent the disk from rotating continuously, two diametrically opposed holes are cut into the disk. These holes add resistance to the flow of eddy currents caused by the voltage flux. Earnshaw's Theorem explains that a conductor in a flux field tends to move to a position of least coupling between the conductor and the source of the flux field. Because of this, the disk will tend to stop at a position in which the anti-creep hole causes the greatest reduction in the eddy currents (sometimes moving backward a portion of a revolution in order to stop in this position). A laminated disk or one of varying thickness will also tend to stop in a position of least coupling.

FREQUENCY CHARACTERISTICS

Because of frequency stability of modern systems, variations in meter accuracy due to frequency variations are negligible. As frequency is increased, the shunt coil reactance increases and its exciting current decreases. The reactance of the eddy current paths in the disk is raised, thus limiting and shifting the phase of the eddy currents. Also, an increase in frequency raises the proportion of reactance to resistance in the shunt coil and the meter tends to become over-lagged. Any increase in reactance of the quadrature adjuster shifts its phase angle so that its action is to reduce the flux more and more, thus decreasing torque. Watthour meters are therefore slow on high frequencies, with the percent registration at 50% power factor lagging will be higher than that for unity power factor. Because of the stability of modern systems, specific frequency compensation is not required and in modern meters frequency variation errors are kept to a minimum by proper design.

Figure 7-27 shows the effect of frequency variations on modern meters.

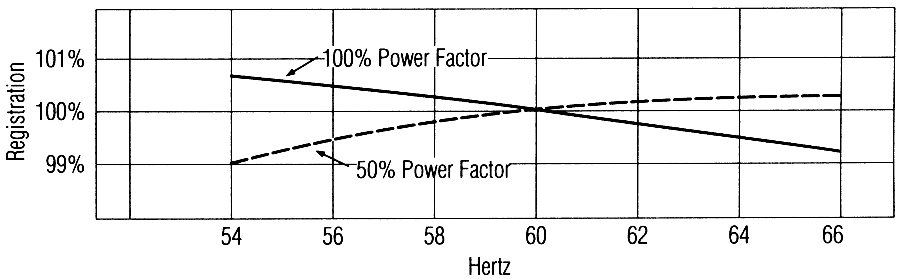


Figure 7-27. Frequency Curve of Modern Meter.

WAVEFORM

In determining the effects of harmonics on an electromechanical watthour meter's performance the following facts must be borne in mind:

1. An harmonic is a current or a voltage of a frequency that is an integral multiple of the fundamental frequency for example the third harmonic has a frequency of 180 hertz in a 60 hertz system;
2. A distorted wave is a combination of fundamental and harmonic frequencies which, by analysis, may be broken down into such frequencies;
3. Currents and voltages of different frequencies do not interact to produce torque. An harmonic in the voltage wave will react only with the same harmonic in the current wave to produce torque;
4. To produce torque, two fluxes with time and space displacement are necessary;
5. An harmonic present only in the voltage circuit may have a small effect on meter performance due to the torque component produced by the light-load adjustment;
6. Minor damping effects of harmonics in either voltage or current elements are possible.

The magnetic shunt used for overload compensation can introduce harmonics in the current flux which are not necessarily present in the load current, particularly at high loads. To a lesser extent, this is also possible in the voltage flux. In general, unless extreme distortion of waveform exists, the errors due to harmonics will not degrade meter accuracy beyond normal commercial limits. However, when working with high accuracy watthour standards, the errors due to harmonics may be bothersome. In these cases it must be remembered that all meters, even when of the same manufacture and type, do not exhibit identical reactions to the same degree of harmonics.

Waveform distortion and resulting meter inaccuracies may be caused by over-excited distribution transformers and open-delta transformer banks. Some types of equipment, such as rectifiers and fluorescent lamps, may also cause distortion of the waveform. Welders cause poor waveform and present a continuing metering problem, but other factors may have greater influence on meter errors.

In extreme cases of distortion a separate analysis is necessary because each waveform has different characteristics. The distorted wave should be resolved into the fundamental and the various harmonic sine waves and then calculations can be made from this information.

METER REGISTERS

The third basic part mentioned in the beginning of this chapter is the register. The register is merely a means of recording revolutions of the rotor which it does through gearing to the disk shaft. Either a clock (pointer-type) or a cyclometer-type register may be used.

Figure 7-28 shows a clock-type register and a cyclometer register. Both perform the same function, but the pointer-type has numbered dials on its face and the pointers turn to indicate a proportion of the number of revolutions the disk has made. In the cyclometer-type registers, numbers are printed on cylinders that turn to indicate a proportion of the number of revolutions of the disk. Since the purpose of the register is to show the number of kilowatthours used, the reading is proportional rather than direct. The necessary gearing is provided so that the revolutions of the disk will move the first (or right-side) pointer or cylinder one full revolution (360°) each time the rotor revolves the number of times equal to ten kilowatthours of usage. This is known as the gear ratio, or Rg. The register ratio, known as Rr is the number of revolutions of the wheel which meshes with the pinion or worm on the disk shaft for one revolution of the first dial pointer.

METER ROTOR BEARINGS

In order to support the shaft on which the rotor is mounted, bearings which will give a minimum amount of friction are used. Magnetic bearings are used in present-day meters. The weight of the rotor disk and shaft is 16 to 17 grams.

Modern meters have magnetic bearings consisting of two magnets that support the shaft and disk. The rotor is held in position by mutual attraction when the bearing magnets are located at the top of the disk shaft and by repulsion of the magnets when they are located at the bottom of the shaft. One magnet is fastened to the meter frame and the other magnet is mounted on the disk shaft. Vertical alignment is provided by guide pins mounted on the meter frame at the top and bottom of the disk shaft, which has bushings mounted in each end. The only bearing pressures in this type of rotor support are slight side thrusts on the guide pins, since the shaft does not otherwise touch either the top or bottom supports, making the system subject to less wear. No part of this system requires lubrication. Additional advantages of this type of bearing system are reduced maintenance, less tilt error, and better ability to withstand rough handling. More details are available in the manufacturers' literature.

With the meter properly adjusted, the disk will revolve at a specified speed at full load. This speed and the rating of the meter determine the watthour constant, or K_h, which is the number of watthours represented by one revolution of the disk. The watthour constant, K_h, may be found by use of the formula:

$$K_h = \text{Rated Voltage} \times \text{Rated Current}/(\text{Full-Load RPM} \times 60)$$

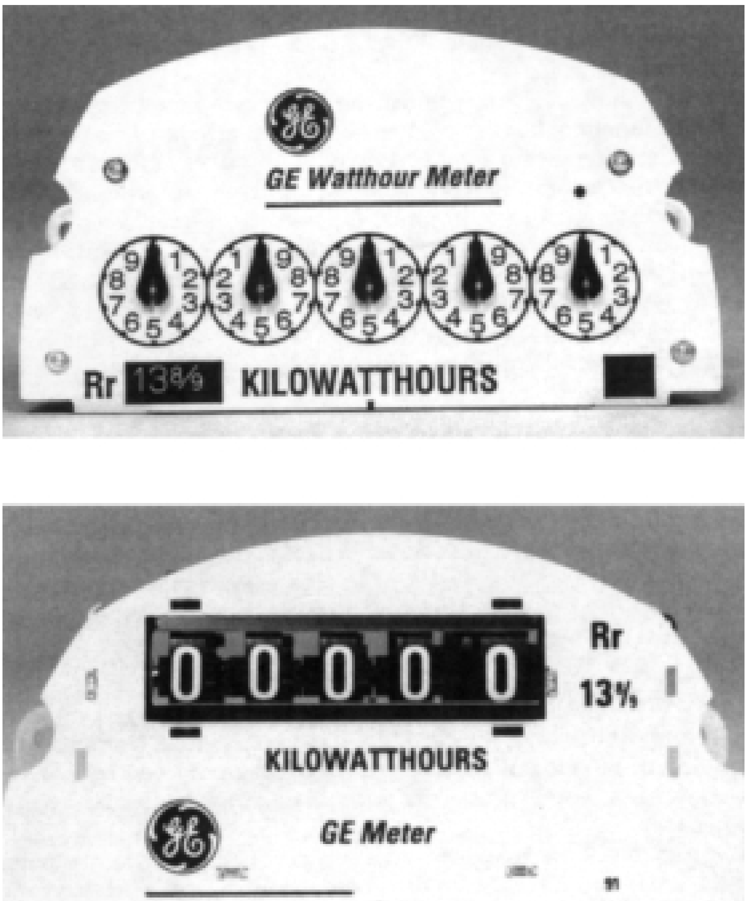


Figure 7-28. Clock-Type (top) and Cyclometer-Type Meter Registers.

MECHANICAL CONSTRUCTION OF THE METER

The basic parts of the meter are assembled on a frame, mounted on a base, and enclosed with a glass cover. The cover encloses the entire meter and is sealed to the base. The base and cover are so designed that it is almost impossible to tamper with the adjustments of the meter without leaving evidence.

Meters are maintained weathertight mainly by the design of the cover, base, and dust guard. The meter is allowed to breathe by providing an opening at the bottom of the base. This opening also allows any condensate that may form on the inside of the cover to drain out. The chief aid in allowing meters to operate outdoors and under varying humidity conditions is the self-heat generated in the meter which causes the cooler cover to act as the condenser under high-humidity operation. This is the reason meters should not be stored outdoors without being energized even though they are basically designed to be weathertight.

The materials and coatings used to prevent corrosion are generally the best materials economically available during that period of manufacture. Present-day meters are almost completely made from high corrosion-resistant aluminum, which has minimum contact with copper or brass materials. The steel laminations are coated with paint selected by the manufacturer to provide the best protection. A plastic base, glass or plastic cover, and stainless-steel (or other material) cover ring complete the picture to give the meter its excellent corrosion resistance. In the application of corrosion-resistant finishes, consideration must be given to the particular function of the part in question, such as exposure to the elements, wear resistance, and use as a current-carrying part.

There are a variety of processes that can be used to protect the metals within a meter. These processes are constantly under evaluation. Iridite is a chromate-dip finish that may be used on cadmium-plated steel parts. This process applies an oxide coating and seals at the same time. One of the finishes applied to aluminum is anodizing. This finish converts the surface to aluminum oxide, which is a very hard, corrosion-resistant finish. This protection may be further improved by applying a sealer that closes the pores in the oxide and prevents the entrance of moisture. Another finish for aluminum is alodine. This is a complex chromate gel that is applied to the surface and seals the metal in one operation. When applied to aluminum, the parts take on an iridescent finish. It may be used on parts such as the grid, register plates, and other parts not subject to wear or abrasion.

The copper and copper-bearing alloys that carry current are tin-plated on contact surfaces, such as socket-meter bayonets. This not only gives protection against corrosion, but improves contact resistance.

Brass screws may be protected by a heavy nickel plating. Steel parts, such as register screws, may also be nickel-plated.

For the protection of ferrous metals, such as voltage and current electromagnet laminations, these parts may be immersed in a hot solution of phosphoric acid. This converts the surface to a hard iron phosphite that is further hardened by a sealer, usually paint. The voltage and current laminations may be sealed with several coats of paint.

All the finishes described are constantly being improved and as new agents to prevent corrosion are developed, they are used.

Lightning and surge protection is provided by a combination of high insulation and surge levels built into the voltage coil and current coil and the provision of a ground pin in calibrated proximity to the current leads on the line side so that a lightning surge will jump the spark gap prior to entering the coils. The ground-pin gap is such as to cause a spark over at some voltage between 4,000 and 6,000 volts. The ground pin is attached to a strap in contact with the socket enclosure, which is grounded. The factory testing consists of hi-potting of both voltage coils and current coils at about 7,000 volts. The voltage coil is exposed to a 10,000 volt surge of a 1.2×50 (crests in 1.2 microseconds, decays in 50 microseconds) wave shape to pick out any shorted turns in the windings. This combination has proved very successful in allowing meters to withstand repeated lightning surges and still allow continued accurate meter operation.

Present-day meters are built with permanent magnets that are practically unaffected by lightning surges.

Two- or Three-Wire Electromechanical Meters

Some single-stator electromechanical meters are made so that by means of a very simple rearrangement of internal connections the meter can be converted from the connections used on 120 volt circuits to those needed for use on 240 volt circuits. Coil ends are brought to terminal boards and usually the connections can be changed with a screwdriver. The basic theory, inherent accuracy, stability of calibration, insulation, and other desirable features of modern watthour meters are unaffected by the minor changes of internal connections and this meter has the advantage of not becoming obsolete if the customer changes from 120 volt to 240 volt service.

The voltage coils are wound to give uniform flux distribution whether connected for 120 volt or 240 volt usage. A constant resistance-to-reactance ratio is maintained as the change is made; therefore a constant phase-angle relationship exists and no readjustment of the lag compensation is necessary.

The Kh constant is the same for either connection, since one current coil is used for 120 volt operation and two are used when the meter is connected for 240 volt operation. These meters are of standard dimensions so they are interchangeable with other single-phase, 120 volt or 240 volt standard-size meters. In general, changing internal connections has so little effect on calibration of the meter that it may be considered negligible. Details of internal connections may be found in Chapter 12, “Meter Wiring Diagrams.”

Electromechanical Multi-Stator Meters

The single-stator, two-wire meter is the most accurate form of the induction meter under all load conditions. To measure a four-wire service, three two-wire meters may be used with their registrations added to obtain total energy. From the point of view of accuracy this is the ideal method of measurement. It is awkward, however, and introduces difficulties when measurement of demand is required.

The polyphase meter is basically a combination of two or more single-phase stators in one case, usually with a common moving element with such modifications as are necessary to balance torques and meet mechanical limitations. However, when single-phase stators are combined in the polyphase meter, the performance under imbalanced conditions does not always follow the independent single-phase characteristics. It must be understood that after compensation for interference and proper adjustments for balance, the accuracy of the multi-stator meter closely approaches that of the two-wire, single-stator meter.

The modern electromechanical polyphase meter is essentially a multi-element motor, with a magnetic braking system, a register, a means for balancing the torques of all stators, and all the various adjustments and compensating devices found in single-stator meters. Most of the modern design features developed for single-stator meters are being applied to the multi-stator meter. These components are assembled on a frame and mounted on a base that also contains the terminals. The base, the cover, and the terminals vary in their design according to the installation requirements of the meter. Magnetic-type bearings are being used on all meters of current manufacture for United States use.

POLYPHASE ELECTROMECHANICAL METER CHARACTERISTICS AND COMPENSATIONS

Multi-stator polyphase electromechanical meters have, in general, temperature, overload, voltage, and frequency characteristics similar to those of the single-stator meter and they are compensated in the same manner to improve these characteristics. Detailed explanations of these compensations have been given previously in this chapter.

DRIVING AND DAMPING TORQUES

In order to fully understand the theory of operation of a multi-stator electromechanical watthour meter, it is necessary to analyze the driving and damping torques. Considering the single-stator, two-wire meter, the driving torque is directly proportional to voltage and load current and the cosine of the angle between them except for a slight non-linearity due to the magnetizing characteristics of the steel. Damping torque should also theoretically be proportional to load but this is not strictly true. The overall damping flux has three separate components; namely, permanent-magnet damping, voltage-flux damping, and current-flux damping. The former is relatively constant and provides damping torque directly proportional to speed. Voltage damping flux is also relatively constant since line voltage variations are normally small. Current damping flux varies with the square of the current. It therefore causes a definite divergence between torque and speed curves as the current load increases. This characteristic can be influenced during design by changing the ratio of the current or variable flux to the constant flux produced by the voltage coil and the permanent magnet. It cannot be eliminated.

In a typical modern single-stator meter at rated test-amperes and normal voltage, the damping torque from the permanent magnet is 96.7% of the total. The voltage flux furnishes 2.8% and the remaining 0.5% comes from the current flux. Since the current-damping component increases with the square of the current, the speed curve will obviously be below the torque curve as the load current increases. An uncompensated meter having 0.5% current damping at rated test amperes would be 2% slow at 200% test-amperes.

These underlying principles also apply to polyphase meters. However, the combining of two or more stators to drive a common moving element introduces factors in performance that are not apparent from the performance of independent single-stator meters.

INDIVIDUAL-STATOR PERFORMANCE

Consider the simplest form of the polyphase meter-two stators driving a common moving element. The meter will perform as a single-phase meter if both elements are connected together on single-phase, that is, with the current coils connected in series and the voltage coils in parallel. With this connection it is, for all intents and purposes, a single-phase meter and has all the characteristics of a single-phase meter. The fact that the two stators are coupled together on a single shaft makes no difference except to average the characteristics of the individual stators.

The same will be true, with the exception of interference errors, when the meter is connected in a polyphase circuit and the load is completely balanced. When the loads are not balanced, the polyphase meter no longer performs as a single-phase meter. If only one stator is loaded, the polyphase meter will tend to register fast. This is best illustrated by putting balanced loads on the two stators and checking the calibration. Then remove the load from one stator. The meter will be found to register fast all the way along the load curve as compared to the speed curve on combined stators. This is due to the variation of the overall damping torque caused by the change in the current damping component.

CURRENT DAMPING

Assume that a polyphase meter when operating at rated test-amperes has its damping components in the following typical relationships: 96.7% from a permanent magnet, 2.8% from voltage at rated voltage, and 0.5% from current at rated test-amperes.

When the load is taken off one stator, the driving torque drops 50%, but the total damping drops more than 50% since the current damping on the unloaded stator is eliminated, whereas it was a part of the total damping torque when both stators were loaded.

This characteristic changes with increasing load. For example, in a two-stator meter that runs 0.4% fast on a single stator at rated test-amperes as compared to the registration with balanced load on both stators at rated test-amperes, the difference in registration between single and combined stators may be as much as 3% at 300% rated test-amperes. This can be seen from the fact that the current-damping component from the stator that is not loaded would be nine times as great at 300% rated test-amperes as at 100% rated test-amperes. Therefore its elimination at 300% rated test-amperes takes away nine times 0.4 or about 3.6% from the total damping.

IMBALANCED LOADS

Due to the effect of current damping, a factor exists in the performance of polyphase meters that is not generally recognized. If the stators are unequally loaded, the registration will differ from when the load is equally balanced or when the total load is carried by one stator, since the overload compensation causes the torque curve to go up in direct proportion to the increase in current damping on balanced loads. The departure from balanced-load performance, particularly for heavy loads, will be in proportion to the amount of overload compensation in the meter.

Take for example, a 5-ampere, two-stator, polyphase meter with 5 amperes applied to each stator. The total current damping will be proportional to (5 amperes)^2 plus (5 amperes)^2 or 50 current-damping units. On the other hand, if 10 amperes is applied to one stator only, current damping will then be proportional to (10 amperes)^2 or 100 current-damping units. This is the same total energy and total flux, but they are divided differently in the stators and consequently produce different current damping. The current-squared damping law applies only to current flux produced in a single stator. It does not apply to the total currents in separate stators. In this case, the current damping of the single stator with 10 amperes is twice that of two elements with 5 amperes each.

Suppose the load is imbalanced so that there are 8 amperes on one stator and 2 amperes on the other. Then the total current damping is proportional to 8^2 plus 2^2 or 68 current-damping units as compared to 50 units with 5 amperes on each stator.

INTERFERENCE BETWEEN STATORS

Polyphase meters must have a high degree of independence between the stators. Lack of this independence is commonly known as interference and can be responsible for large errors in the various measurements of polyphase power.

Major interference errors are due to the mutual reaction in a meter disk between the eddy currents caused by current or voltage fluxes of one stator and any interlinking fluxes that may be due to currents or voltages associated with one or more other stators. Specifically, these mutual reactions fall into three groups: voltage-voltage, current-current, and current-voltage or voltage-current. The following three paragraphs explain these interferences.

Voltage-Voltage Interference

The first, voltage-voltage interference, is due to the interlinkage of flux in the disk set up by the voltage coil of one stator with eddy currents caused by flux from the voltage coil of another stator. The magnitude of the interference torque resulting from this reaction depends on the relative position of the two voltage coils with respect to the center of the disk (for coils displaced exactly 180° this torque is zero), and on the phase angle between the two voltage fluxes. This torque could be very high unless these factors are thoroughly considered in proper design.

Current-Current Interference

The second, current-current interference, is due to interlinkage of flux set up by the current coil of one stator with eddy currents in the disk caused by flux from the current coil of another stator. The magnitude of this second reaction again depends on the relative position of the two stators (zero if at 180°), and on the magnitude of and the phase angle between the two current fluxes.

Current-Voltage or Voltage-Current Interference

The third interference, which may be described as current-voltage or voltage-current, is due to the interlinkage of flux set up by the voltage or current circuits of one stator and the eddy currents in the disk caused by the current flux from one stator and the voltage fluxes from another stator. The magnitude of this third type of reaction depends on the relative geometrical position of the stators and the power factor of the circuit. The effect on the registration is a constant, which is independent of the current load on the meter.

INTERFERENCE TESTS

Comparative tests to evaluate interference effects in a watthour meter have been established within the ANSI-C12 standard.

Interference tests are not part of the usual meter calibration procedure and are not performed in the meter shop. Since such tests are made to evaluate the manufacturer's design of a particular polyphase meter type, they are usually performed in the meter laboratory.

The specialized interference tests require the use of a two-phase power source with two-stator meters and a three-phase source with three-stator meters. The test results do not give the specific interference errors that will be obtained in actual service, but if the results are within the established tolerances, assurance is obtained that the interference effects will not be excessive. Complete details of the tests may be obtained by reference to the previously mentioned national standards.

DESIGN CONSIDERATIONS TO REDUCE INTERFERENCE

Interference in a single-disk meter is reduced by proper design that includes control of the shape of the eddy current paths in the disk and the most favorable relative positioning of the coils and stators. One of the common methods of reducing interference has been mentioned—positioning two stators symmetrically about the disk shaft exactly 180° from each other. This eliminates two of the three possible forms of interference.

Another method of reducing all types of interference is to laminate the disk. A number of separate laminations are used. Each lamination is slotted radially to form several sectors and the laminations are insulated electrically from each other. Because of the radial slots, the eddy currents in the disk are confined to the area around the stator which causes them, and they cannot flow to a portion of the disk where they could react with fluxes from another stator to create interference torques. The lamination slots are usually staggered during manufacturing to provide sufficient mechanical strength and smoother driving torque during each disk revolution.

A third common method of reducing interference is to provide magnetic shielding around the voltage or current coil of each stator to keep the spread of flux to a minimum. Combinations of the preceding methods are also employed.

Meters with stators operating on separate disks or completely separate rotors are inherently free from the various effects listed before. Proper design and spacing is still required to prevent voltage or current flux from one electromagnet reacting with eddy currents produced by flux from a second electromagnet.

MULTI-STATOR METER ADJUSTMENTS

The following is a description of the calibrating adjustments found in multi-stator electromechanical meters. Details on the procedure involved in using these adjustments may be found in Chapter 14, "Electricity Meter Testing and Maintenance."

Most polyphase electromechanical meters now in service contain two or three separate stators so mounted that their combined torque turns a single rotor shaft. As in single-phase meters, the adjustments provided for polyphase meters are the usual full-load, power factor, and light-load adjustments. In addition to these adjustments, polyphase meters have a fourth adjustment, torque balance, designed to allow equalization of individual stator torques with equal applied wattage for accurate registration. There is no requirement for torque balance in a single-phase meter.

Each stator in a multi-stator meter may contain a light-load adjustment, or a single light-load adjustment of sufficient range may be provided on one stator. All stators must contain power-factor compensation so that the phase relationships are correct in each stator. The power-factor compensation is adjustable on most meters, but some manufacturers make a fixed power-factor compensation at the factory which is not readily changed in the field. Only one full-load adjustment is provided on most modern polyphase meters, even though more than one braking magnet may be used. Torque-balance adjustments may be provided on all stators, on only one stator in two-stator meters, or on two stators of a three-stator meter. In all cases it is possible to equalize stator torques.

Torque-Balance Adjustment

For correct registration, the torque produced by each stator in a multi-stator electromechanical meter must be the same when equal wattage is applied. A two-stator meter with one stator 5% fast and the other stator 5% slow would show good performance with both stators connected in series-parallel for a calibration test on single-phase loading. However, if this meter were used to measure polyphase loads involving either low power factor or imbalance, the registration would be in serious error. To correct for this, each stator should be calibrated and adjusted separately to insure that each produces the same driving torque. The full-load adjustment cannot be used because it has an equal effect on the performance of all stators, so the torque-balance adjustment is provided for independently adjusting the torque of each stator.

Since the torque developed by a single stator is dependent upon the amount of flux produced by the electromagnet that passes through the disk, it follows that the torque for a given load can be varied by any method that will change the flux through the disk. A convenient way to change this is by providing a magnetic shunt in the air gap of the voltage-coil poles in the electromagnet. Moving this shunt into or out of the air gap bypasses a greater or a lesser portion of the voltage flux from the disk. This changes the disk driving torque through a narrow range. The adjustment obtained this way is sufficient to equalize the torques of the individual stators in a polyphase meter.

Two methods in general use for torque balancing are shown in Figure 7-29. The first method uses two steel screws which can be turned into or out of the gaps in the voltage-coil iron just below the coil windings. The second method uses a U-shaped soft iron wire that is inserted in the air gaps. This wire is attached to a yoke carried on threaded studs which permits the magnetic shunt to be moved in and out of the air gap. After these adjustments have been set so that the torques of all stators are alike, the other meter adjustments can be made as for single-phase meters.

Interdependence of Adjustments

Another characteristic of the polyphase meter is that any change in a full-load or light-load adjustment affects all stators alike. This does not apply to the power factor or torque balance adjustments.

The torques of the stators can be balanced at any unity power factor load value, but it is customary to make the balance adjustment at the rated test-ampere load. The balance of the individual stator torques at other unity power factor load points will depend on how well the stator characteristics are matched. Any divergence that may exist cannot be corrected or minimized by the light-load adjustment or otherwise, except by attempting to select stators of the same characteristics. This is neither practical nor important.

In calibrating a polyphase meter at light-load it is proper to excite all voltage circuits at the rated voltage. Under such conditions, the overall accuracy is the same regardless of whether a single light-load adjuster is used for the complete calibration or whether, where more than one adjuster is provided, each is moved a corresponding amount. In the latter case, when a considerable amount of adjustment is necessary, it is the usual practice to move the adjusters of all stators about the same amount to assure a sufficient range of adjustment and to avoid changes in torque balance at the 50% power factor test load.

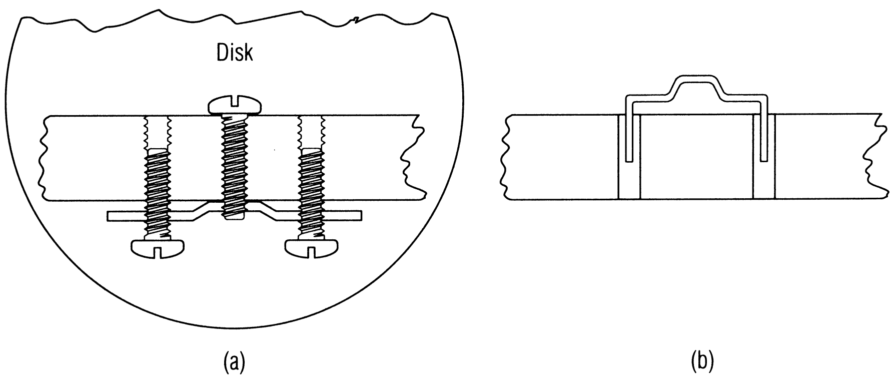


Figure 7-29. Methods of Shunting Voltage-Coil Air Gap for Torque-Balancing Adjustment in Multi-Stator Meters.

SPECIAL METERS

Universal Multi-Stator Electromechanical Meters

Universal multi-stator metering units permit the measurement of any conventional single-phase or polyphase service with a single type of meter. The meter is generally of the Class 10 or 20 socket type constructed with two split current coils and dual-range voltage coils. Associated instrument transformers are furnished for use within the meter-mounting enclosure or external instrument transformers may be used. A specially designed terminal block in the meter-mounting enclosure provides independent connection of the meter. Correct measurement of any service depends on proper connection of the terminal block making internal meter connection changes unnecessary. The universal unit is also available in self-contained ratings with provision for future use of instrument transformers.

SOLID-STATE METERS

All watthour metering approaches require power to be measured, accumulated, and the results stored and displayed. All approaches require that the voltage and current for each electrical phase be sensed (or approximated), voltage and current for each electrical phase must then be multiplied, the resultant power must be accumulated, and the accumulated watthours must be stored and displayed. Electromechanical meters have evolved over many years and all manufacturers use very similar approaches. The same can not be said for totally electronic meters.

Significant design variations occur in every electronic meter on the market today. These variations even occur within a given manufacturer's product line. These reflect the individual trade-offs each designer felt were appropriate. Ultimately, it is the users or regulatory agencies that determine if the trade-offs are indeed appropriate. This is usually determined by detailed evaluation and qualification testing of each design. Following a brief review of the evolution of electronic watthour metering, the remainder of this chapter will deal with the most common approaches for performing the various metering subsystems.

EVOLUTION OF SOLID-STATE METERING

The Watt/Watthour Transducer

Solid-state metering was introduced to the electric utilities in the early 1970s in the form of a watt/watthour transducer. See Figure 7-30. The advantages of solid-state electronic circuitry produced increased stability and accuracy surpassing the capabilities of the conventional electromechanical watthour meter, but at significantly higher costs. Consequently, the watt/watthour transducer was most suitable to energy interchange billing and special applications where analog watt and digital watthour outputs were required. They are used in these applications today, although multi-function electronic meters are starting to replace them.

The watt/watthour transducer provides an analog (watt) output signal in the form of a DC current and also a pulse (watthour) output from a form C mercury-wetted relay or solid-state relay. The analog output may be used to drive a panel meter or strip-chart recorder, or telemetered to a supervisory control system. The pulse output may be used to drive a totalizing register, magnetic tape recorder, or a solid-state recorder.

Figure 7-30. Solid-State Watt/Watthour Transducer.

The Electronic Register

In the 1970s, the register function for solid-state transducers began to be provided with electronic components. In 1979, the first microprocessor-based electronic register was introduced as an addition to the electromechanical meter. This combination was referred to as a hybrid meter or as an electronic meter. Compared with mechanical registers, electronic registers were more reliable when performing complex functions (demand) and could be provided at lower cost. In addition, electronic registers provided features not feasible with mechanical registers; such as, time-of-use measurements, sliding demand intervals, switchable registers, tamper detectors, and self-tests.

Today, automatic or remote meter reading is the most common application of electronic registers on electromechanical meters. These registers typically detect the disk rotation using some form of optical detector and communicate the energy consumption to a near-by meter reader or central system. Communication may be by radio frequency, power-line carrier, telephone, cable, or other appropriate media.

Commercial Solid-State Meters

Totally electronic meters were originally used in high cost, high precision metering applications. In the early 1980s there were a number of field tests to provide economical solid-state metering. By the mid-1980s, one manufacturer was providing a totally electronic meter replacement for the electromechanical, four-wire, wye meter. By the late 1980s, multiple manufacturers had totally electronic replacement meters for all electromechanical polyphase meter services. These still tended to be more expensive than the electromechanical meters, but provided more accuracy and greater functionality.

In 1992, polyphase metering changed dramatically with the introduction of a totally electronic meter that was highly accurate and cost competitive with the electromechanical demand meter. In addition, multiple service voltages and multiple service wirings could be handled with the same physical meter. In the mid-1990s, additional functionality, such as instrumentation and site diagnostics, was added to the basic solid-state polyphase meter. Today, these features are the norm for polyphase metering.

Also in the mid-1990s a practical single phase solid-state meter was introduced for practical time-of-use and demand applications. By the late 1990s, other manufacturers had introduced more cost effective solid-state meters for lower-end single phase applications.

The Solid-State Watthour Meter Principle of Operation

A functional block diagram of an early watt/watthour transducer is shown in Figure 7-31. The watt section is an electronic multiplier which uses the time-division-multiplier (TDM) principle to produce a pulse train which combines pulse-width and pulse-amplitude modulation. The pulse initiator section receives a DC current signal proportional to power from the watt section. Output pulses, proportional to a convenient watthour-per-pulse rate, are fed from the KYZ output circuit to a register, tape recorder, electronic pulse counter, or other pulse-operated device. A complete description of the operation of the time-division-multiplier is included later in this chapter.

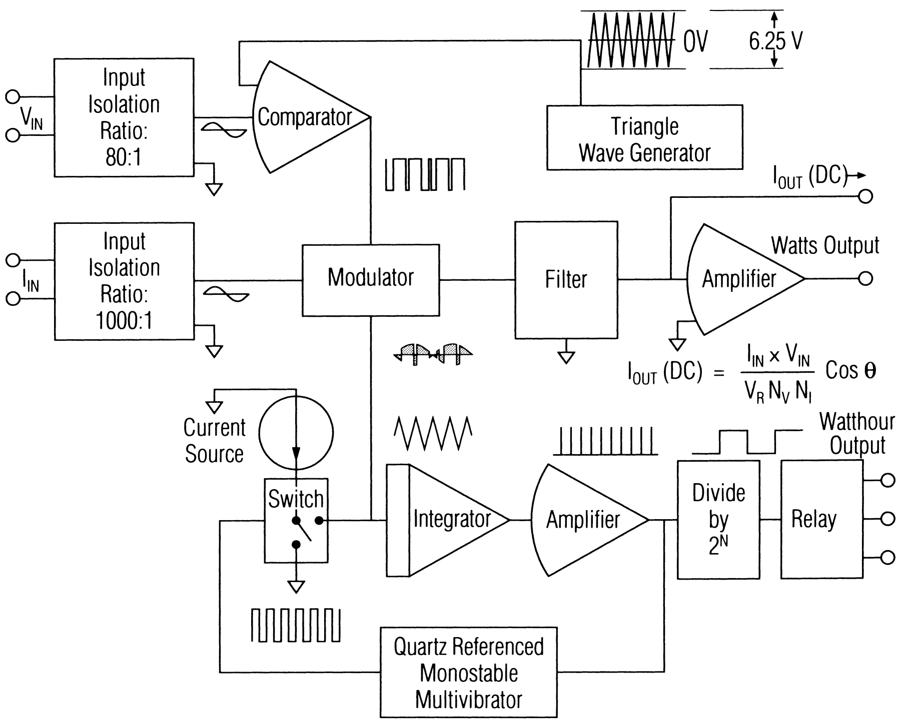


Figure 7-31. Functional Block Diagram Watt/Watthour Transducer.

Solid-State Watthour Meter

A typical meter consists of two sections: the multiplier and the register. In an electromechanical meter the multiplier consists of the voltage and current coils, and the meter disk; the register consists of the gears and dial indicators which count, store, and display the results of the multiplier. For clarity, the following definitions apply: a multiplier is a device which produces the product of a given voltage and current; a register is a device which counts and displays the results of the multiplier; a meter is an assembly which includes a multiplier and a register.

An electronic register is found on hybrid meters (meters with electromechanical multipliers and electronic registers), and on solid-state meters. Most registers use a microprocessor which follows instructions stored as firmware to control the counting, storing, and displaying of data received from the multiplier.

All solid-state meters must convert analog voltage and current signals into digital data. The digital data is sent to the register as serial or parallel data. Serial data is a series of pulses where each pulse has a predetermined value, such as 0.6 watthours per pulse. Parallel data is typically in bytes and represents a new value.

To implement an electronic multiplier, meter manufacturers use one of these four approaches: time-division multiplication, Hall-effect technology, transconductance amplifiers, or digital sampling techniques. Each method has advantages and disadvantages and some manufacturers offer more than one type of electronic multiplier.

Characteristics common to all electronic multipliers are: the original input signals are scaled down to lower voltages to be compatible with solid-state components, analog signals are converted to digital equivalents within the multiplier, and the phase angles between voltage and current are not measured directly.

CURRENT SENSING

All currents must be reduced to a signal level that the electronics can process. The current sensor needs to accurately reflect the current magnitude and phase angle over the expected environmental and service variations. Because the current sensor measures the currents on lines that are at line voltage, current sensors must be isolated from each other on systems with multiple line voltages. The current sensor must also provide protection from power transients.

The most common current sensor circuits are typically current transformers. Transformers allow the line voltages to be isolated from each other. A current transformer's linearity is defined by the magnetic material used for its core. Typically, a high permeability material is used to assure a linear performance, minimal phase shift, and immunity to external magnetic fields. Care must be taken to assure the material does not saturate under normal conditions. High permeability materials will saturate with DC currents, but these are not normally present on an AC electrical system.

A current sensor similar to the current transformer is the mutual inductance current sensor. This sensor uses air or a very low permeability material for the core because these materials are generally inexpensive, and will not saturate (as is the case with air) or require very high magnetic fluxes to cause the material to saturate. They also tend to have very good DC immunity. The drawback to this sensor is that it is more susceptible to external magnetic fields, often have stability issues with time and temperature, and can not supply much current. As such, it tends to have large phase shifts that vary with sensor loading. Typically, a voltage is measured from the sensor instead of a current.

A common sensor used in two wire meters (particularly in Europe) is the current shunt. This sensor defines a geometry in the meter's current conductor that causes part of the total current to pass through a resistance so that a voltage will be developed that is proportional to the load current. This voltage is then measured and represents the current. Because copper has a low resistance and a very large temperature coefficient, a special material is used for the shunt. The main disadvantages of this sensor is that it is not isolated from the line voltage and it is difficult to control the sensor's performance over a wide temperature range.

A current sensor can be produced using the Hall effect. The Hall effect can best be explained as follows: When a current flows through a material which is in a magnetic field, a voltage appears across the material proportional to the product of the current and the strength of the magnetic field. This principle is illustrated in Figure 7-32. There is no magnetic field and no voltage appears across the material. In Figure 7-32b, the magnetic field perpendicular to the path of the electrons displaces electrons toward the right side of the material. This produces a voltage difference side-to-side across the material. The voltage is proportional to the strength of the magnetic field and the amount of current flowing in the material. The Hall effect device is usually inserted in a gap in a toroidal-shaped magnetic core. Because it measures the magnetic field of the current through a conductor, there is electrical isolation in the current sensor. The Hall effect device can also be used for multiplication with the line voltage, as discussed below. Depending on the voltage measurement approach, isolation may be lost. Historically, phase shift, and temperature and frequency output variations have been problems for Hall effect devices, but there have been significant improvements in the performance of meters using these sensors.

There are numerous variations of the above current sensors. Shunts can be combined with current transformers. Compensating wirings can be used on a current transformer made with a low permeability material. Generally, most of the performance issues related to a particular current sensor technology can be compensated in the associated electronics. How these issues are addressed will be unique to each meter design.

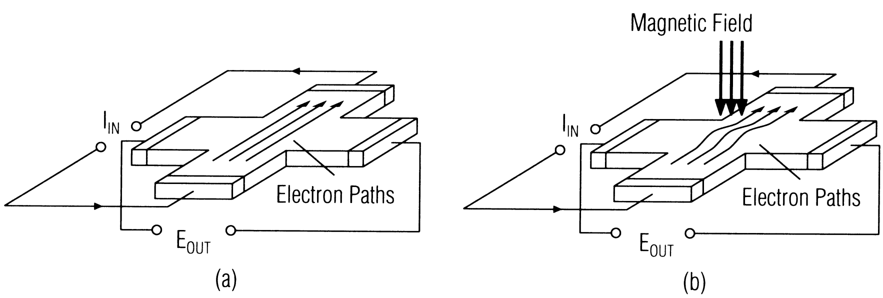


Figure 7-32. Hall Effect.

VOLTAGE SENSING

All voltages must be reduced to a signal level that the electronics can process. Like current sensing, the reduced voltage needs to accurately reflect the voltage magnitude and phase angle over the expected environmental and service variations. It must also provide protection from power transients.

Historically, the voltage reduction circuits were transformers. Transformers allow the line voltages to be isolated from each other, but often have a limited operating range, have an intrinsic phase shift that varies with frequency, and are relatively expensive. Most of today's solid-state meters use a resistor-divider network, because of the reduced cost and a very wide dynamic operating range with accurate reproduction of magnitude and phase angle. A drawback of this approach is that the designer must use great care to assure the meter operates properly over all defined services. Perhaps more serious drawback, is that the electronics of the meter may have line voltage present in some services. This can represent a safety and equipment issue for the meter technician if he is unaware of the potential hazard.

MULTIPLICATION

Time-Division Multiplication

Time-division multiplication (TDM), also called mark-space-amplitude multiplication, is the approach used in the earliest commercial solid-state meters and many metering transducers and standards. It computes power by using the common calculation of length times width to measure the area of a rectangle. The TDM multiplier develops a series of pulses where the width of each pulse is proportional to input voltage and the height of each pulse is proportional to input current, or vise versa. The area of each pulse is proportional to power. Power can be integrated over time to develop an output signal for energy.

Figure 7-33 is a block diagram of a TDM multiplier and the waveforms within the multiplier.

The signal from the voltage (or current) sensor is compared with a triangular wave with a magnitude greater than the maximum of the input voltage signal. The frequency of the triangular wave varies with each manufacturer, with values typically between 800 Hz and 10 kHz. The comparator compares the input voltage with the reference voltage. For the positive half of the input voltage cycle, if the reference voltage is greater than the input signal, the comparator output is negative; if the reference voltage is less than the input signal, the comparator output is positive. For the negative half of the input voltage cycle, if the reference voltage is more negative than the input signal, the comparator output is negative; if the reference voltage is less negative than the input signal, the comparator output is positive. Figure 7-33b, graph C, illustrates these comparisons. Graph D shows the output from the comparator, a signal with a fixed amplitude and a pulse width proportional to the input voltage.

The output from the comparator controls an electronic switch. When the comparator output is positive, the switch is set to input 1. When comparator output is negative, the switch is set to input 2.

Signal from the current sensor (or voltage sensor) is applied to switch input 1, and the inverse of that input is applied to switch input 2.

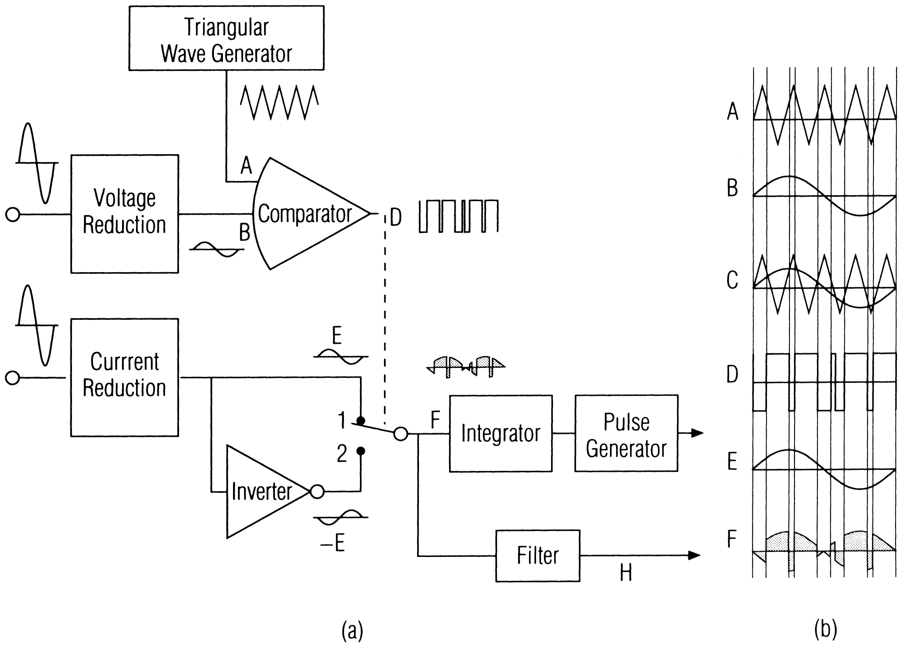


Figure 7-33. Time-Division Multiplication Waveforms.

The output of the switch is shown on Figure 7-33b, graph F. The width of each shaded area is proportional to the width of the switch control signal, which is proportional to the input voltage. The height of each shaded area is proportional to the input current. The area of each shaded area is proportional to power for that period of time. While there appears to be positive as well as negative areas in the graph, the negative areas do not indicate power flow in the reverse direction.

The integrator and pulse generator convert power into energy measurements and the analog information into digital data. The integrator sums individual areas, both positive and negative. When the accumulated total exceeds a predetermined value, the predetermined value is subtracted from the accumulated total and a pulse output is generated. The output of the pulse generator is sent to a register for storage and display.

By passing output signal F through an electronic filter, a signal proportional to instantaneous power can be produced. This waveform is labeled as signal H, and can be transmitted to a Supervisory Control and Data Acquisition (SCADA) system for monitoring and control purposes.

A comparison of Figure 7-32 with Figure 7-33 shows that while several years have passed since the watt/watthour transducer of Figure 7-32 was designed, the basic principles of TDM remain unchanged. The significant changes in the two designs result from the trend toward smaller lower cost components. In modern TDM multipliers, design variations among manufacturers include: the frequency used by the triangular reference waveform; the rate at which integrated data is converted into pulses; the electronic components selected for the comparator, switch, and integrator; calibration and adjustments made available; method for scaling down voltage and current inputs; power supplies; and the technology used for the display.

Hall Effect Multiplication

The Hall effect device can be used for current measurement and it can also be used for the multiplication of the voltage with the current signal. Figure 7-34 illustrates application of the Hall effect to metering. Current flows in the Hall effect device, based on line voltage across the device after a reducing resistor. Current in a conductor looped around the magnetic core creates a magnetic field. The magnetic field flows around the core and through the Hall effect device, perpendicular to the flow of current.

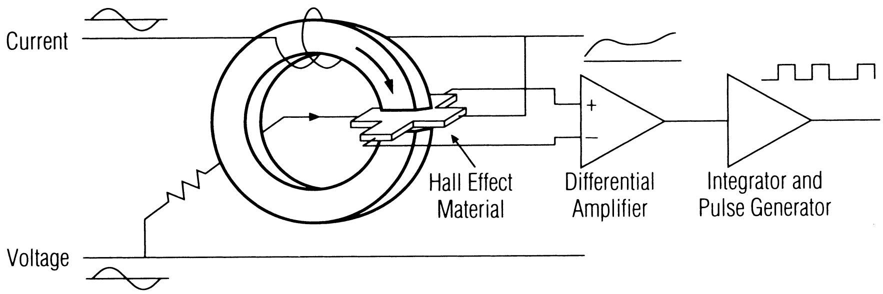


Figure 7-34. Hall Effect Applied to Metering.

The Hall effect voltage is sensed by a differential amplifier and supplied to an integrator and pulse generator. The integrator and pulse generator convert the power measured to an energy measurement, and convert analog information into digital data. The integrator calculates the area under the power curve and stores accumulated data. When the accumulated total exceeds a predetermined value, the predetermined value is subtracted from the accumulated total, and a pulse output is sent to a register for counting, storing, and display of the measured data.

Transconductance Multiplier

The transconductance multiplier uses a differential amplifier, where bias current varies with an input signal. The circuit is illustrated in Figure 7-35. In a metering application, input current is applied to the emitter of both transistors through resistor R_1. Input voltage is applied across the base of both transistors causing one transistor to conduct more than the other transistor. The current flow difference causes different voltage drops across resistors R_2 and R_3. Output voltage V_{OUT}, is proportional to the bias current multiplied by the input voltage.

Figure 7-36 illustrates application of a transconductance amplifier for metering purposes. Bias current is developed from resistors R_1, R_2, and R_3 connected across the power line. Input voltage V_{IN} is developed from a secondary winding on a transformer (in this example a toroid core), where the primary winding carries line current. The output signal is fed to an integrator and pulse generator.

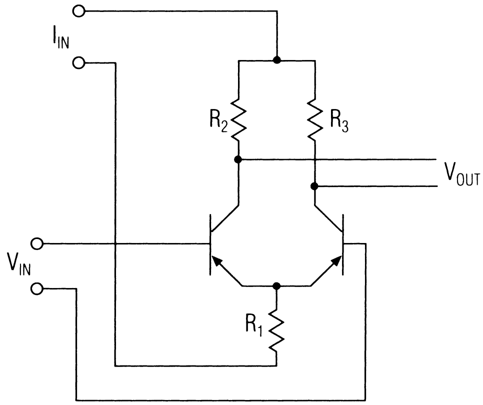


Figure 7-35. Transconductance Multiplier.

The integrator calculates the area beneath the power curve. When the sum of several areas exceeds a predetermined value, the predetermined value is subtracted from the integrated total and an output pulse generated. Output pulses are sent to a register for counting, storing, and display of the measured data.

Digital Multiplier

For all three multipliers described above, the analog voltage and current signals are multiplied and the results are converted to digital format. With the digital multiplier, the voltage and current analog inputs are immediately converted to digital equivalents, then multiplied using digital circuits.

An analog-to-digital converter measures the instantaneous value of the waveform and converts each value to an equivalent digital word. An input sine wave for example, can be sampled many times within one cycle and a digital equivalent of each instantaneous value can be stored in memory. Important specifications for analog-to-digital converters are: conversion time, the number of bits of resolution, and linearity.

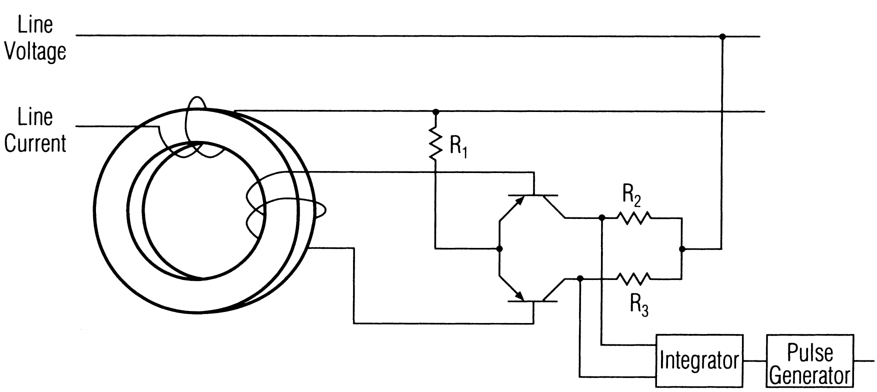


Figure 7-36. Transconductance Multiplier Applied to Metering.

Modern analog-to-digital conversion times are typically in the range of 20 to 50 microseconds. When the conversion time is short, changes to the input signal during the measuring window are small, increasing the accuracy of the measurement. When the time for each conversion is short, more samples can be taken during each cycle of the analog input, making the data collection process more accurate.

When sampling a voltage or current signal, the sampling rate determines the accuracy with which the signal is measured. The Nyquist Theorem states: When sampling an analog signal, to capture sufficient information about that signal, the sampling rate must be at least twice the highest frequency of interest in the analog signal. For example, if the highest frequency of interest in a signal is 60 Hz, the signal must be sampled at least 120 times per second to get a valid representation of that signal. If higher frequencies are of interest, a higher sampling rate must be used. For example, if measuring the seventh harmonic which has a frequency of 420 Hz is of interest, the signal must be sampled at least twice 420 or 840 times per second. Unfortunately, Nyquist is dealing with the presence of a frequency in a stable waveform. The load currents may be considered stable over short time periods, but this is very application dependent. To accurately reflect a changing current signal, a much higher sample rate is required. The performance of a meter under these conditions is difficult to measure, because most test equipment uses stable current signals for the test and is limited in its ability to deal with frequencies other than the fundamental.

The sampling rate of solid-state meters varies by model and by manufacturer. Typical rates are 10s to 100s of samples per 60 Hz cycle and per phase. Because two parameters, voltage and current, must be measured, often multiple analog-to-digital converters are used. Because multiple phases must be measured, the digital multiplier must process information at two to three times these sampling rates. A three-phase meter taking two readings for each of three phases processes information at speeds over 15,000 new readings each second.

The number of bits of resolution determines the granularity of the measurement. For example, if a 2-bit analog-to-digital converter is used to convert an analog signal which varies from 0 to +10 volts, the converter can output only four different digital values representing the input, or steps of 2.5 volts each. If a 12-bit analog-to-digital converter is used to convert a signal varying from 0 to +10 volts, the converter can output 4,096 different digital values, or steps of 2.44 millivolts each. In the second example, a change of only 2.44 millivolts at the analog input will cause a one-bit change in the output digital value. The resolution of analog-to-digital converters used in solid-state meters varies by model and by manufacturer, depending on the accuracy of the application. Typical resolutions are 12 to 21 bits.

A block diagram of a digital multiplier in a power meter is shown in Figure 7-37. This example shows two analog-to-digital converters although more could be used, especially in polyphase meters. The input voltage and current signals are scaled down by their respective reduction circuits, then applied to the analog-to-digital converters. The converter outputs are multiplied by the microprocessor, with the results stored in memory along with an accumulating total of the results. When the accumulated total reaches a predetermined value, that predetermined value is subtracted from the total and one output pulse is generated. The output pulse indicates that one predetermined increment of power has been measured. The pulse is sent to an electronic register for storage and display.

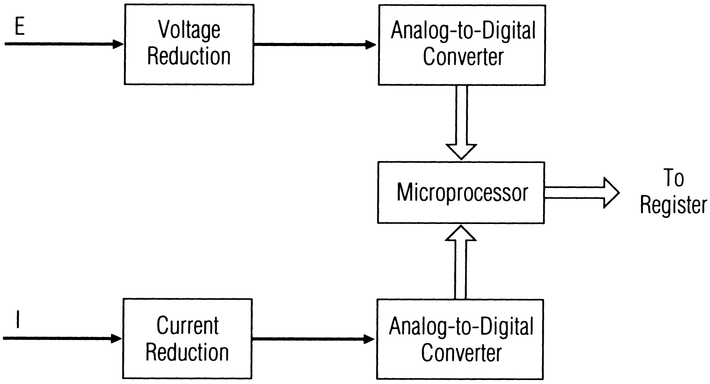


Figure 7-37. Digital Multiplier Block Diagram.

Variations of digital multiplier designs are shown in Figure 7-38. The sample-and-hold amplifiers shown in Figure 7-38a allow the meter to measure voltage and current at the same instant, thus eliminating time skew in taking two readings. The multiplexer shown in Figure 7-38b allows the meter to switch one analog input at a time to one analog-to-digital converter. This approach eliminates the cost of another analog-to-digital converter.

Today, most digital solid-state meters use a special type of analog-to-digital converter, known as a delta-sigma converter, or 1-bit converter. These converters use very high sample rates to over-sample the signal and process multiple over-samples to produce a single reported sample. The benefit of this type of converter is that it takes very little silicon space and overcomes the issues of linearity for high resolution samples.

The digital multiplier calculates instantaneous power by multiplying digitized equivalents of the voltage and current signals and can calculate other values as well. By summing the products of a number of multiplications, then dividing by that same number, the result is average power consumed during the period. Increments of average power can be summed over time to determine energy. To determine V_{rms} and I_{rms}, instantaneous values for voltage and current can be squared, their square roots computed, and the result is rms values of voltage and current. If V_{rms} and I_{rms} are multiplied and integrated over a period of time, the result is an arithmetic apparent power and energy (VA and VAhrs). There are a number of approaches used to compute reactive power. Two approaches are very similar. In these, reactive power (VAR) can be computed by multiplying the current and the voltage shifted 90° in phase. This can be accomplished by integrating or differentiating the voltage or current, and applying the appropriate sign for the desired result. The problem with these approaches is that any harmonics will have the wrong magnitude. A third approach is to use a time delay equivalent to a 90° phase shift at the fundamental. In the digital meter this is accomplished by fixing the sampling rate for the digital multiplier at 4 or a multiple of 4, times the fundamental frequency of the voltage and current, so current and voltage are sampled every 90°. To compute VAR, multiply the digitized values for current and the corresponding digitized values for voltage, which were sampled 90° apart. The problem with this approach is that a 90° time delay is dependent on the frequency

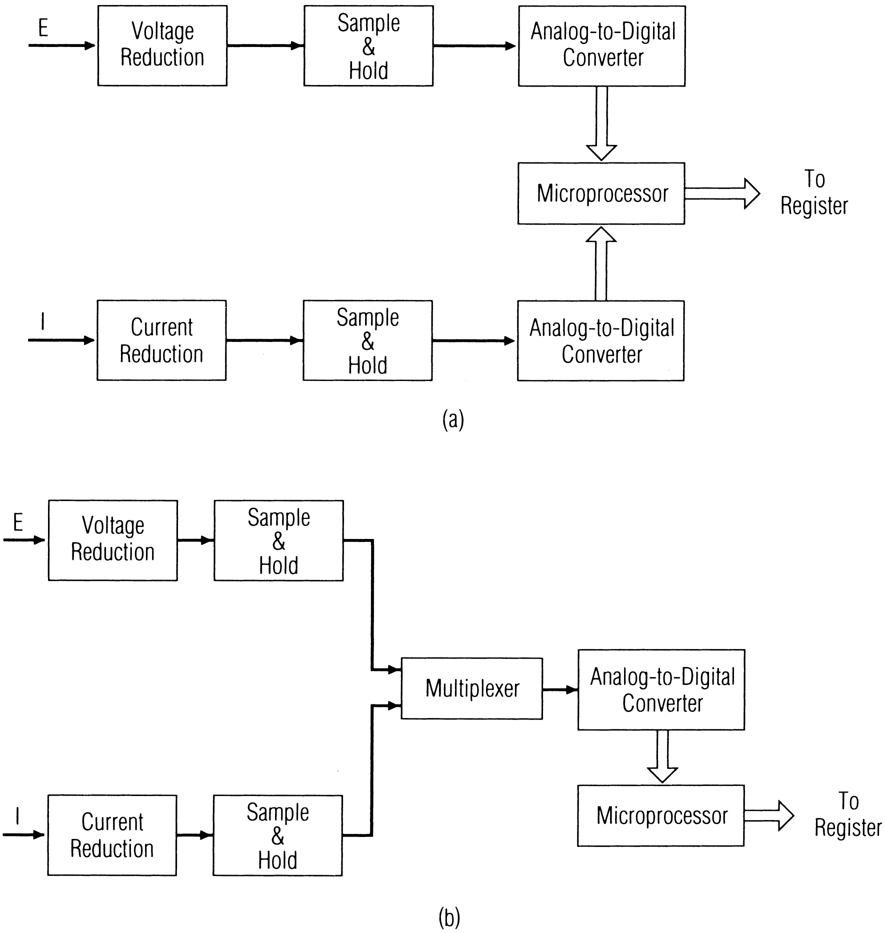


Figure 7-38. Variations on Digital Multiplier Designs.

of the fundamental, and it is difficult to change the sample rate based on the frequency of the fundamental. A second problem is that any harmonics are not handled correctly. A fourth approach is to compute the VARs from the VA and Watts calculation using the formula:

$$VAR = \sqrt{VA^2 - Watts^2}$$

The problem with this approach is that the sign of the VAR is lost in the conversion and must be supplied by some other means. Also, if harmonics are present, harmonic VAR and harmonic distortion power is included in the reported VAR value.

Figure 7-39 is a simplified block diagram of a typical three-function meter. Voltage and current inputs from instrument transformers are first reduced to low values by the input voltage resistive dividers and current transformers. These signals are then fed to appropriate analog-to-digital converters and digital multiplier

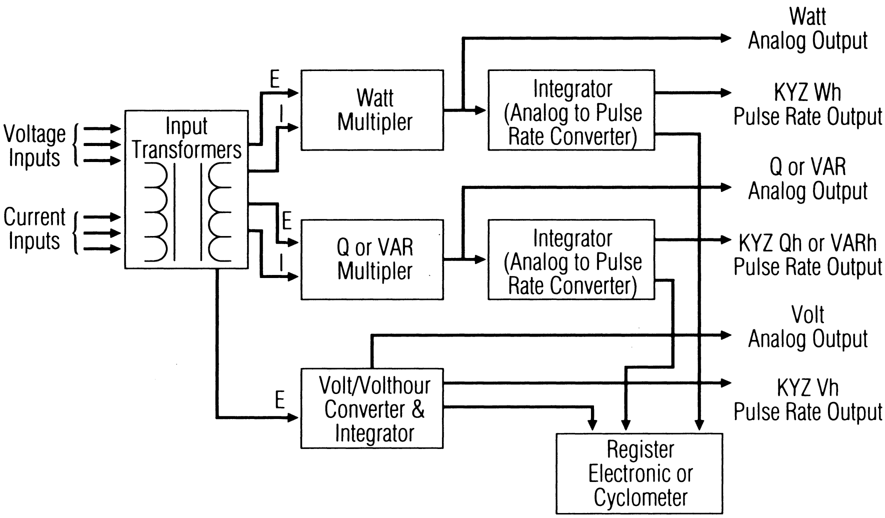


Figure 7-39. Solid-State Three-Function Meter Block Diagram.

where they are converted to power and accumulated for energy. The energy is converted to a pulse train that is passed to an electronic register for further processing, storage, and display.

Figure 7-40. Electronic Single-Phase and Polyphase Meters.

Figure 7-41. Electronic Polyphase Multifunction Meter.

CHAPTER 8
DEMAND METERS

EXPLANATION OF TERM "DEMAND"

KILOWATT DEMAND is generally defined as the kilowatt load averaged over a specified interval of time. The meaning of demand can be understood from Figure 8-1 in which a typical power curve is shown. In any one of the time intervals shown, the area under the dotted line labeled *demand* is exactly equal to the area under the power curve. Since energy is the product of power and time, either of these two areas represents the energy consumed in the demand interval. The equivalence of the two areas shows that the demand for the interval is that value of power which, if held constant over the interval, will account for the same consumption of energy as the real power. It is then the average of the real power over the demand interval.

The demand interval during which demand is measured may be any selected period but is usually 5, 10, 15, 30, 60, and in similar increments up to 720 minutes. The demand period is determined by the billing tariff for a given rate schedule.

Demand has been explained in terms of power (kilowatts) and usually this information has the greater usefulness. However, demand may be expressed in kilovoltamperes reactive (kVAR), kilovoltamperes (kVA), or other suitable units.

DEFINITIONS

Coincidental Demand—Many utility customers have two or more revenue meters that meter separate electrical loads. A common example is a large factory that has multiple meters at different locations. Assuming each revenue meter measures demand, then each meter would provide a maximum demand. Coincidental demand is the maximum demand that is obtained when all metered loads are summed coincidentally. The summation of the individual demands must be performed on a demand interval basis.

In other words, when all measured demands from each individual meter are summed on each interval of the billing period, the maximum total demand obtained from the summation is the coincidental demand. The individually metered maximum demands typically do not occur at the same demand interval in which the coincidental demand occurs. Therefore, the summation of the individually metered maximum demands will normally be higher than the demand that occurs at the demand interval in which the total coincidental demand occurs. This is due to the variation in the time in which electrical equipment operates. The total coincidental peak demand is usually less than the sum of the individual maximum demands.

Aggregated Demand—Aggregated demand is similar to coincidental demand in that it is derived from the summation of multiple meters. Typically, aggregated demand is obtained from the aggregation of load profile data from multiple meters.

Totalized Demand—Totalization, as applied to revenue metering, is the addition of two or more metered electrical loads. Totalization is often requested by customers that have two or more metered loads. Benefits of totalization include the ability to obtain coincidental demands, simplified meter reading, and billing and subsequent accounting procedures.

Totalization is the algebraic sum of two identical energy values performed on a real time or near instaneous basis. Simple totalization could be the addition of the kilowatthour useage of two metered loads. Complex totalization could be the algebraic sum of multiple metered loads from different locations, some of which could be negative values. Refer to Chapter 10, “Special Metering,” for additional information on totalization.

It is important to note that totalized demand is derived from totalized energy. Energy is summed on a near instantaneous basis. Because the totalizing device or software knows the time interval over which the demand is desired, totalized demand can then be obtained from the simple relationship, Demand = Energy/Time.

WHY DEMAND IS METERED

Two classes of expenses determine the total cost of generating, transmitting, and distributing electric energy. They are:

1. *Capital investment items:* depreciation, interest on notes, property taxes, and other annual expenses arising from the electric utility’s capital investment in generating, transmitting, and distributing equipment, and in land and buildings,
2. *Operation and maintenance items:* fuel, payroll, renewal parts, workmen's compensation, rent for office space, and numerous other items contributing to the cost of operating, maintaining, and administering a power system.

In billing the individual consumer of electricity, the utility considers to what extent the total cost of supplying that consumer is determined by capital investment and to what extent it is determined by operation and maintenance expenses. Furnishing power to some consumers calls for a large capital investment by the utility. With other consumers, the cost may be due largely to operation and maintenance. The following two examples illustrate these two extremes of load.

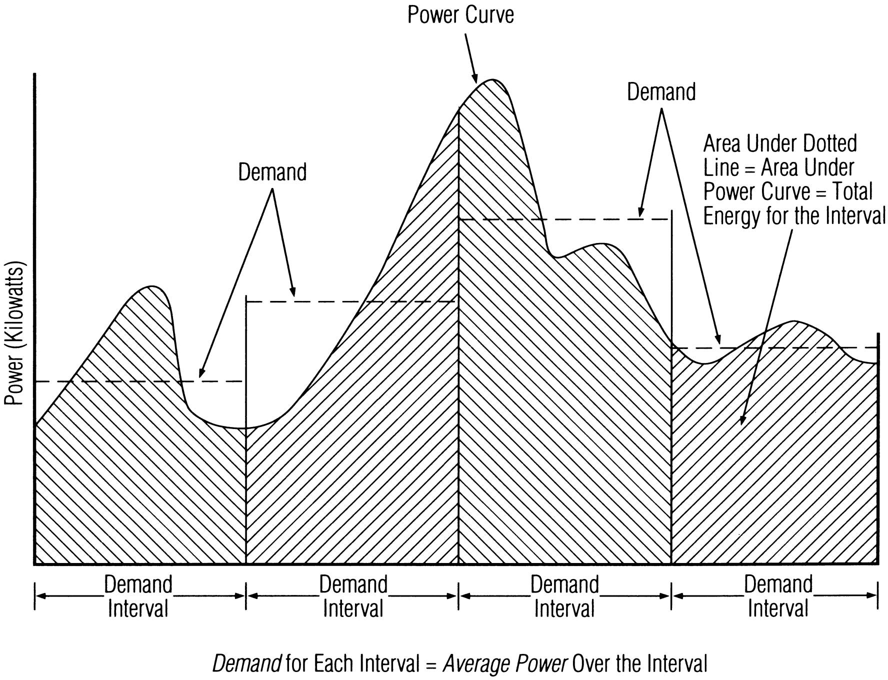


Figure 8-1. Power Curve Over Four Successive Demand Intervals.

1. In a certain plant, electricity is used largely to operate pumps, which run at rated load night and day. The power consumed by the pump motors is low and the plant shares a utility-owned transformer with several other consumers. The amount of energy used each month is large because the pumps are running constantly. Therefore, the cost of supplying this consumer is largely determined by operating expenses, notably the cost of fuel. The capital investment items are relatively unimportant.
2. Another factory uses the same number of kilowatthours of energy per month but consumes all of it in a single eight-hour shift each day of the month. The average power is therefore three times greater than for the pump plant and the rating (and size) of equipment installed by the utility to furnish the factory with energy must also be about three times higher. Costs rising from capital investment are a much greater factor in billing this consumer than in billing the operator of the pump plant.

Demand is an indication of the capacity of equipment required to furnish electricity to the individual consumer. Kilowatthours or energy per month is no indication of the rating of equipment the utility must install to furnish a particular maximum power requirement during the month without overheating or otherwise straining its facilities. What is needed in this case, is a measure of the maximum demand for power during the month. The demand meter answers this need. More importantly, the true demands that the equipment experiences are the maximum kilovoltamperes (kVA). This takes into account the real power watts, and the reactive power VARs, as one quantity. With electronic meters, the meter calculates kVA demand from the coincident peak demand of the real and the reactive power. This represents the true maximum stress on the power equipment.

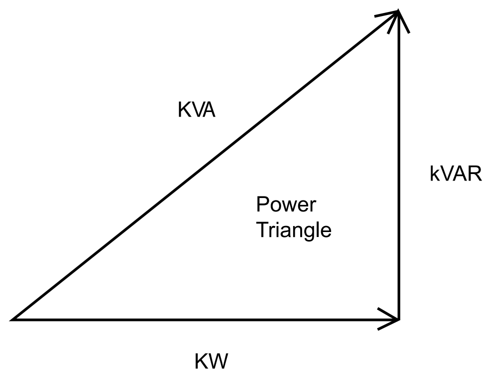


Figure 8-2. Power Triangle.

MAXIMUM AVERAGE POWER

A commonly used type of demand meter is essentially a watthour meter with a timing function. The meter sums the kilowatthours of energy used in a specific time interval, usually 5, 10, 15, 30, or 60 minutes, and in similar increments up to 720 minutes. This demand meter thus indicates energy per time interval, or average power, which is expressed in kilowatts.

By means of a demand function, a wattmeter is made to preserve an indication of the maximum power delivered to a consumer over a month or some other period. This method of measuring demand came about because the electromechanial meter could only measure one quantity at a time, power, for example. Measuring only real power to determine the maximum demand the customer is using is only part of the real load. The maximum load is the maximum kilovoltamperes, KVA, demanded by the customer.

MAXIMUM AVERAGE KILOVOLTAMPERES

Another commonly used type of demand meter is essentially a multi-function meter with a timing function. The meter measures the kilowatthours of energy and kiloVARhours of quadergy used in a specific time interval, usually 5, 10, 15, 30, or 60 minutes, and in similar increments up to 720 minutes. This demand meter calculates the KVA per time interval, or average KVA, which is expressed in kilovoltamperes.

By means of a demand function, a mutlti-function meter is made to preserve an indication of the maximum KVA delivered to a consumer over a month or some other period.

The capacity of most electrical equipment is limited by the amount of heating it can stand, and heating depends on the apparent current flowing through the equipment by two components, the real current and the reactive current. Maximum stress on the equipment not only depends on the size of the load or the apparent current, but on the length of time the current is maintained. A momentary overload such as the starting surge of a motor will not cause a temperature rise sufficient to break down insulation or otherwise damage the equipment.

Therefore, the utility does not use a momentary value of maximum KVA, but maximum average KVA over an interval as a basis for billing.

GENERAL CLASSES

There are several types of demand meters:

- Instantaneous demand recorders, strip chart
- Integrating demand recorders, mechanical
- Thermal or lagged demand meters
- Offsite demand recorder (i.e., MV90, Remote Register, AMR data collection)
- Pulse-operated demand registers, mechanical
- Pulse-operated demand registers, electronic
- Pulse-operated demand recorders, electronic
- Electronic demand meters
- Electronic demand meters with time-of-use (TOU) registers
- Electronic demand meters with TOU and internal data recorder under the meter cover

All of these meters have a common function which is to measure power in such a way that the registered value is a measure of the load as it affects heating and therefore the load-carrying capacity of the electric equipment. Some demand meters have other functions that provide billing and load information for use in pricing.

INSTANTANEOUS DEMAND RECORDERS

Instantaneous demand recorders are mechanical wattmeters with a moving lever arm that moves proportional to watts flowing through the meter. The lever arm houses an ink pen or other marking device which draws a line on a circular drum or chart which is scaled to indicate load levels. A timer motor rotates the chart coincident with the time increments on the chart. The vertical position on the chart indicates load level and the horizontal position on the chart indicates the time-of-day. The operator can easily see how large peak demand was and the scale on the chart indicates when that peak occurred during the billing period.

Integrating Demand Recorders

All integrating kilowatt demand meters register the average power over demand intervals which follow each other consecutively and correspond to definite clock times. For example, if an integrating meter with a 15-minute interval is put into operation at 2:15 p.m. on a certain day, the first interval will be from 2:15 to 2:30 p.m., the next will follow immediately and will be from 2:30 to 2:45 p.m., and so on.

Integrating kilowatt demand recorders are driven by watthour meters. The registering device turns an amount proportional to the watthours of energy in the interval. A timing mechanism returns the demand registering device to the zero point at the end of each interval. The final displacement of the registering device just before the timing mechanism returns it to zero is also proportional to the demand in the interval. This is true because the demand in the interval is equal to the energy consumed during the interval divided by the time, which is constant.

The integrating demand recorders indicate only the maximum demand over a month or other period. The gears, shafting, and pointer-pusher of all integrating demand recorders turn an amount proportional to the demand in every demand interval. In other words, a meter which indicates only maximum demand has a pointer-pusher and a pointer that indicates the maximum demand that has occurred during any interval since the pointer was reset to zero.

An integrating kilowatt demand meter is basically a watthour meter with added facilities for metering demand. The watthour meter is the driving element. The watthour and demand registering functions may be combined in a single device. Frequently the demand register is physically separated from the driving element, sometimes by many miles.

Thermal or Lagged Demand Meters

Electromechanical

In the electromechanical thermal or lagged-type demand meter, the pointer is made to move according to the temperature rise produced in elements of the meter by the passage of currents. Unlike the integrating demand meter, the lagged meter responds to load changes in accordance with the laws of heating and cooling, as does electrical equipment in general. Because of the time lag, momentary overloading, instead of being averaged out, will have a minor effect on the lagged meter unless the overloading is held long enough or is severe enough to have some effect on the temperature of equipment. The demand interval for the lagged meter is defined as the time required for the temperature sensing elements to achieve 90% of full response when a steady load is applied. Like the integrating meter, the lagged meter is generally designed to register kilowatt demand.

The lagged type is essentially a kind of wattmeter designed to respond more slowly than an ordinary wattmeter. An important difference in these methods of metering demand is in the demand interval. In the integrating meter, one demand interval follows another with regularity, giving rise to the term block interval. The thermal or lagged meter measures average load with an inherent time interval and a response curve which is based on the heating effect of the load rather than on counting disk revolutions during a mechanically timed interval.

Electronic

Electronic thermal demand emulation is the logarithmic average of the power used, with a more recent load being weighted more heavily than a less recent load, (approximated exponentially). The meter will record 90% of a change in load in 15 minutes, 99% in 30 minutes, and 99.9% in 45 minutes. Because thermal demand emulation is the logarithmic average, the demand is not set to zero on a demand reset. On a demand reset, present demand becomes the new maximum demand.

These general classes of demand meters and their common principles and uses, are discussed in the following text.

OFFSITE DEMAND RECORDER

The offsite demand recorder is essentially a remote data collection device—a computer system—that communicates with a meter and extracts the interval data from the meter's recording memory. The offsite demand recording system then calculates the peak demand and total energy from interval data received from the meter.

PULSE-OPERATED DEMAND REGISTERS

The pulse-operated demand register is affixed to a kilowatthour meter and receives pulses from its internal pulse initiator and calculates the peak demand using the registers internal fixed interval-timing element. The register can be reset to start accumulating peak demand information for the next billing cycle.

ELECTRONIC DEMAND METERS WITH TIME OF USE AND RECORDER

Electronic demand meters incorporating sufficient memory and register capacity can be used to register time-of-use data and store interval data for retrieval either locally by a handheld reader or remote via a communications mechanism.

WATTHOUR DEMAND METER

The watthour demand meter, as its name implies, combines in a single unit a watthour meter and demand meter. Such a meter may contain an electromechanical watthour element combined with a mechanical or electronic demand device or an electromechanical watthour element and a thermal demand unit. The thermal and electronic demand meters will be discussed later in this chapter. Discussion here covers the method of mechanical demand measurement.

In a mechanical watthour demand meter, the watthour disk shaft drives two devices:

1. The gears and dial pointers through which the revolutions of the rotor are summed as kilowatthours of energy;
2. The gears and shafting, which, working in conjunction with a timing motor or a clock, sum the revolutions of the rotor during each demand interval in terms of kilowatts of demand.

These two devices, which, after their initial gearing to the disk shaft are independent of each other, comprise two separate registers. They are commonly combined physically and referred to as the watthour demand register.

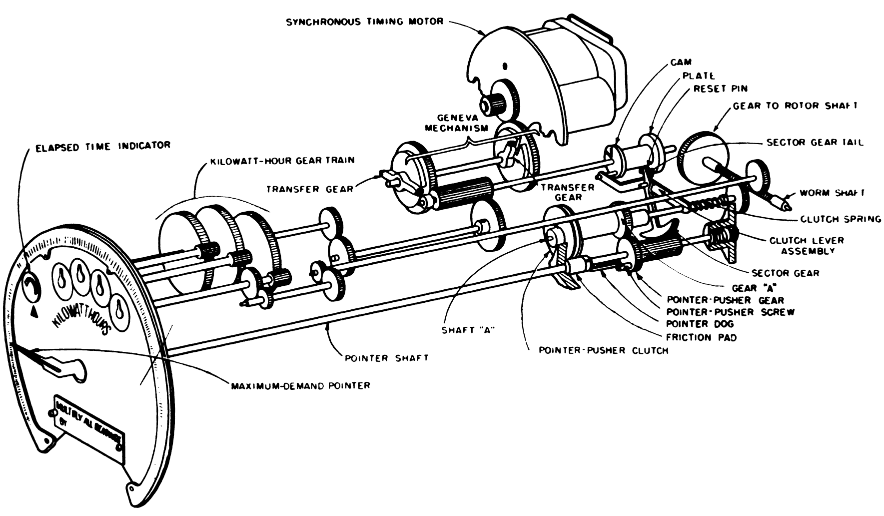


Figure 8-3. Gear Trains and Interval-Resetting Mechanism of an Indicating Watthour Demand Register.

Three types of mechanical watthour demand recorders are manufactured:

1. The *indicating type*. This type indicates only the maximum average demand for each month or other period between resettings;
2. The *cumulative type*. This type also indicates the maximum demand during the period between resetting, and by means of the resetting operation, the maximum demand for the period just ended is transmitted to dials and added to the total of previous maximums;
3. The *recording type*. By means of a pen moving across a chart, a record of the instantaneous demand for every demand interval is kept.

The gears, dials, and pointers by which the disk rotations of a watthour demand meter are translated into kilowatthours of energy are the same, in principle, as those in the watthour meter register.

The demand pointer-pusher or recording device rotates a number of degrees proportional to energy utilization of each demand interval. Every 15 minutes, half-hour, or other demand interval, the timing mechanism performs two operations:

1. It releases a clutch, mechanically breaking the connection between the meter rotor and the pointer-pusher or recording mechanism;
2. It returns the pointer-pusher to the zero point.

Then the clutch is re-engaged and the summing-up process begins again. The process of returning the pointer-pusher to zero at the end of each interval takes only a few seconds.

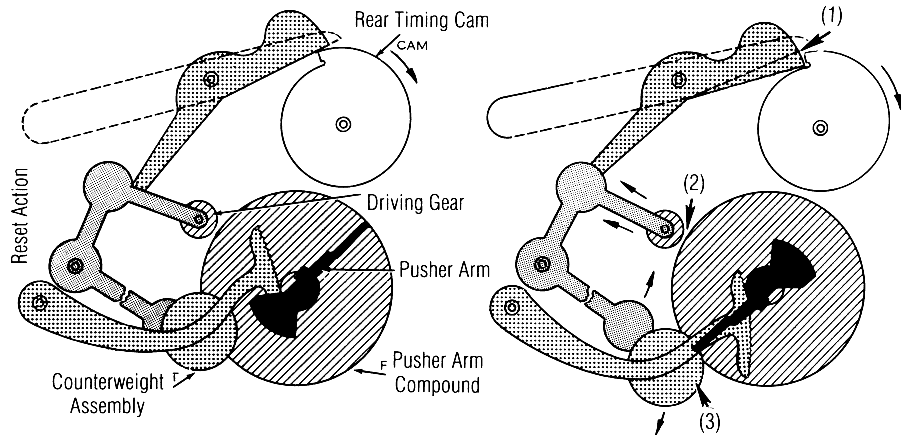
The timing mechanism may be actuated by voltage from the metered circuit or by voltage from a separate circuit, or the mechanism may be a spring-driven device.

Indicating Type (Pointer Type)

The maximum demand is indicated on the graduated scale by the sweep-hand pointer. During each demand interval the demand pointer-pusher advances proportionally to the kilowatts demand. If the demand for a given interval is higher than any previous demand since the pointer was last reset, the pointer-pusher pushes the pointer upscale to indicate the new maximum demand. The pointer is held in this position by the friction pad.

At the end of each demand interval, the pointer-pusher is automatically returned to the zero point. See Figure 8-3. Gear A, which meshes with and drives the pointer-pusher gear, is free to rotate on shaft A. Throughout each demand interval, the gear is driven by shaft A through the pointer-pusher clutch drives the gear. At the end of the interval, the cam, driven by the synchronous timing motor through gears, transfer gears, and shafting, lifts the tail of the clutch lever causing this lever to compress the clutch spring, taking pressure off the clutch, disengaging it, and leaving the pointer-pusher assembly free to rotate. At this instant, the reset pin on the plate (which is also rotated by the synchronous motor) engages the tail of the sector gear and causes the gear to turn the pointer-pusher assembly backward to the zero point. Then the cam acts to close the clutch and registration is resumed.

An important variation of returning the pointer-pusher to zero is the gravity reset method. The energy for the reset operation is provided by a weight and pivot assembly geared to the pusher-arm shaft. The operation of the reset mechanism is triggered by dual timing cams. The drop-off of each of the cams is slightly displaced thus triggering the disengaging and resetting action. The resetting operation consists of the actions in Figure 8-4.



(1) Rear weighted lever arm drops off rear timing cam.

(2) Lever assembly pivots and lifts driving gear from pusher arm compound.

(3) With pusher arm compound freed from driving gear, counterweight assembly pulls pusher arm to zero position. .LS PUSHER

(4) Front counterweight lever arm falls off front timing cam.

(5) Resulting gravity action re-engages pusher arm driving gear with pusher arm compound. MPOUND.

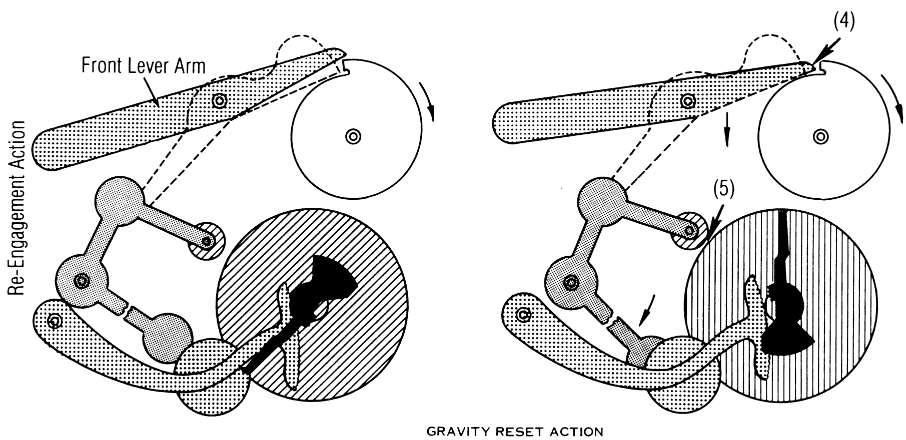


Figure 8-4. Gravity Reset for Indicating Demand Register.

Indicating Type (Dial)

The dial type demand register uses an indicating type demand register mechanism where the demand reading is in dial form. The dials return to zero when the monthly reset is performed. This type of demand display has better resolution than the pointer type due to a longer equivalent scale length.

Cumulative Type

The cumulative watthour demand meter goes one step further than the indicating watthour demand meter. A pointer, moved across a scale by a pointer-pusher mechanism, preserves the maximum demand until the meter is reset. The principle is the same as in the indicating meter but the pointer and scale are much smaller. In addition, the meter preserves a running total of the maximum demands for consecutive months on small dials similar to watthour meter dials. The maximum demand for each month is added to the previous maximums on the dials when the meter is reset at the end of the month.

Except for the resetting device and the cumulative gear train, pointers, and dials, the cumulative demand register is the same in principle and operation as the indicating demand register. See Figures 8-5 and 8-6.

Recording Type

Recording watthour demand meters are usually designed for use in polyphase circuits with instrument transformers. They keep a permanent record of the demand for every demand interval. Instead of driving a pointer-pusher mechanism, the meter rotor drives, through shafting and gearing, a pen which moves across a chart a distance proportional to the kilowatt demand. At the end of the interval, the pen is returns to zero.

The chart is moved a uniform amount each interval and the date and hours of the day are marked on the left side. Thus, the chart shows at a glance the demand which has occurred in each interval of each day.

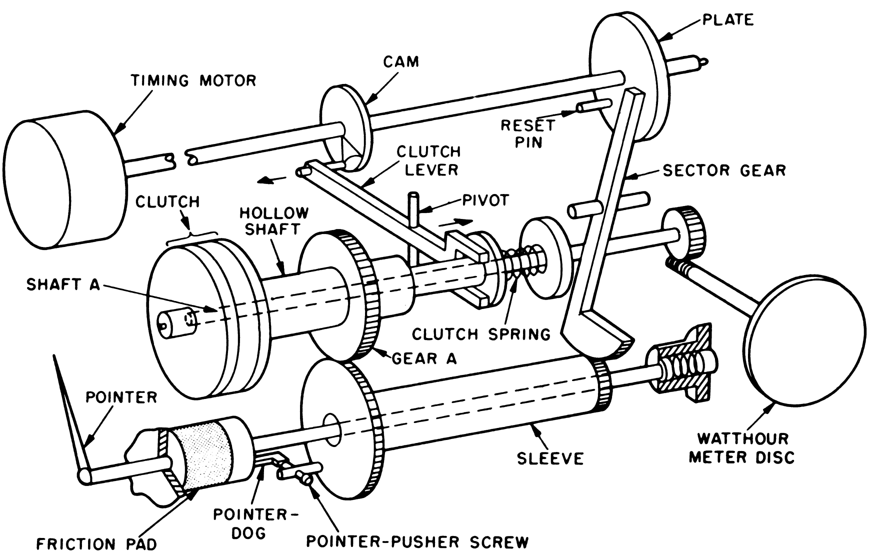


Figure 8-5. Simplified Schematic of the Interval-Resetting Mechanism of an Indicating Watthour Demand Meter.

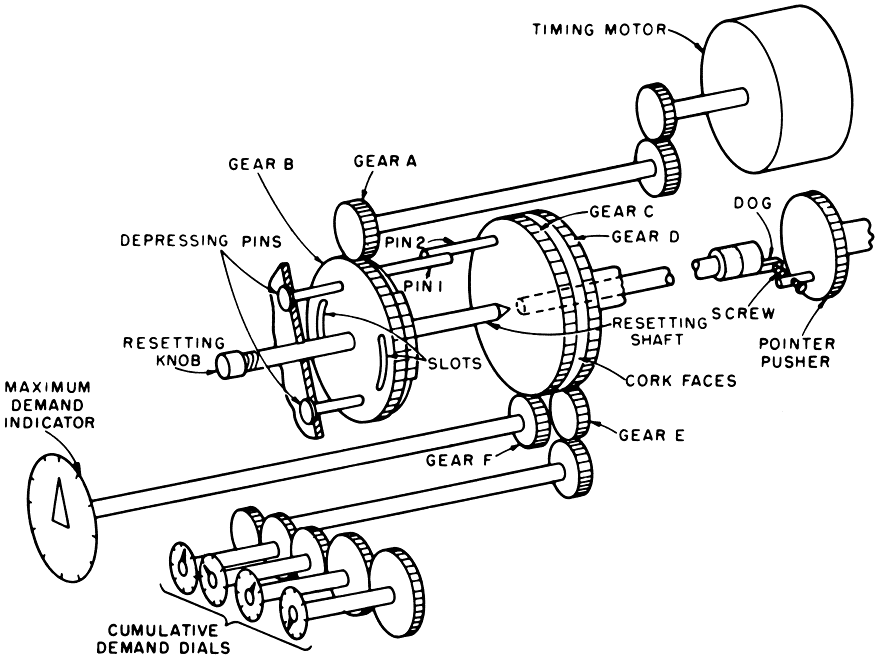


Figure 8-6. Simplified Schematic of the Cumulative-Resetting Mechanism of a Cumulative Watthour Demand Meter.

Register Differences

There are two major differences among the various types of indicating demand registers: (1) the method of engagement between the demand pointer-pusher and the driving mechanism; (2) the method of resetting the pointer-pusher.

The method of engagement between the demand pointer-pusher and the driving mechanism may be by means of a flat disk clutch with felt facings or by means of a purely metal-to-metal contact, such as three fingers engaging the circumference of a disk. The clutch is released at the end of the demand interval, separating the pointer-pusher from the watthour meter driving gears so that the pointer-pusher can be returned to zero.

The return of the pointer-pusher to zero is done automatically in a minimum length of time by means of one of the following methods:

1. The demand interval timing motor;
2. A spring which is wound up during the demand interval;
3. A gravity reset mechanism which becomes operative as the clutch is released;

Re-engagement of the pointer-pusher mechanism occurs and the meter rotor begins its movement of the pointer-pusher upscale for the next demand interval.

Another form of block-interval demand register was announced in 1960. In this register the fixed scale, sweep-pointer type of demand indication was replaced by three small dials which show kilowatts demand in the same manner as the conventional kilowatthour dials. The register timing mechanism operates in the usual manner and resets the demand pointer driving and sensing pins to zero at the end of each demand interval. The driving and sensing pins do not change the demand reading unless a higher demand occurs, in which case the pins engage the demand pointers at the old value and drive them to the new value. The demand pointers are reset to zero by the meter reader operating the reset mechanism. This type of register provides a higher demand range allowing greater flexibility in application and improved accuracy at less than full scale.

Register Application

The load range of watthour meters has been extended over the years until the 1961 design of self-contained meters is capable of carrying and measuring loads with currents up to 666% of its test-ampere value. Naturally, the full-scale values of demand registers had to keep pace with the meter capabilities. Use of a single fixed scale for demand registers, which had a $666^2/_3$% full-scale value, would lead to serious errors in demand measurement. Nominal single-pointer demand register accuracy is 1% of full-scale value; if the high scale were used on meters with lower capacity or on low-capacity services, the resulting values would produce low-scale readings with possible high error rates. Consequently, a number of different full-scale demand values are available in this type of register, so that with proper register selection, the demand readings will be above half-scale to give good accuracy.

Manufacturers normally supply registers with three overload capacities. These are capable of measuring demand with maximum load currents of $166^2/_3$%, $333^1/_3$%, and $666^2/_3$% of the meter rated test-ampere values. Some manufacturers apply class designations of 1, 2, and 6, respectively, to these register capacities. The full-scale demand values are available with the various register ratios normally used on a manufacturer's meters, thus allowing selection of a register with proper consideration being given to meter rating and service capacity. The various full-scale kilowatt values are obtained by changes in the gearing to the demand pointer-pusher with no change in register ratio, which is another indication of the independence between the kilowatthour gear train and the demand gear train in a demand register.

When using single-range demand registers, it is necessary to change the entire register to obtain a change in full-scale kilowatt value or class. The new dual-range registers are designed to allow operation in two different classes with a single unit. A gear shifting mechanism is provided which changes the full-scale demand value. When this shift is made, the demand scale or kW multiplier should be changed to correspond. The dual-range register may, therefore, be changed by a simple operation to perform in either of two different register classes without a change in register ratio or kilowatthour multiplier.

KILOVAR OR KILOVOLTAMPERE DEMAND METER

It should be noted that the mechanical and the electronic type of demand meters can also be used to measure kiloVAR demand or kilovoltampere demand by connection of the watthour meter voltage circuits to appropriate phase-changing voltage auto-transformers or internal electronic phasing shifting circuits.

In one type of recording kilovoltampere demand meter, one method is used to obtain the kilowatt demand and kilovoltampere demand, as well as instantaneous power factor and integrated kiloVARhours, kilovoltamperehours, and kilowatthours in the same instrument.

The meter consists of two watthour meter elements with a separate reactive compensator (auto-transformer) provided so that one set of the watthour meter elements of the combination can be connected to measure kiloVARhours.

The values of kilovoltampere demand and instantaneous power factor are obtained by mechanical vector addition of active and reactive components of the power as shown in the equation $VA = \sqrt{W^2 + VAR^2}$.

This method of demand measurement is described in Chapter 9, "KiloVAR and Kilovoltampere Metering."

PULSE-OPERATED MECHANICAL DEMAND METER

Pulse-operated mechanical demand recorders may be used in single circuits or in totalizing systems to determine the combined demand of several circuits. Distinctive features of pulse-operated demand recorders are described in the manufacturer section. The pulse operated demand recorders may be located close to the meters which supply the pulses or they may be located some distance away with the pulses being transmitted over telemetering circuits.

The basic elements of a pulse-operated mechanical type demand meter are the demand-registering mechanism and the timing or interval-establishing mechanism. The demand-registering mechanism is energized through the remote actuating pulse generator. The same or, in some cases, a different source of voltage drives the timing mechanism and, in recording instruments, the chart drive mechanism when it is motor operated.

As the pulse initiator opens and closes, the operating current is intermittently interrupted, energizing and de-energizing the actuating assembly of the registering mechanism. This actuating assembly, for different types of meters, may consist of an electromagnet, a solenoid, or a synchronous motor and contact arrangement. In either scheme the pulses received by the demand meter are converted to mechanical rotation, which advances the position of an indicating pointer, pen or stylus, or printing wheels, depending on the type of meter.

The timing mechanism, usually motor-driven, establishes the interval through which the registering device is allowed to advance. At the end of the predetermined demand interval, it effects a disengagement of the registering mechanism and returns the indicator pusher or recording device to a zero position ready to begin registration for the new demand interval.

Pulse-Operated Electronic Demand Recorders

These demand recorders are similar in principle to mechanical demand recorders, but having no moving parts they can accumulate pulses at a faster rate and provide better resolution and accuracy. Electronic demand meters are described later in this chapter.

Indicating Type

As in the direct-driven indicating meters, the pulse-operated sweephand indicating demand meter provides no record of demand when the demand pointer is manually reset at the end of the reading period.

Recording Type

Strip-chart and round-chart recorders produce a permanent demand record. Several styles of charts are available to suit particular applications. They may vary in scale marking, finish (for stylus or ink), duration, or other features.

Paper-Tape Type

The tape type of pulse-operated demand meter totals initiated pulses for each demand interval and may record these pulses on paper tape as a printed number or as a coded punching. Either form may be read manually or translated automatically to determine the demand values for each period.

THERMAL DEMAND METERS

Thermal demand meters are essentially ammeters or wattmeters of either indicating or recording type. Unlike the ordinary ammeter or wattmeter, which immediately indicates any change of load, the thermal demand meter responds very slowly to load changes. See Figure 8-7. Therefore, the indication of a thermal demand meter at any instant depends not only on the load being measured at that instance but also on the previous values of the load. It represents, then, a continuous averaging of the load and so constitutes a measure of demand.

A block-interval-type demand meter, as well as a thermal demand meter, measures demand by averaging the load over a period of time. In block-interval demand, the average is a straight arithmetic average over a definite period of time with equal weight given to each value of load during that period.

In thermal demand, the average is logarithmic and continuous, which means that the more recent the load the more heavily it is weighted in this average and, as time passes, the importance of any instantaneous load value becomes less and less in its effect on the meter indication until finally it becomes negligible. While there may be some theoretical preference for logarithmic as compared to block demand, there is little difference in practice since the measurement of demand by either method gives comparable responses. It is true that on certain types of loads where severe peaks exist for short periods, considerable difference may result between the indication of block and logarithmic type meters. There can also be considerable differences between the readings of two similar block demand meters due to peak splitting if they do not reset simultaneously.

Thermal watt demand meters are commonly combined with watthour meters to form a single measuring unit of energy and demand. In such combination meters, the potential to the thermal demand section may be supplied from separate small voltage transformers in the meter or from secondary potential windings on the potential coils of the watthour elements. Current to the thermal elements may be the entire load current or small through-type current transformers that use the line conductors as single-turn primaries to reduce it.

The advantages of the dual-range feature versus single-range thermal demand meters are the same as previously described for the dual-range mechanical demand register.

The discussion that follows covers the theory of operation of the single-range thermal demand meter.

Operation

The general principle of operation of a thermal demand meter is shown in Figure 8-7. The bimetallic coils, each of which constitutes a thermometer, are connected to a common shaft in the opposing directions. The outer ends of these coils are fixed in relation to each other and to the meter frame. The shaft, supported between suitable bearings, carries a pointer. As long as the temperature of the two coils is the same, no motion of the pointer results even though this temperature changes. The tendency of each of these coils to expand with rising temperature of one coil is higher than that of the other, resulting in a deflection of the pointer which is proportional to the temperature difference between the coils. The pair of coils constitutes a differential thermometer which measures a difference of temperature rather than an absolute temperature.

A small potential transformer in the meter has its primary connected across the line and its secondary line connected in series with two non-inductive heaters. Each heater is associated with an enclosure and each enclosure contains one of the bimetallic strips. With potential only applied to the meter, a current $E/2R$ circulates through the heaters as shown in Figure 8-8. This circulating current is directly proportional to the line voltage and passes through each one of the heaters. With only the potential circuit energized, heat is developed in the first heater at a rate:

$$W_1 = \left(\frac{E}{2R}\right)^2 \qquad R = \frac{E^{\,2}}{4R}$$

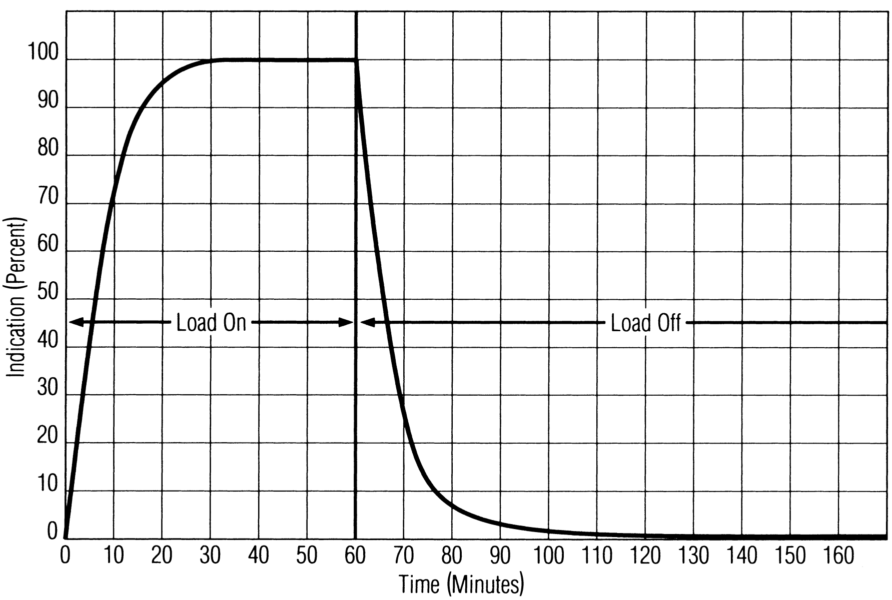


Figure 8-7. Time-Indication Curve of a Thermal Watt Demand Meter.

and in the second heater:

$$W_2 = \left(\frac{E}{2R}\right)^2 \qquad R = \frac{E^2}{4R}$$

Analyze this same circuit with the current section energized with line current I. This line current enters the mid-tap of the voltage transformer secondary which is very carefully proportioned so as to cause the line current to divide into two equal parts. Now $I/2$ passes through the heaters in parallel, then adds together to form again the line current I. Considering only the line current, heat is developed in the first heater at a rate:

$$W_1 = \left(\frac{I}{2}\right)^2 \qquad R = \frac{I^2R}{4}$$

and in the second heater:

$$W_2 = \left(\frac{I}{2}\right)^2 \qquad R = \frac{I^2R}{4}$$

Note that the currents $E/2R$ and $I/2$ add in one heater but subtract in the other. Heat is developed in the first heater at a rate:

$$W_1 = \left(\frac{E}{2R} + \frac{I}{2}\right)^2 \qquad R = \left(\frac{E^2}{4R^2} + \frac{EI}{2R} + \frac{I^2}{4}\right)R$$

and in the second heater:

$$W_2 = \left(\frac{E}{2R} - \frac{I}{2}\right)^2 \qquad R = \left(\frac{E^2}{4R^2} - \frac{EI}{2R} + \frac{I^2}{4}\right)R$$

subtracting:

$$W_1 - W_2 = 2\frac{EI}{2R}R = EI$$

If the temperature rise in each enclosure is proportional to the heat input, the temperature difference between the two enclosures will be proportional to the difference between these two values or simply EI. Since current and voltage are taken as instantaneous values, the temperature difference is proportional to the power measured regardless of power factor. If the current and voltage had been taken as effective, or root-mean-square values, then the addition and subtraction of the circulating current and the line current would have been phasorial, which would introduce a cosine term and would show that the temperature difference would be proportional to $EI \cos \theta$ or again the power measured by the meter.

It should be noted that in the wattmeter the deflection is proportional to the first power of EI cos θ and the wattmeter scale is approximately linear.

To obtain different capacities of meters, the basic element may be shunted or supplied through a current transformer. (The current circuit is non-inductive since the heaters are non-inductive and the current flows in opposite directions through the secondary of the voltage transformer.) While some demand meters carry line current, shunted or unshunted through the heater elements, the use of the current transformer permits carrying the design of the meter to higher current ranges and has the advantage of increasing the flexibility of design and permitting operation of the heater itself at a lower insulation level, since it is completely isolated from line voltages. When current and voltage transformers are employed, the resistance value of the heater circuits may be increased to take advantage of smaller connecting leads and lower thermal losses.

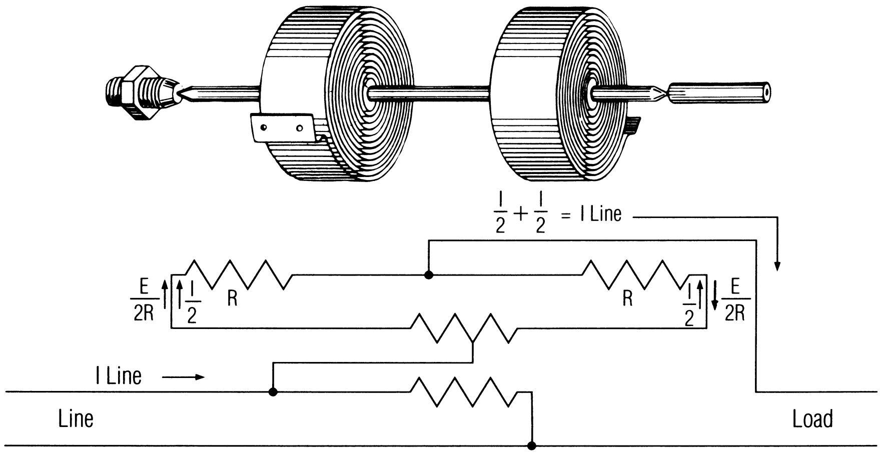


Figure 8-8. Two-Wire Watt Demand Meter with Current and Potential Circuits.

PULSE-OPERATED ELECTRONIC DEMAND RECORDERS
SOLID-STATE DEMAND RECORDERS

Solid-state recorders use microelectronic circuits to count and store incoming pulses from the watthour meter. Low-power, large scale integrated (LSI) circuits provide the solid-state recorders with new capabilities. Tamper detection, on-site data listing and display, and built-in modems which allow remote access to the demand recorder data via the telephone network, are some of the functions that a solid-state recorder can provide.

Solid-state recorders have given rise to complete electronic metering systems that provide utilities with the ability to collect remote metering data that in turn improves utility cash flow and prevents revenue loss by the early detection of defective metering equipment.

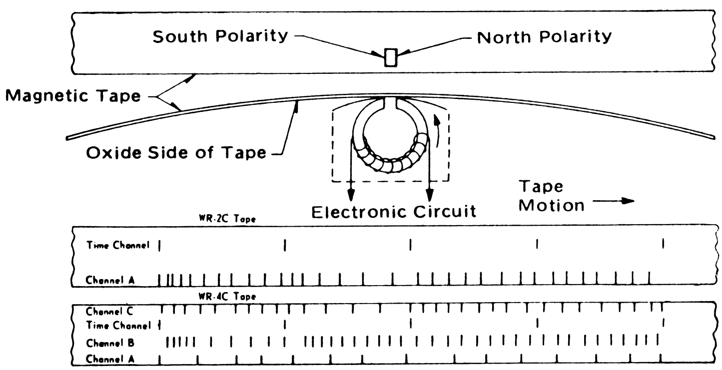


Figure 8-9. Recording Process, Principles of Operation.

Figure 8-10 is a block diagram of a typical solid-state demand recorder. The circuits and methods employed in this device which counts and stores pulses are representative of the use of solid-state technology in a demand recorder design and are described further below.

Computer

The control of a solid-state recorder is performed by the main computer which consists of a Central Processing Unit (CPU) with Read Only Memory (ROM) and Random Access Memory (RAM).

The CPU fetches and executes program instructions stored in ROM and RAM. Generally speaking, the stored program instructs the CPU to perform three important tasks: maintain time, count, and store incoming energy pulses from the watthour meter pulse initiator.

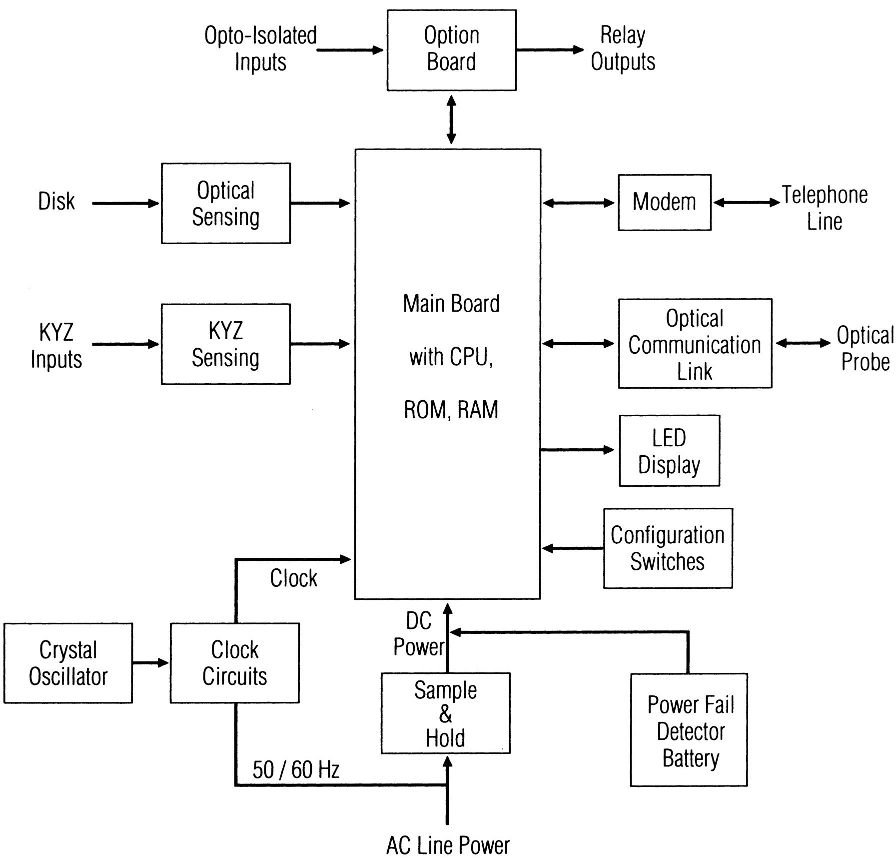


Figure 8-10. Solid-State Demand Recorder, Block Diagram.

Timekeeping

Solid-state demand recorders can be programmed to accommodate a variety of demand interval periods. Intervals of 1, 5, 15, 30, and 60 minutes are commonly applied throughout the electric utility industry.

When the recorder is energized from system AC sources, it maintains time by tracking the line frequency of the utility system. If system voltage is lost or drops below a predetermined value, a crystal oscillator powered by a battery takes over as the source for timing pulses.

Timekeeping, whether using the 60 hertz line frequency or the oscillator frequency, is generally performed by the CPU. When powered by the AC line, the CPU senses and counts each zero-crossing of voltage. Two zero-crossings indicate one cycle, and 3,600 cycles indicate an increment of one minute which can be the basis for demand interval timing and a "real time" clock. When powered by the internal battery, the CPU is programmed to count pulses from the crystal and to establish the time reference. In some designs, a special clock chip circuit develops the time reference.

Pulse Accumulation and Storage

The CPU counts pulses sent by the watthour meter pulse initiator and stores the count in RAM. Solid-state demand recorders are available with a variety of optional input channels and data storage configurations. Commonly encountered recorder configurations provide many data input channels and sufficient RAM for demand interval data storage. There is generally ample amount of RAM to store many months of information.

Typically, each solid-state memory location corresponds with one demand interval. The limitation to the number of pulses stored per interval is the byte size of the digital storage location (i.e., 12 bits store 4,096 pulses or 16 bits store 65,536 pulses.)

Power Supply

A power supply transforms system AC line voltages (e.g., 120 VAC, 240 VAC, or 277 VAC) into the regulated low-power DC voltages required by the solid-state circuits. Supply voltages between 5 and 15 VDC and currents of less than one ampere are typical power requirements of solid-state recorders.

Since the AC power to the recorder can sometimes be interrupted, recorder designs include a backup source of electrical power for use during power outages. Rechargeable nickel-cadmium batteries, non-rechargeable lithium cells, super-caps, and lead acid cells are common battery technologies used in recorders.

Display

Some demand recorders are equipped with displays for on-site presentation of metering information. Liquid crystal display (LCD) technology is the most popular. LCDs operate at very low power and are readable even in direct sunlight.

Output Circuits

Solid-state recorders have outputs for functions such as:

1. *Load Control*—Relay or solid-state outputs to control external electrical loads in accordance with a pre-programmed time schedule;

2. *Demand Threshold Alert*—Relay or solid-state outputs to indicate that current demand exceeded a programmed demand level;
3. *Printer Output*—Solid-state outputs to a printer for on-site printing of metering information;
4. *End-of-Interval Indicator*—Relay or solid-state output to indicate completion of a demand interval;
5. *Pulse Input Indicator*—Solid-state output, usually connected to an indicating lamp, to indicate that incoming pulses from a pulse initiator are being received by the recorder.

Self-Monitoring Capability

Many solid-state recorders are equipped with self-monitoring diagnostic programs which continuously monitor critical operations. These diagnostic checks may test the RAM, ROM, program execution, and need for battery-backup. If the fault is serious, the self-monitoring program may trigger an orderly shutdown of recorder operations.

Communications

Information stored by solid-state recorders can be loaded automatically into portable terminals using an optical communication port or sent by various communications techniques to a centralized computer system.

Physical Description

Solid-state recorders are generally available in a number of packaging configurations. Figure 8-11 shows a recorder that is mounted under the cover (glass) of the watthour meter along with the pulse initiator. This configuration is generally used when internally generated pulses are to be recorded (i.e., watts and at VAR single locations.) This packaging style provides for simple, plug-in socket installation without the need for external wiring.

An alternative enclosure is shown in Figure 8-12. This configuration is often used when multiple channels of information are to be recorded and/or totalized such as revenue metering of a multi-unit industrial complex.

ELECTRONIC TIME-OF-USE DEMAND METERS

Rising costs, environmental concerns and regulatory mandates have prompted many utilities to establish load management programs. A example of one such program is time-of-use (TOU) metering.

Unlike a conventional tariff which charges the user for the quantity of energy used, a time-differentiated rate structure also considers *when* the energy is used. The user is charged a higher price for energy used during time periods when generation and delivery costs for the utility are higher.

Introducing the requirement to measure when energy is used increases the complexity of the meter. Mechanical gear trains controlled by electronic circuits were typical of the earliest TOU meters. These electromechanical meters have been replaced with completely electronic meters. See Figure 8-13.

Figure 8-11. Single Channel Recording Meter.

Time-of-use meters are designed with the flexibility to accommodate a variety of rate structures defined by the utility. They are often equipped with programmable displays and rate schedules which accommodate energy (kilowatthours) and demand (kilowatt) registration for up to four daily rate periods. Some meter displays can be programmed to show the current rate of consumption or cumulative consumption for demand intervals. For some meters, the measurement of rolling demand can be selected, and rolling demand will be calculated and displayed for programmed subintervals.

The indicated demand values can be reset (zeroed) by a mechanism mounted on the meter cover or by an accessory device, such as a portable reader programmer or internally generated self-read, self-reset, feature.

ELECTRONIC DEMAND REGISTERS

Electronic demand registers were made practical with the development of non-volatile memory. This type of memory can store billing data and programming constants and retain this information during power interruptions without need for a battery. When the supply voltage drops below a minimum value, programming constants and billing data are transferred to the non-volatile memory from which it is recalled when power is restored.

The heart of the electronic register is a microcomputer that processes data. Figure 8-14 is a simplified block diagram of an electronic demand register showing the typical inputs to, and outputs from, the microcomputer.

Meter Disk Sensing

When used with an electromechanical meter, an electronic register must sense disk rotation. Most electronic registers use optical sensors which produce several pulses for each disk revolution by sensing marks on the disk, or by detecting motion of a shutter mounted on the meter disk shaft.

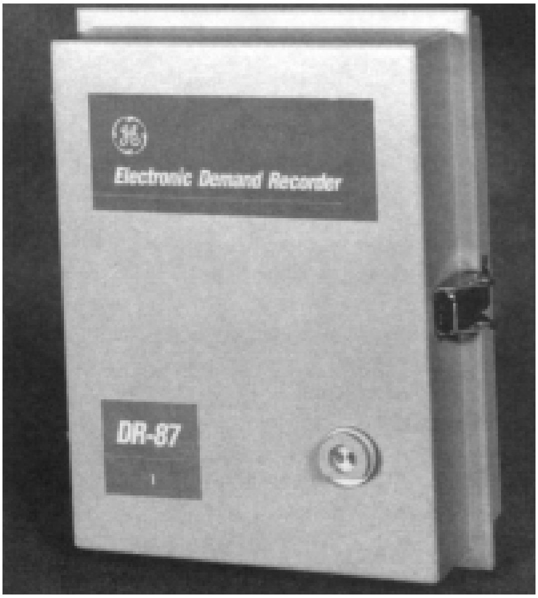


Figure 8-12. Solid-State Demand Recorder.

When built into a totally electronic meter, the register receives pulses directly from the meter measurement circuits. Each pulse represents a value of energy consumed. Regardless of how pulses are generated, the microcomputer is programmed to convert each incoming pulse into an energy value.

Figure 8-15 illustrates a typical electromechanical meter. These meters are also available as models without dials and mechanical registers.

Digital (Pulse) Processing Microcomputer

Electronic demand registers process incoming pulses and perform the following functions:

1. Establish accurate and precise time intervals;
2. Count and accumulate pulses, convert pulse-counts into engineering units, store, and display data;
3. Count and accumulate pulses for successive demand intervals, detect and store the interval in which power consumption was maximum, and, at the end of each interval, reset the count to zero in preparation for the next interval.

Programming

Electronic registers may be pre-programmed with parameters such as:

1. The energy value of each input pulse;
2. Demand interval length (for fixed, or rolling calculations);
3. Type of demand display (maximum, cumulative, continuously accumulative);
4. Display format (how many digits, and the decimal location);
5. Items to be displayed;
6. The function of the output switch (e.g., pulse initiator, end-of-interval, demand threshold alert);

Figure 8-13. Time-of-Use Demand Meter.

Making changes in software allows one hardware design to serve a variety of applications. Program changes are analogous to a mechanical meter manufacturer selecting different gear ratios, dial scales, and timing motor speeds.

Rolling-Demand Capability

Mechanical registers use external pulse-operated demand recorders and translators to perform rolling-demand calculations. Electronic registers may have the ability to calculate rolling demand eliminating the need for separate pulse-operated recorders and subsequent translation of the data.

Rolling demand, also called "sliding window", is a process by which intervals are divided into a fixed number of subintervals. Instead of calculating demand at the end of each interval, the calculation is performed at the end of each subinterval, and totaled and averaged for the entire interval. Greater accuracy results and in some cases parameters such as maximum demand for an interval can change. For example, in the two curves shown in Figure 8-16 the power consumption is the same, but maximum demand is greater when subinterval data is the basis for the calculation. Notice that the interval length does not change and subinterval demand calculations always use the most recent consecutive subintervals which make up the interval.

Display Modes

Electronic demand registers display several types of information. The normal display mode presents information needed on a regular basis such as data related to billing. An alternate mode can display information useful to field technicians or shop personnel for verifying register program constants. A test mode provides information for testing, like demand run up.

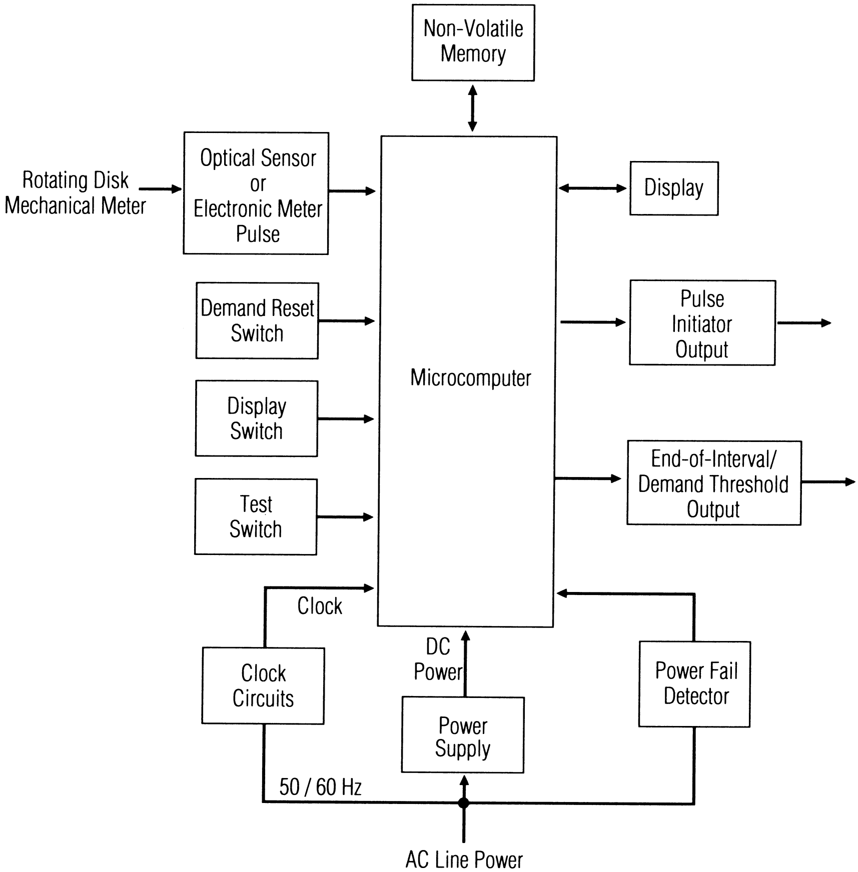


Figure 8-14. Electronic Demand Register, Block Diagram.

Output Signals

Most electronic demand registers are capable of providing output signals for communicating with external monitoring and control equipment. These output signals are generally a relay closure activated by the microprocessor. Outputs can include: pulse initiator output (KYZ), end-of-interval signal, and demand threshold alert.

Demand Accuracy

The accuracy of mechanical and thermal demand registers is typically expressed as a percent of full scale value. With these meters there is a fixed magnitude of error which can be present anywhere on the scale. The lower on the scale a reading is taken, the larger this fixed error is as a percent of actual reading. To minimize the effect of this error, meters are supplied with several full-scale values and, by proper register selection, readings can be taken above half-scale and provide reasonable accuracy. Manufacturers normally supply mechanical registers with three overload capacities designated as Class 1, 2, and 6 to indicate register overload capacity.

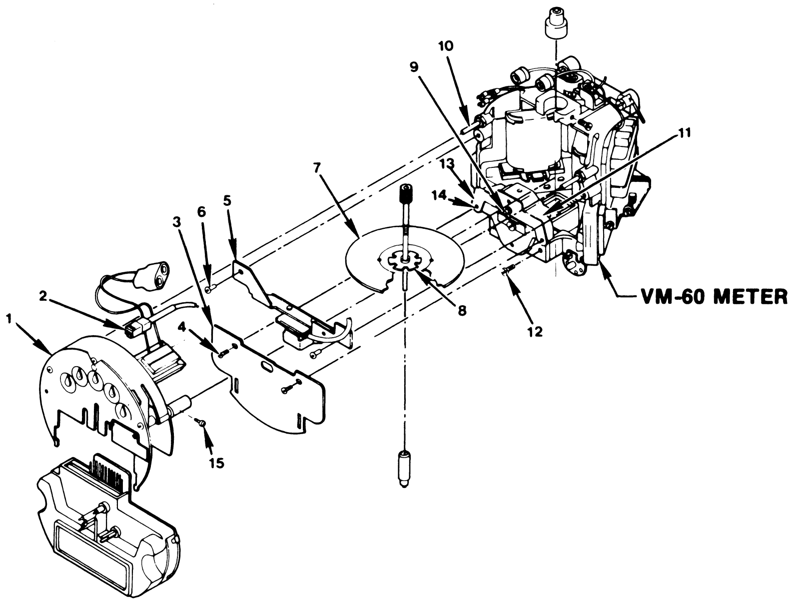


Figure 8-15. Electromechanical Meter with Electronic Demand Register.

Electronic demand registers are pulse-operated; the electronic counter receives a fixed number of pulses per disk revolution. The accuracy of electronic registers is typically expressed in terms of a pulse-count deviation over a given period of time. With electronic registers, accuracy is always within a few tenths of a percent, even at readings of less than 50% of "scale point." With electronic registers, it is not necessary to designate register classes and readings are equally accurate throughout the scale range.

Demand Resolution

Many electronic registers provide resolution of one or more places to the right of the decimal point. This increased resolution makes it possible to capture readings closer to the actual demand. In most cases, the improvement in resolution yields a higher reading.

Improved Testability

Mechanical demand registers are tested by inputting enough meter disk revolutions, directly or from a test board, to drive the demand pointer(s) to a reading above 25% of full scale, within the time window of the register's demand interval. If adjustment is required the test is repeated, requiring several demand intervals of time to complete the test procedure.

Electronic registers are not adjusted or calibrated. If a register is defective, the electronic module is simply replaced. Registers which incorporate a "Test Mode" further assist the test by injecting a few test pulses to verify the demand calculations are being performed correctly.

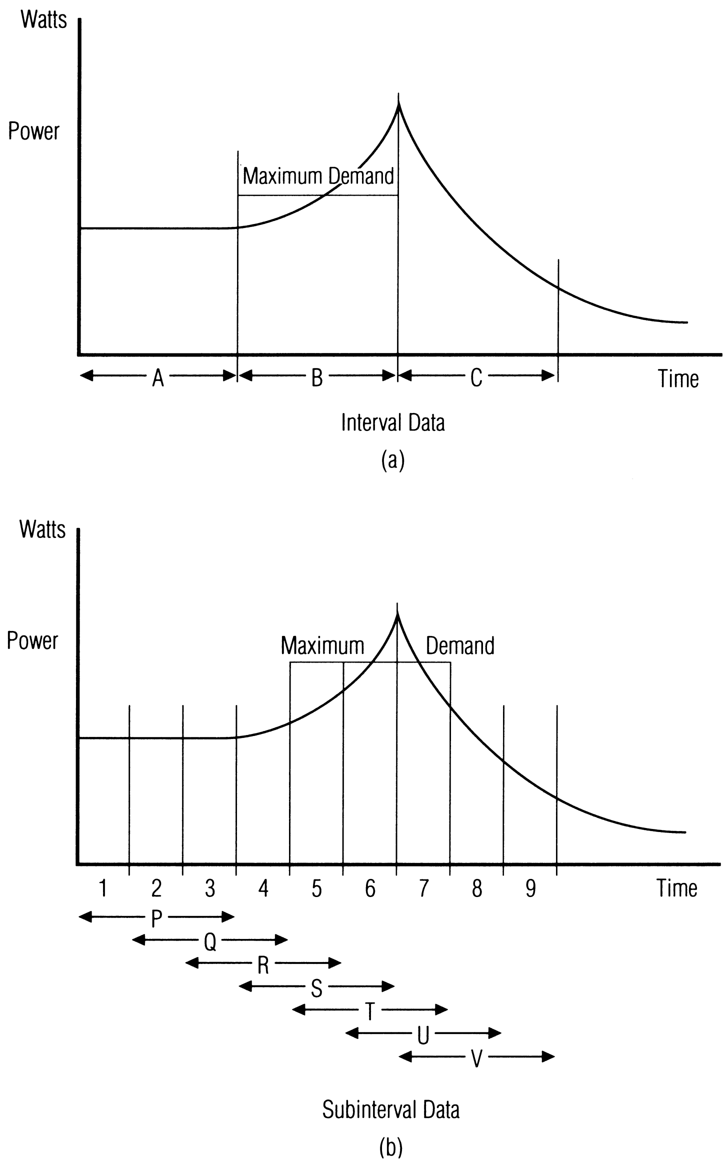


Figure 8-16. Fixed-Demand, Rolling-Demand Calculation.

Electronic Demand for Multi-Function Meters

Multi-function demand meters (registers) log and display demand and energy quantities for bi-directional, multi-function meters. Examples of the parameters displayed are kWh, kW, kVARh, kVARd, kQh, kQd, kV^2, power factor, average current and voltage per phase, and various maximum values with the appropriate times and dates.

Some multi-function registers have TOU functions with sufficient internal memory to perform interval recording. Some multi-function registers display energy and reactive power in four-quadrant values, such as forward and reverse kWh and kVARh.

Multi-function registers are similar to single-function registers, in that both monitor time, date, and other calendar data for a billing period.

CHAPTER

9

KILOVAR AND KILOVOLTAMPERE METERING

THE DESIGN OF an electric utility system is based on the total kilovolt-ampere (kVA) load to be served. The kVA load reflects equipment sizing requirements and provides an indication of losses in the system caused by the loads. This is defined as the product of the rms voltage and the rms current. In a system where the voltages and currents have no noise or harmonics, kVA may be regarded as consisting of two compo-nents: kilowatts (kW) and kiloVARs (kVAR). Often revenue is derived from only one of these components, kilowatts. The ratio of kW to kVA is the power factor. It may also be defined as the ratio of power-producing current in a circuit to the total current in that circuit:

$$\frac{\text{kW}}{\text{kVA}} = \text{Power Factor} = \frac{\text{KW Current}}{\text{Total Current}}$$

A poor ratio of kW to kVA, low power factor, has a serious effect on the economic design and operating costs of a system. When power factor is low and rates are based only on kW, the utility is not being compensated by that consumer for all the kVA it is required to generate, transmit, and distribute to serve that customer. Instead, these costs are spread throughout the consumers subject to that rate. To more equitably distribute these costs, rate schedules have been established which take into consideration the power factor of the load being measured. These schedules take a variety of forms, but in general, they penalize poor power factor or reward good power factor.

The principal purpose of kVAR and kVA metering is to support these power factor rate schedules by the measurement of one or more of the quantities involved: power factor, kVA, kVAhours (kVAh), kiloVARs (kVAR), or kiloVARhours (kVARh).

As more and more sophisticated electronic loads are added to the system (such as adjustable speed drives and computers), these loads cause harmonics and other noise to be added to the system. Instead of having a single frequency (60 Hz), the voltage and current waveforms consist of several frequencies (harmonics) superimposed on each other. The harmonic currents are part of the total current and impact copper losses and equipment sizing of the system.

In three phase systems, harmonic currents can add in the ground wire instead of canceling, resulting in grounding problems. The harmonic voltages produce larger eddy currents in magnetic materials resulting in greater core losses and impacting equipment sizing. Harmonics can also cause errors in historic metering equipment or may not be measured at all in historic metering equipment. Metering equipment, techniques, and simplifying assumptions used to meter power were adequate because these harmonic loads were very limited and any meter technology limitations had little impact.

Today and in the future, these harmonic loads must be carefully reviewed and new metering technologies used as needed to accurately measure these values. In some cases, for historical reasons, the older techniques must be emulated to achieve consistent results although their validity is questionable. Some may believe that existing rates dictate that historical techniques be emulated. Others may feel that applying newer metering techniques will cause commercial issues with their customers. These issues require care to avoid measurement or other problems.

BACKGROUND

Historic measurement techniques assumed all currents and voltages were perfect sine waves. Some instruments and methods will be in error if the sine wave is distorted. The current required by induction motors, transformers, and other induction devices can be considered to be made up of two kinds: magnetizing current and power-producing current.

Power-producing current or working current is that current which is converted into useful work. The unit of measurement of the power produced is the watt or kilowatt.

Magnetizing current, which is also known as wattless, reactive, quadrature, or non-working current, is that current which is required to produce the magnetic fields necessary for the operation of induction devices. Without magnetizing current, energy could not flow through the core of a transformer or across the air gap of an induction motor. The unit of measure for magnetizing voltamperes is the VAR or kiloVAR. The word “VAR” is derived from “voltamperes reactive” and is equal to the voltage times the magnetizing current in amperes.

The total current is the current which would be read on an ammeter in the circuit. It is made up of the magnetizing current and the power producing current which add phasorially (vectorially).

$$\text{Total Current} = \sqrt{(\text{kW current})^2 + (\text{kVAR current})^2}$$

Similarly,

$$\text{kVA or Apparent Power} = \sqrt{(\text{kW}^2 + \text{kVAR}^2)}$$

These relations are easily shown by triangles. See Figure 9-1.

In a polyphase service, historically the kW for the service was measured with one meter and kVAR was measured with a second meter. As such, the kW for each phase were combined resulting in a net kW and the kVAR were combined for each phase resulting in a net kVAR. These net values were then combined vectorially to produce kVA per the above equation. This was referred to as the vectorial calculation of voltamperes or simply vectorial VA.

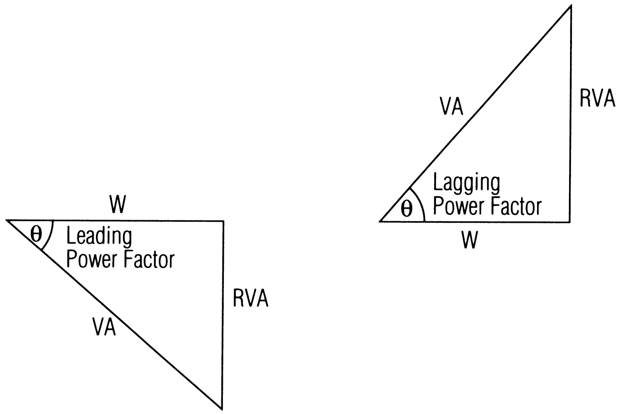


Figure 9-1. Power Triangles (Single-Phase or Three-Phase).

Once harmonics or phase imbalances are encountered in the circuit, the vector sum equations shown above begin to lose accuracy. As the harmonic content increases, they become increasingly inaccurate. It becomes necessary to use meters that can calculate true rms readings in order to capture the total current. The same is true for voltamperes. By taking true rms readings for both voltage and current on each phase, the total voltampere load can be determined. Summing the VA on each phase is called an arithmetic calculation of voltamperes or simply arithmetic VA. In a four-wire circuit arithmetic VA is defined as:

$$[\text{kVA Total} = E_a{*}I_a + E_b{*}I_b + E_c{*}I_c]$$

True rms response is important when accurate voltampere metering of loads with distorted waveforms is needed. Arithmetic summing results in more accurate metering than vector summing when voltage, power factor, or load imbalance exists. Vector summing is required to obtain voltamperes when separate kWh and reactive meters are used to feed data collecting equipment. Under all voltage and load conditions, the arithmetic sum will always be equal to or greater than the vector sum and will more accurately meter the true voltampere load.

Referring to Figure 9-2, vector kVA is the straight line from one to four. Arithmetic kVA is the sum of line segments one to two, plus two to three, plus three to four. By inspection, the vector kVA sum is less than the sum of the individual kVAs of the individual phases.

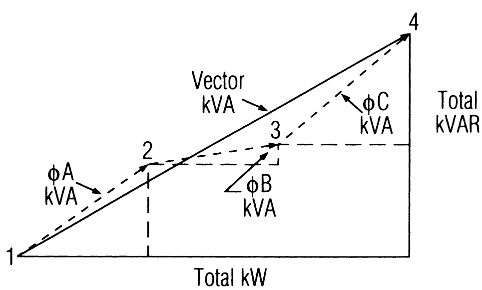


Figure 9-2. Comparison of Vector and Arithmetic Summing.

PHASOR RELATIONSHIPS

In a single phase circuit which contains only resistance, the current *I* is in phase with the voltage *E*. See Figure 9-3a. In this ideal case, watts equal voltamperes.

When reactance (inductive or capacitive) is introduced into the circuit, the current is displaced or shifted out of phase with the voltage by an angle θ, depending on the relative amounts of resistance and reactance. Normally the reactance is inductive and the current *I* lags the voltage *E*. See Figure 9-3b. If the reactance is capacitive, the current will lead the voltage.

The current *I, in a two wire circuit* can be considered to be made up of two components: I_W which is in phase with *E* and which produces watts; and I_V which is displaced 90° from *E* and produces reactive voltamperes. By trigonometry:

$$I_W = I \cos \theta$$
$$\text{and } I_V = I \sin \theta$$

then:

$$E \times I \cos \theta = \text{watts}$$
$$\text{and } E \times I \sin \theta = \text{VAR}$$

Again by trigonometry, the cosine varies from zero for an angle of 90° to one for an angle of zero degrees. As power factor improves, the displacement angle becomes smaller. When the power factor is unity, watts and voltamperes are equal to each other and reactive voltamperes equal zero.

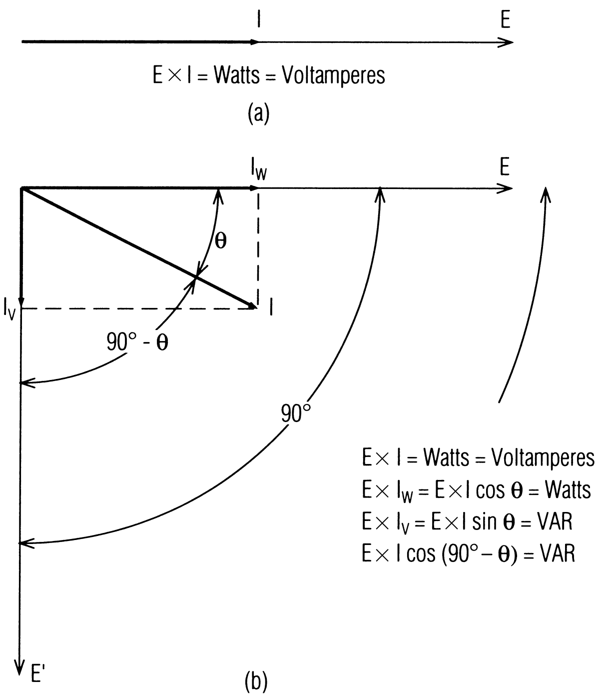


Figure 9-3. Phasor Relationships.

VOLTAMPERE METERING

As previously stated, voltamperes is simply the product of the voltage and current without consideration of the phase angle. This is shown in the following definition:

$$\text{Voltamperes} = |V|*|I|$$

Where the |V| is the rms value of the voltage and |I| is the rms value of the current. Note that there is no mention of phase angle. This definition is accurate under all waveform conditions including the presence of noise and harmonics on the line. Another method of calculating VA when the waveform has 60 Hz only is to combine Watts and VAR vectorially,

$$\text{Voltamperes (vector)} = \sqrt{\text{watts}^2 + \text{VAR}^2}$$

This can be seen from the familiar power triangle illustrated in Figure 9-4.

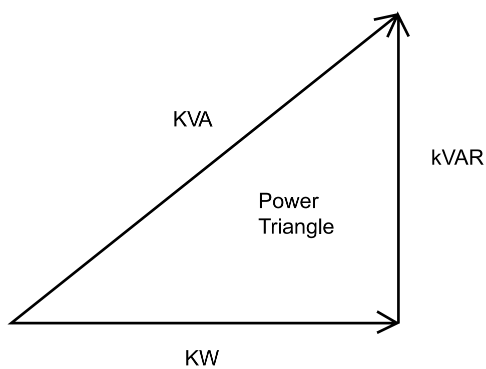


Figure 9-4. Voltamperes Power Triangle.

This method of calculating VA is called Vector VA.

Electromechanical kVA Metering

Thermal Demand Meters for kVA Apparent Power (Traditional Method)

Conventional electromechanical meter technology does not provide for apparent energy billing meters. (Expensive laboratory instruments could measure apparent energy but these are not suitable for common billing application by electric utilities.) Where apparent power measurements were required by some utilities for the purposes of billing, such measurements were made with thermal demand meters. These meters were constructed using conventional energy meters, to which were attached temperature sensing devices containing heater elements—one heater connected to the voltage and one to the current circuits.

The heater elements activated a specially calibrated thermometer which pushed an indicating pointer upscale according to the amount of heating inside the unit. While providing a reasonable approximation of apparent power, these meters had limited accuracy and the indicated kVA readings could not be easily correlated with the readings from the real energy meters to which they were attached.

Use of Two Conventional Meters: Real and Reactive

Prior to the development of electronic meters capable of performing accurate measurement of apparent energy, the approximate value of this quantity typically was measured by combining readings from a real energy meter and a reactive energy meter. For the billing time period, kVAh is calculated vectorially from the square root of the sum of the squares of the readings from both the real and reactive energy meters. Hence, this calculation method produces an average vector kVAh for the billing cycle. Normally, the sign of the real power is assigned to the apparent power (positive if delivered by the utility, negative if received). Some in the industry will argue that by definition apparent power should always be positive. Others argue they want apparent power to have a sign to determine where it was generated, supplier or consumer. Thus, the "correct" determination and display of apparent power quantities is defined by the user.

A more expensive, but more accurate "vector method" is to perform the vector calculation for each demand measurement interval. Historically, a multichannel load profile recorder is attached to both the real and the reactive meters to determine kVAh or kVA demand for a specific time interval, "demand intervals". This data was recorded as sets of simple pulses each representing a known quantity of energy. The time resolution on the load profile recorder typically was programmed for either a 15 or 30 minute demand interval (depending upon local billing regulations). Energy pulses, both real and reactive, were counted for each demand interval and the total pulse count for each quantity was recorded for the interval in the appropriate data channel.

Later, in computer translation systems, the pulse count data was retrieved for each recorded interval and the equivalent kVAh and kVA quantities were calculated. This permitted the utility to determine the total kVAh apparent energy quantities for the entire billing period and to select the various maximum kVA apparent power quantities that may be used in the billing process. There are four potential areas of inaccuracy when using this classical method.

First, in a simple traditional meter, the individual phases of the meter sums kWh energy measurements (the kVARh quantities). The recorded pulses represent only the total of all three phases combined. If the load is perfectly balanced over all three phases, this is satisfactory. If the phase angles vary between metered phases (not uncommon for an imbalanced three-phase load), significant errors may be introduced. For accuracy under all load conditions, the apparent energy should be calculated for each phase individually and then combined. As previously discussed, summing the apparent energy calculation on individual phases instead of on the combination of the phase energies is known in electricity metering as the "arithmetic method".

Second, the concern is that the time resolution is relatively coarse (15 or 30 minutes). Again, this is not a concern for a steady load over the measurement interval. Unfortunately, in the presence of changing loads over the interval in which the pulses are recorded, the load variations can introduce significant errors into the calculation of apparent power.

Third, the calculation relies on using the reactive energy quantities which normally will be inaccurate for all of the reasons previously stated.

Fourth, the calculation is performed on an integral number of pulses which means that fractions of a pulse are not considered in the current interval. In fact, part of the first pulse in the interval is usually from the last interval. These fractions tend to correct for each other, but for low pulse counts the errors for some intervals can be large. If the pulse count in the same interval for either quantity is high, this is less of a concern due to the nature of the vectorial calculation. This concern can be reduced by matching the selection of any current transformers, pulse output from the watthour meter, and/or the divider of the recorder to the expected load.

ELECTRONIC KVA METERING

Various types of electronic meters may use significantly different methods to measure apparent energy.

1. Some meters improve the measurement of reactive energy but otherwise compute apparent energy in the traditional vectorial method.
2. Some meters will employ the arithmetic method instead of the vector method.
3. Some meters will compute the apparent energy more frequently over shorter intervals of time, improving the accuracy of the measurement.
4. Most electronic meters simply continue to combine real and reactive energies, derived in the traditional manner, and are thus limited by the accuracy of the reactive energy measurement.
5. Some electronic meters compute the apparent power by integrating the product of RMS voltage and RMS current for each phase over some brief time interval. The individual phase values are then integrated over a longer time interval to obtain values of apparent energy and a basis for calculating VA demand.

The last method can be the most accurate method of computing apparent power. Assuming an adequate sampling and computation rate, this method provides the best harmonic measurement. A concern for the designer (and utility) is that if care is not taken by the meter designer to minimize noise generated by the system electronics, this method can have a limited dynamic range. Using this preferred method to generate apparent energy readings and combining accurate real energy readings, very accurate reactive energy values can be calculated using the following formula on each phase:

$$\text{VAR} = \sqrt{\text{VAs}^2 - \text{Watts}^2}$$

Assuming that an adequate sampling and computation rate is used, the only drawback with using this method is that the sign of the reactive energy is lost. This may or may not be a problem depending upon the local practices and legislation for utility tariffs. In any case, more sophisticated electronic meters can be used to provide alternate measurement methods to overcome this possible concern. Note that in the presence of harmonics, this quantity is not just VAR as historically defined, but a very accurate value of

$$\sqrt{\text{VAR}^2 + \text{D}^2}$$

which includes the Harmonic effects.

In this case, the VAR measurement of the primary (fundamental) frequency is distorted by the inclusion of the harmonics. However, this is not viewed as a significant issue because VAR and distortion power "D", affect the electrical system in a similar manner. Indeed, it can be argued that for the purpose of determining system loads and billing for all of the inherent impacts of customer-induced harmonics, this value is the preferred value to use!

HOW SHOULD APPARENT ENERGY BE MEASURED?

With the variations and possibilities described above, it is understandable that there exists some confusion in the metering industry and continuing debate over what measurement and computation methods are "correct". Accordingly, it must be recognized that the correct method of measuring apparent energy is open to some combination of personal opinion, local traditions, and even local legal requirements.

It must be recognized that the local tariff regulations do not necessarily depend upon rigorous scientific definitions of the measured quantities! Most utilities want to improve the accuracy of the apparent power measurements, and obtain greater accuracy than that available when using the traditional combination of readings from electromechanical meters.

Even so, the debate continues over whether the values obtained should be mathematically accurate or more simply, should just be derived from more precise measurement with the existing measurement technique. Ultimately, the answer must depend upon the needs of the individual utility and the local legislation governing the development and implementation of tariffs.

The Alternative Positions for "Correct Measurement"

First, consider the argument that reactive and apparent power should be measured as accurately as possible; proper rates should be developed to compensate for the actual power used. Logically, this statement is valid regardless of how the tariffs might be constructed using the various possible combinations of real, reactive, and/or apparent power.

Alternatively, some require that the new and more accurate meters simply must collect data in a form that will be used in existing tariffs—tariff structures that were formulated when meters were less accurate and less capable of accurate complex measurements. To further complicate the issue, in many locations legislation requires that all customers on a specific utility tariff must be measured and billed on exactly the same basis.

Thus, where apparent power is used for billing purposes (and when all metering sites will not simultaneously be changed to new metering equipment), it is important only to calculate apparent power in the traditional (legally mandated) manner. Note that even when adhering to the "same basis" approach, meter products seldom will produce an identical reading in the presence of harmonics. Thus same basis can only apply to measurement and computation for the ideal fundamental system frequency.

Vectorial Versus Arithmetic kVA Calculation

In the utility industry, a debate rages over whether vectorial versus arithmetic kVA calculation is more correct. The vectorial method states that the correct values are obtained when real watthours and VARhours are measured over the demand interval using conventional methods, then the kVA is calculated for the totals accumulated during the interval using the conventional square-root of the sum of the squares

$$VA = \sqrt{Watts^2 + VAR^2}$$

The arithmetic method requires that actual kVAh energy values be obtained from moment to moment and added arithmetically over the demand measurement interval to determine a precise kVA demand value.

Unfortunately, the results obtained, using even the most accurate basic metering, will normally be quite different!

For example, in Figure 9-5, assume that demand is to be determined for a 30-minute demand measurement interval. For the first 15 minutes of the period, the load is pure resistive load at 100 kW (consuming a total of 25 kWh during that first 15 minutes). For the next 15 minutes, the load is pure inductive and 100 kVAR, drawing no watts but 25 kVARh during the remainder of the demand interval.

kVA=?

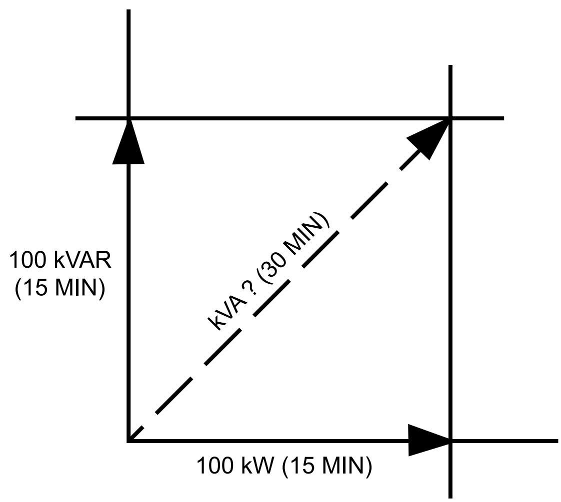


Figure 9-5. Vectorial Example.

What is the kVA demand for the 1/2-hour interval?

1. *Vectorial Method*

   Using the vectorial method and the traditional (ideal) devices which precisely measure either kWh or kVARh, we have the result that for 15 minutes, 25 kWh are drawn and 25 kVARh are drawn by the load. In this case, kVA is calculated as follows:

$$kVAh = \sqrt{kWh^2 + kVARh^2} = \sqrt{(25)^2 + (25)^2} = \sqrt{1250}$$

Thus, kVAh = 35.355

The average kVA demand = kVAh times the intervals per hour = 35.355 kVAh × 2 = 70.71 kVA

2. *Arithmetic Method*
Using the arithmetic method and an "ideal" measuring device, we determine the kVA at each moment during the measurement interval and integrate it over the time period of interest. In this case, we know that for the first 15 minutes (.25 hours), the kVA = kW and we have 25 kWh or 25 kVAh metered in our ideal measurement device (100 kW × .25 hours). Similarly, for the next 15 minutes, we draw 25 kVARh and therefore, exactly 25 kVAh again.

Therefore:

kVAh = 25 + 25 = 50 and

kVA demand = 50 kVAh times the interval per hour = 50 × 2= 100 kVA

Which is correct? Both! This illustrates how two "completely accurate" methods of measuring apparent power and energy can result in dramatically different values. In this particular example, the vectorial method returns a "correct" answer that is almost 30% lower than the arithmetic method! Even so, it is useful to observe that the equipment capacity had best be set by the arithmetic measurement result!

As there is no universally accepted correct way, meter manufacturers have provided metering solutions enabling all utilities to obtain better and more accurate basic data, regardless of the local requirements for power calculations.

Delta Services: VA Metering

The availability of electronic meters that calculate kVA using the arithmetic method instead of the vector method has raised a debate in the electric utility industry as to which is the correct method to be used in revenue metering.

It is presumed that given a choice most meter engineers would prefer that the harmonic performance and real-time measurement of kVA should be derived from rapid sampling and integration of the RMS voltage and RMS current on each phase. Such meters generally are designed to compute kVA using the arithmetic method instead of the vector method. Most utilities will accept and many prefer the arithmetic method for four-wire wye services. This can easily be justified, and as long as the load is balanced and harmonics are minimal, the indicated values of usage are quite similar for either the arithmetic method or the traditional vector method.

Delta services behave differently requiring additional judgment on which methods should be used. This concern arises because normal polyphase loads draw phase currents (from the supplying transformers and systems) at angles 30° different than the line-to-line voltages of the service. This is true even if the load is purely resistive. Typical metering voltage connections provide line-to-line voltage values, but the line current values being monitored are the vector sums of two of the phase currents ($I_{lineA} = I_{ac} + I_{ab}$). This gives rise to a legitimate debate over, "What properly represents the correct apparent or reactive power in a delta service?"

Phase currents from a delta-connected transformer bank are summed vectorially to supply a single-phase load current. The traditional vector method of calculating kVA will indicate that there are no VAR in the system.

$$\text{VARs} = I_{\text{lineA}}{}^{*}\text{Vab} \sin(+30) + I_{\text{lineC}}\,\text{Vcb}^{*}\sin(-30) = 0$$

This is due to the VAR computed in one phase being equal to the other phase, but of the opposite sign. Thus, when the VARs are combined they sum to zero and the apparent energy will exactly equal the real energy. Proponents of this method will argue that it is just the way it should be, because a resistive load should not produce VARs.

In contrast, the arithmetic method of computing VA will provide an apparent energy value at least 15.47% higher than the vector method. Intuitively, this might seem to be in error. In physical reality, it may provide the more realistic picture of system load! If two transformers connected in an “open delta” provide the service, the transformers must carry a kVA load value equal to the arithmetic method’s larger apparent power value.

The four-wire delta service also provides a special set of metering issues. (This service is commonly used in North America to provide both three-phase power to large loads and three-wire, single-phase for lighting)

VOLTAMPERE REACTIVE METERING

Electromechanical Basic Methods

It has been established that

$$W = E\,I \cos\theta$$

or watts equal volts times the working component of the current. This quantity is read by a wattmeter.

Similarly,

$$\text{VAR} = E\,I \sin\theta$$

or VARs equal volts times the magnetizing component of the current.

Since the magnetizing component of the current lags the working component by 90°, this quantity could be read by a wattmeter if the voltage applied to the wattmeter could be displaced by 90° to bring it in phase with the magnetizing current.

Voltamperes are the product of volts and amperes without regard to the phase angle between these two quantities. Voltamperes or kVA can be measured by a wattmeter in which the voltage is displaced by the amount of the phase angle between voltage and current. In this case power factor *must be known* and *must be constant*. This technique has been used in years past before other, less limited, more accurate methods were available. Its use is described here to explain the historical usage. Most historic kVA metering applications have used one kWh meter and one kVAR meter as previously discussed.

Note that in both VAR metering and kVA metering a phase displacement to a watthour meter is necessary. Hence, the general term for metering that measures VAR and kVA is “phase-displaced metering”.

There are several basic approaches to phase-displaced metering. The method chosen depends upon the information desired, the meters and instruments available, and the degree of precision required from the measurements.

Some methods are applicable only to spot measurements; others can be used with integrating watthour meters for a continuous record.

Basic methods are:

1. 90° phase shift of voltage to measure VARs;
2. Cross-phasing;
3. Use of special electromechanical meters.

Combinations of two or more of the proceeding methods may be used. To avoid any confusion in phase-displaced measurement, particularly where refinements are necessary, the following should be carefully observed: The power factor of a circuit is the ratio between the active power (kW) and the apparent power (kVA). The power factor of a circuit is never greater than 1.0.

The power factor of a single-phase circuit is the cosine of the angle between the voltage and current and, in a wye system, of the angle between the respective phase voltages and currents.

Two traditional methods of phase-displaced metering used cross-phasing and auto-transformers to obtain the desired phase shift. These methods are subject to error if all phase voltages are not equal and at the proper phase angle displacement from each other.

In a balanced polyphase system, the currents and voltages are symmetrical. For example, the vector addition of the three current vectors in a wye system will be zero. Balanced polyphase system may be applied to a two-phase system as well as to a three-phase system.

The assumption is generally made that the circuit is inductive: line current lags applied voltage, as in Figure 9-3. If the circuit is capacitive and line current leads applied voltage, then VARmeters will indicate downscale and VARhour meters will rotate backward. Most phase-displaced meters can be reconnected to reverse E' (Figure 9-3) and give upscale indication or forward rotation on leading power factor. Electromechanical varhour meters are usually equipped with detents to prevent occasional backward rotation in circuits in which the power factor varies and may sometimes go leading (capacitive).

Phase Sequence

When phase-displaced metering is encountered, designers must have a definite knowledge of phase sequence. Watthour meters and wattmeters for measuring energy and power, respectively, can be correctly connected without consideration for phase sequence. Most modern electronic meters will measure kVA or kVAR correctly without consideration of phase sequence. However, when electromechanical meters are used to measure VARhours or VAR, the phase sequence must be known in order to make correct connections for forward rotation of the meter disk or upscale indication of the wattmeter.

Any phase-sequence identification, either letters, A-B-C or numbers, 1-2-3, may be used. These phase identifications may not necessarily indicate the actual phases emanating from the generating station, but do indicate the sequence in which phase voltages reach their maximum values in respect to time. By common consent, counterclockwise phase rotation has been chosen for general use in phasor diagrams. In diagrams in which the curved arrow is omitted, counterclockwise phase rotation is always implied.

In Figure 9-6, the sine wave E_{10} reaches its maximum value one-third of a cycle (120°) before E_{20}. In turn, E_{20} reaches its maximum value one-third of a cycle before E_{30}. This phase sequence is E_{10} –E_{20} –E_{30} or, in conventional terms, 1-2-3. As the phasor diagram "rotates" counterclockwise, the phasors pass any point in the same sequence, E_{10} –E_{20} –E_{30}.

Some methods of phase-displacement applied with electromechanical meters use cross-phasing or auto-transformers to obtain the desired phase shift. These methods require an integrated connection of all the phases. If the phase sequence were not known, a connection intended to obtain a lagging voltage might result in a leading voltage that would result in incorrect metering. In Figure 9-7a, with supposed phase sequence 1-2-3, phasor E_{23} lags E_{10} by 90°. In Figure 9-7b, with the opposite sequence, the same connection produces phasor E_{23}, which leads E_{10} by 90°. The modern electronic meter requires no special external connection but obtains any necessary phase shift by either digital or analog electronic techniques during the measurement process.

There are various types of phase-sequence indicators available, from a lamp-reactor device to software based measurement inside electronic meters. Digital sampling in electronics meters allows the meters to show a real-time graph of the phasors on a computer screen for direct evaluation of the phase sequence and the phase angle of each of the voltage and current phasors. This can also be used to detect incorrect wiring.

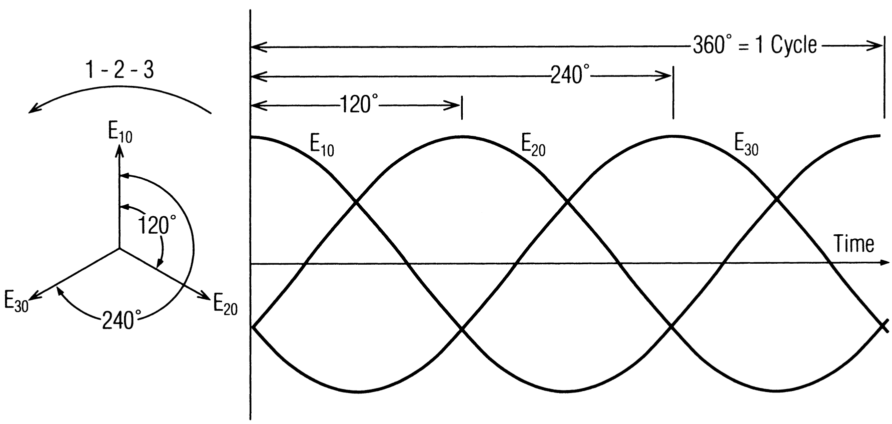


Figure 9-6. Phase Sequence and Phase Rotation.

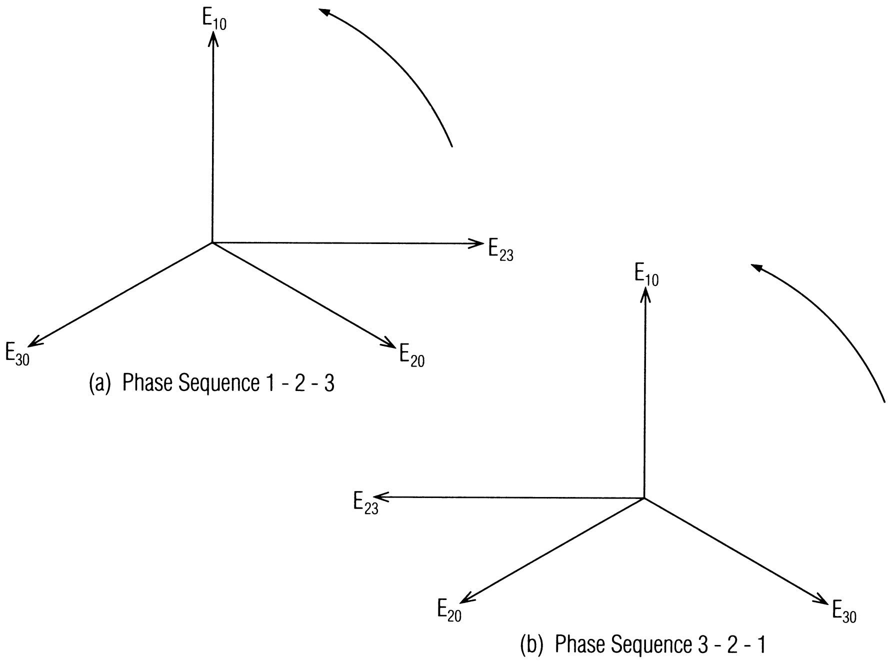


Figure 9-7. The Importance of Phase Sequence.

90° Phase Shift

The most popular method used in VAR metering involves quadrature voltages, i.e., a 90° phase shift of voltage is applied to a wattmeter or watthour meter. The 90° phase shift of voltage can be obtained in several ways.

Wattmeters and watthour meters are designed to indicate or to rotate at speeds proportional to the product of the voltage on the voltage coil, the current in the current coil, and the cosine of the angle between them:

$$W = EI \cos \theta$$

From Figure 9-3, if the voltage E' were substituted for E in the wattmeter or watthour meter, it would indicate:

$$E'I \cos(90 - \theta) \text{ which equals } EI \sin \theta = \text{VAR}.$$

Simultaneous readings of watts and VAR can be used to calculate power factor and voltamperes.

Power factor (PF) is equal to the cosine of the angle whose tangent is VAR/Watts, which in mathematical notation is shown as:

$$\text{PF} = \cos(\tan^{-1}(\text{VAR/Watts}))$$

Power factor is also equal to the cosine of the angle whose tangent is VARhours/Watthours, or in mathematical notation:

$$\text{PF} = \cos(\tan^{-1}(\text{VARh/Wh}))$$

Use of Autotransformers for Electromechanical Meters

The most common method used to obtain the desired phase shift in voltage is a combination of autotransformers. The autotransformers not only shift the voltage of each phase the required number of degrees, but also supply this voltage at the same magnitude as the line voltage by tapping the windings at voltage points which, when added phasorially, result in the desired voltage. See Figures 9-8 and 9-9). The autotransformer combination is known by a variety of names such as phasing transformer, reactive component compensator, reactiformer, voltage phasing transformer, and phaseformer. Figures 9-10 and 9-11 illustrate the application of the phase shifting devices shown in Figures 9-8 and 9-9.

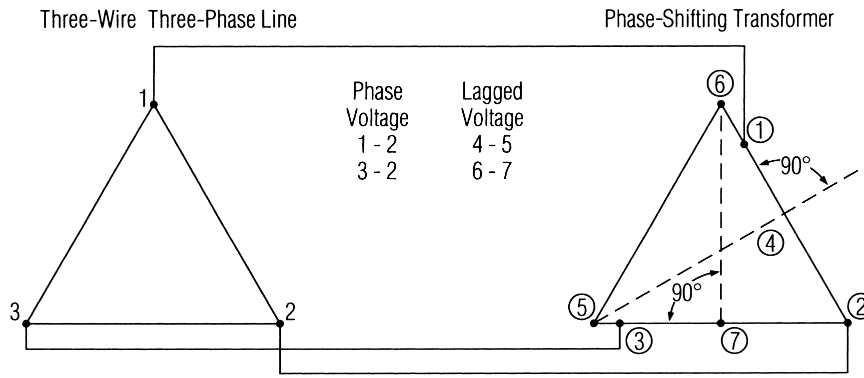


Figure 9-8. Elementary Diagram of Phase-Shifting Transformer for Three-Wire, Three-Phase Circuits.

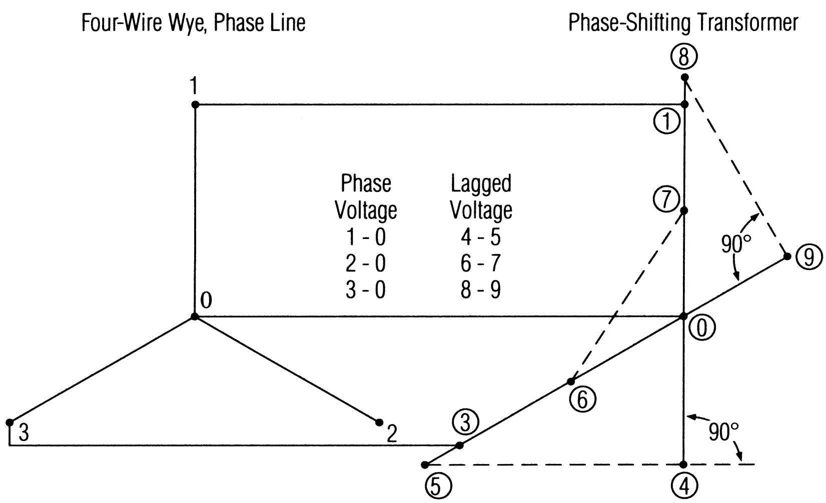


Figure 9-9. Diagram of Phase-Shifting Transformer for Four-Wire Wye, Three-Phase Circuits.

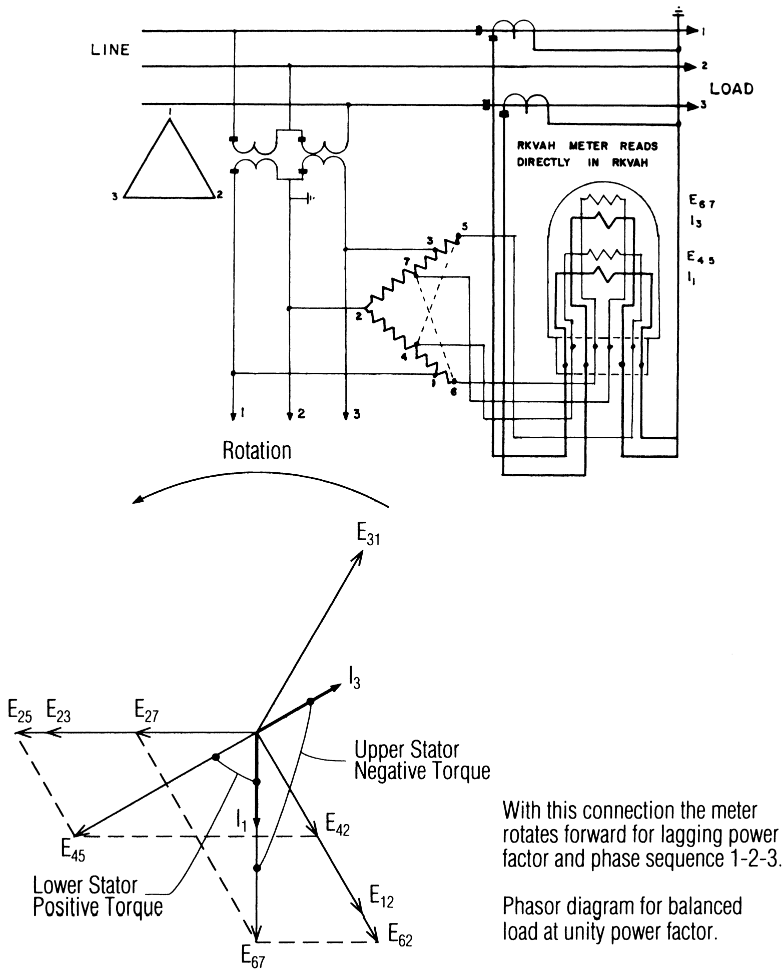


Figure 9-10. Connection of Three-Wire, Three-Phase, Two-Stator VARhour Meter with Autotransformers.

These diagrams do not show all possible methods and connections, but are used to illustrate the principle. It is supposed that manufacturers will be able to supply connection diagrams of whatever variety of autotransformer is purchased.

With the addition of the proper autotransformer, a standard wattmeter or watthour meter becomes a VARmeter or a VARhour meter. Such a VARmeter and a standard wattmeter can be used to derive vector voltamperes and the power factor by applying equations previously mentioned. When watthour meters are used on loads which vary constantly in magnitude and in power factor, the power factor value obtained,

$$\text{Power Factor} = \cos(\tan^{-1} \text{VARhour/Watthours})$$

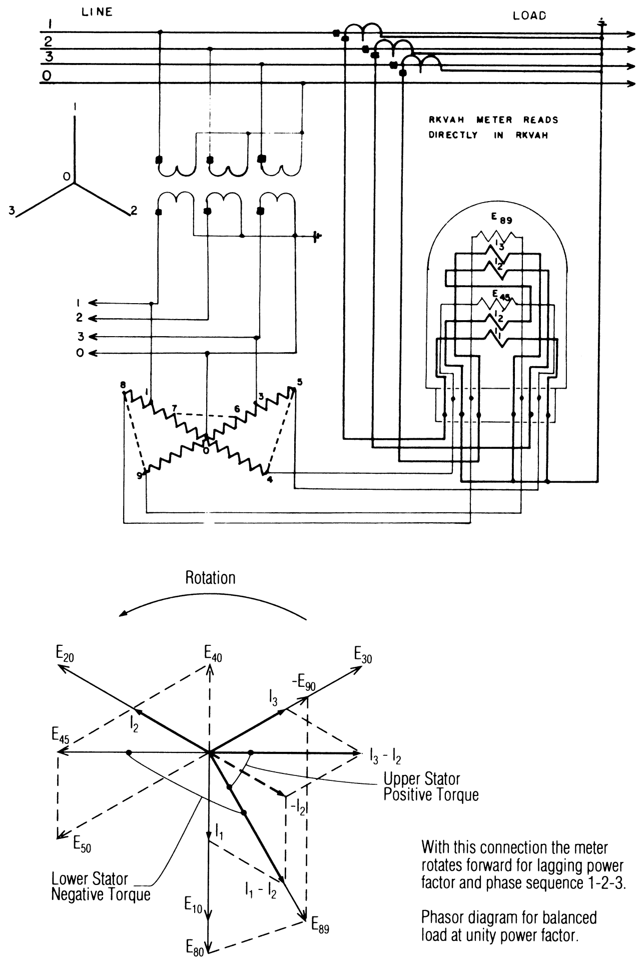


Figure 9-11. Connection of Four-Wire, Three-Phase Wye VARhour Meter with Autotransformer.

is an average power factor and does not necessarily represent the actual power factor at any one time. Similarly voltamperehours calculated from these figures is also an average value and is not necessarily equal to the total voltamperehours delivered (see Figure 9-12).

Since phase-shifting autotransformers are essentially tapped, single-winding voltage transformers, the testing of them consists of verifying the various tap voltages in terms of the input voltage. The test should be performed with the burden, in voltamperes, approximately equal to that which will be used in service.

Because the values in the manufacturer's data table are usually expressed as percent of applied voltage the job may be simplified by using a voltmeter with a special scale or by energizing the transformer in multiples of 100 volts. Voltage readings may then be interpreted as a percent without lengthy calculations.

Cross Phasing for Electromechanical Meters

The inherent nature of a two-phase system readily provides the measurement of reactive voltamperehours. The voltages of the two phases are normally displaced 90°; therefore, by interchanging voltages, the voltage from each phase is made to react with current from the other phase. In addition, the polarity of one of the voltage coils must be reversed in order to produce forward rotation on lagging power factor. See Figure 9-13. This method is known as cross phasing.

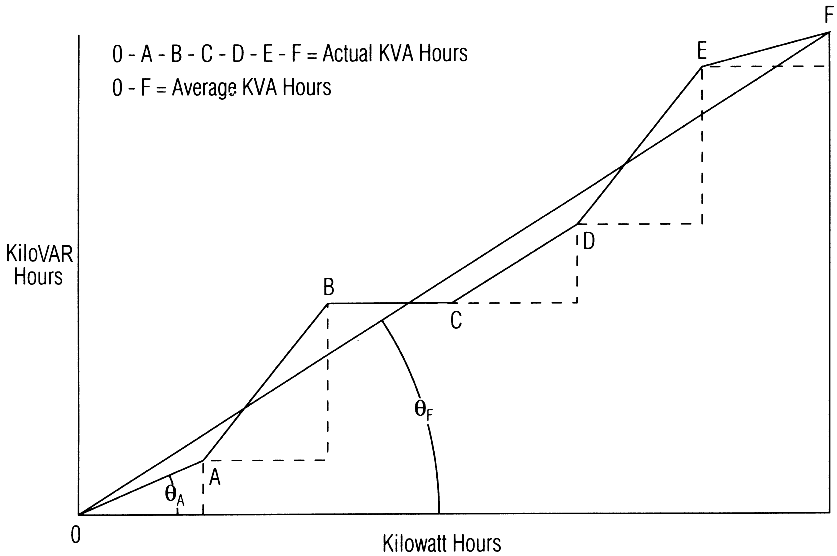


Figure 9-12. Instantaneous Power Factor (Cos θ_A) Does Not Necessarily Equal the Average Power Factor Calculated from kWh and RkVAh Readings (Cos θ_F).

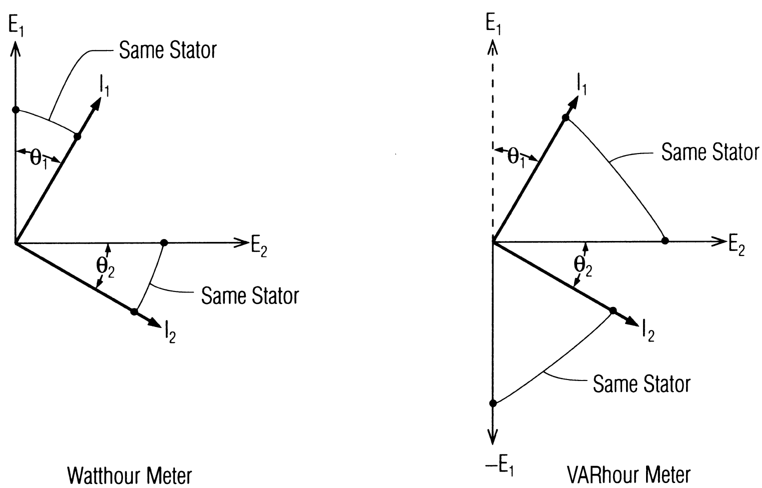


Figure 9-13. Phasor Diagram of Cross Phasing in a Two-Phase System.

A similar method of cross phasing may be applied to three-phase circuits. The current in each phase reacts with voltage between two line wires other than the one in which it is flowing. In a three-wire, three-phase, delta meter cross phasing is accomplished by interchanging voltage leads to the meter (Figure 9-14). As in the two-phase meter, it is also necessary to reverse polarity of one-stator voltages with respect to its current. In Figure 9-13 this has been done by reversing the voltage, although current leads may be reversed with the same result.

When the current in the phase leading the common phase is reversed, the VARhour meter will rotate forward on lagging power factor and backward on leading power factor. When the other current is reversed the opposite is true.

It is necessary to multiply this meter's registration by 0.866 to read correct VARhours.

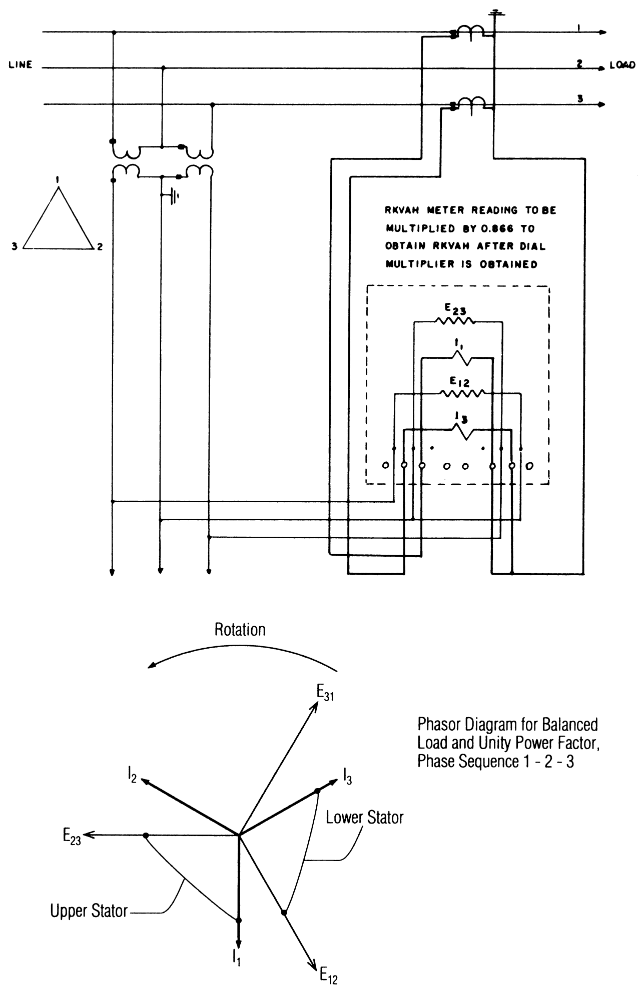


Figure 9-14. Cross-Phase Connection of Three-Wire, Three-Phase, Two-Stator VARhour Meter.

With this connection, the VARhour meter is actually metering only two phases of the three. The multiplier is applied to correct for voltage magnitude and to include the third phase. Therefore, this method may only be used on a system with balanced voltages and currents.

In a wye system, since the voltage coils are impressed with line-to-line voltage which is the $\sqrt{3}$ or 1.732 times as great as the required voltage, the registration is correspondingly high. A factor of 0.577 must be applied for correct registration (Figure 9-15). A 2½-stator meter may be used in the same manner and a two-stator meter may be used if current-transformer secondaries are connected in delta. The 0.577 correction factor also applies in these cases.

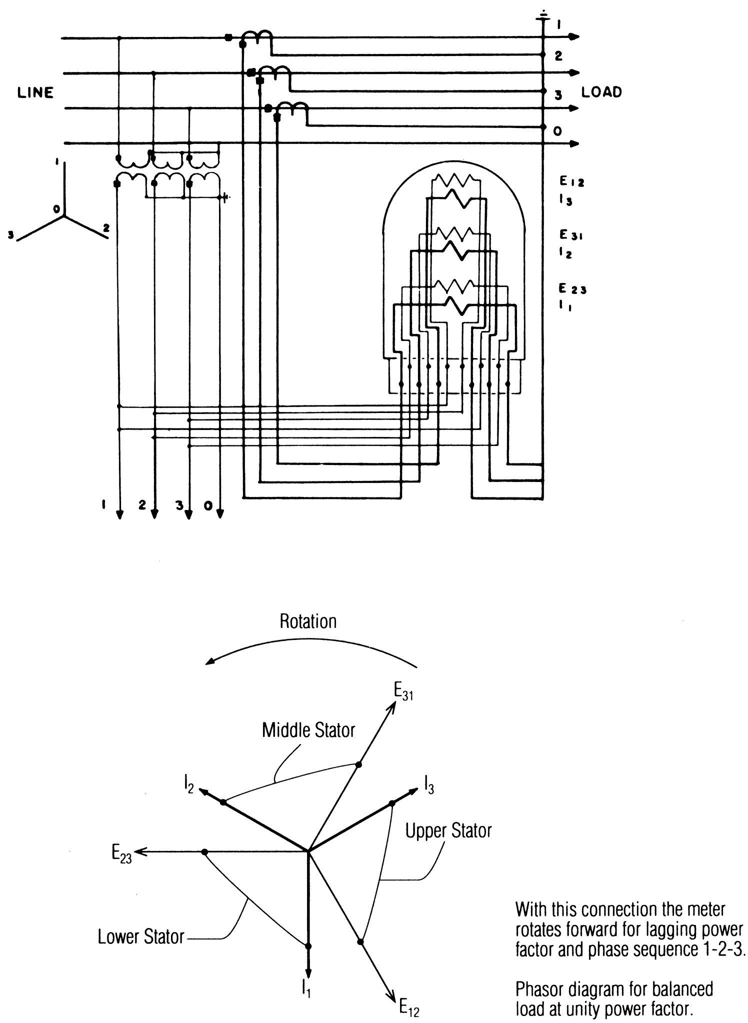


Figure 9-15. Cross-Phase Connection of Four-Wire, Three-Phase Wye, Three-Stator VARhour Meter.

Special Electromechanical Meters

A VARmeter is a meter with built-in means of obtaining the 90° phase shift. The meter may incorporate an internal capacitor-resistance unit or autotransformer. It is installed in the same manner as a wattmeter.

A voltampere meter is similar to a VARmeter but with a built-in phase shift corresponding to the assumed power factor, as described previously.

One special meter includes a watthour meter, a VARhour meter using autotransformers, and a mechanical ball mechanism which adds vectorially the rotations of the two meters to give a reading in kilovoltamperehours. This meter gives actual kilovoltamperehours that may be interpreted on a register that may be a graphic, indicating, or cumulative demand register. Such a meter will yield readings of kilowatthours, kiloVARhours, kilovoltamperehours, kilowatt demand, kilovoltampere demand, and an indication of power factor at the moment the meter is being observed.

Some special VARhour meters are in production. These meters are used on specified phase voltages in conjunction with a watthour meter. No autotransformer or other external means of phase shifting is necessary. Their principle of design is that the quadrature voltage necessary for metering VAR can be obtained for each phase by correct phasor addition of the other two-phase voltages and by applying constant correction factors. This is done by building a multistator meter and passing a given phase current first through one stator with one voltage, then through the second stator with a second voltage. The resulting torque is proportional to the product of the current, the vector sum of the voltages, and the power factor of the angle between them. This torque is equal to VARs. Correction constants are applied in the design of the voltage coils of the meters to avoid a special multiplier as is needed in cross-phased meters.

Detailed information on the design and operation of these meters may be obtained from the manufacturers.

Electromechanical Q-Metering

It was noted previously that a displacement of the watthour meter voltage by 90° produced VAR. By displacing the voltages with any angle other than 0° or 90°, the torque on the watthour meter will not be proportional to watts or VAR, but will be proportional to some quantity called Q.

From Figure 9-16 the following relationships exist:

$$\begin{aligned}\text{Watts} &= E_W I \cos\theta \\ \text{VAR} &= E_W I \sin\theta \\ \text{Q} &= E_Q I \cos(\phi - \theta) \\ |\text{E}_Q| &= |\text{E}_W|\end{aligned}$$

Expanding the equation:

$$\begin{aligned}\text{Q} &= E_Q I \cos(\phi - \theta) \\ \text{Q} &= E_Q I \cos\phi \cos\theta + E_Q I \sin\phi \sin\theta\end{aligned}$$

Since $|E_Q| = |E_W|$

$$\begin{aligned}\text{Q} &= (\text{E}_W \text{I} \cos\theta)\cos\phi + (E_W I \sin\theta)\sin\phi \\ \text{Q} &= (\text{watts})\cos\phi + (\text{VAR})\sin\phi\end{aligned}$$

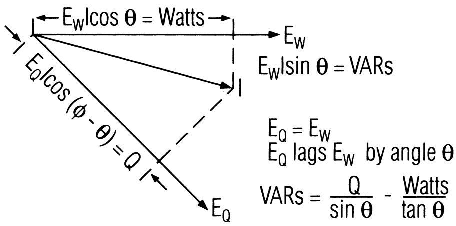


Figure 9-16. Vector Relationships for Q-hour Metering.

After rearranging terms:

$$(\text{VAR}) \sin \phi = \text{Q} - (\text{watts}) \cos \phi$$

or,

$$\text{VAR} = \text{Q}/\sin \phi - (\text{watts}) \cos \phi/\sin \phi$$

But,

$$\cos \phi/\sin \phi = 1/\tan \phi$$

Therefore,

$$\text{VAR} = \text{Q}/\sin \phi - \text{Watts}/\tan \phi$$

This is the general expression for the relationship of watts, VAR and Q for any lagging angle ϕ.

Although any angle of lag is theoretically obtainable by using a phase-shifting transformer, it would be desirable to eliminate the need for another piece of equipment. Fortunately, an appropriate angle of lag of 60° is readily available from both a three-wire, three-phase, and a four-wire wye, three-phase circuit by the simple expedient of cross phasing. A 60° angle of lag will result in the Q-hour meter having forward torque for any power factor angle between 150° (−86.7% PF) lagging and 30° (86.7% PF) leading. Figure 9-17 and 9-18 illustrate how a 60° phase displacement of voltages may be obtained from both four-wire wye, three-phase and three-wire, and three-phase circuits by cross phasing.

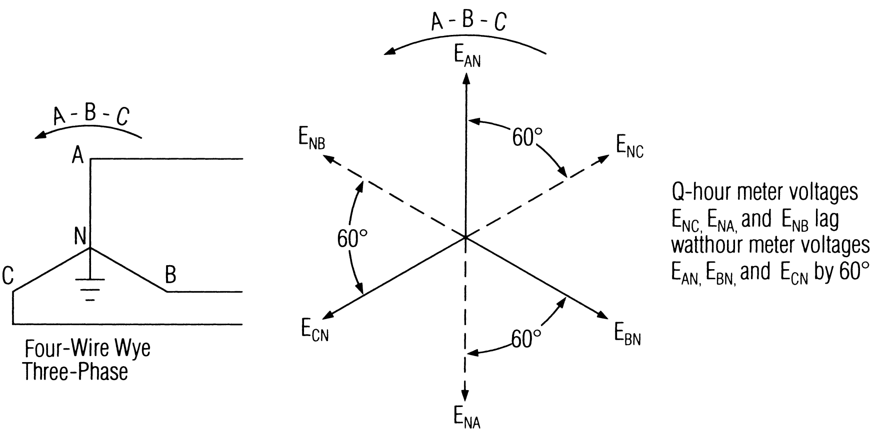


Figure 9-17. Phase Displacement of 60° from Three-Phase, Four-Wire Wye System.

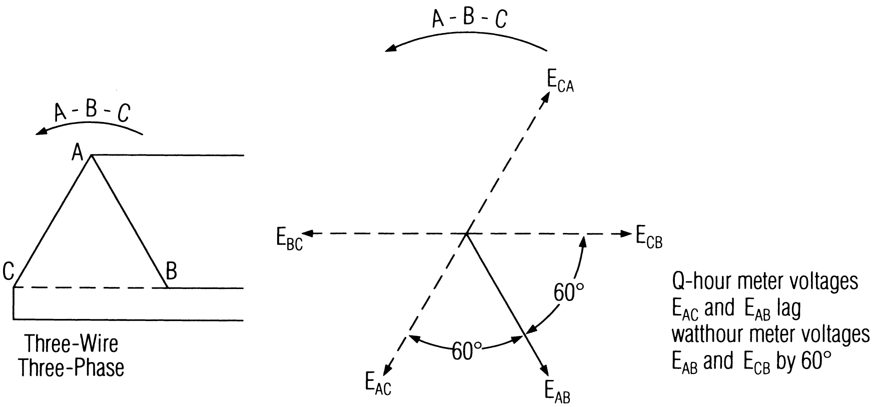


Figure 9-18. Phase Displacement of 60° from Three-Phase, Three-Wire System.

Using an angle of lag of 60°, the general expression for VAR previously developed may be written in a form without reference to trigonometric functions.

Substituting values for sin 60° and tan 60° into the general expression,

$$\text{VAR} = \text{Q}/\sin\phi - \text{Watts}/\tan\phi$$

will give

$$\text{VAR} = \text{Q}/\sqrt{3/2} - \text{Watts}/\sqrt{3},$$

which reduces to

$$\text{VAR} = \frac{2\text{Q} - \text{Watts}}{\sqrt{3}}$$

See Figure 9-19 for the phasor relationships that exist when the Q-meter voltage has been lagged 60° from the wattmeter voltage.

It was noted previously that the Q-hour meter measures both lagging VARhours and leading VARhours over a specified range, the limits of which are determined by the degrees of lag of the Q-hour meter voltages. Figure 9-20 illustrates the useful range of the Q-hour meter using a 60° lag of voltages. It may be noted that forward torque exists on the Q-hour meter from a 90° lagging PF angle to a 30° leading angle.

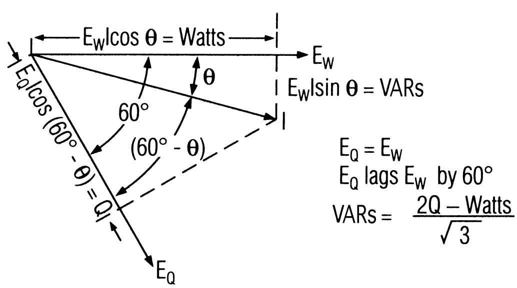


Figure 9-19. Q-meter Voltage Lagged 60° from Wattmeter Voltage.

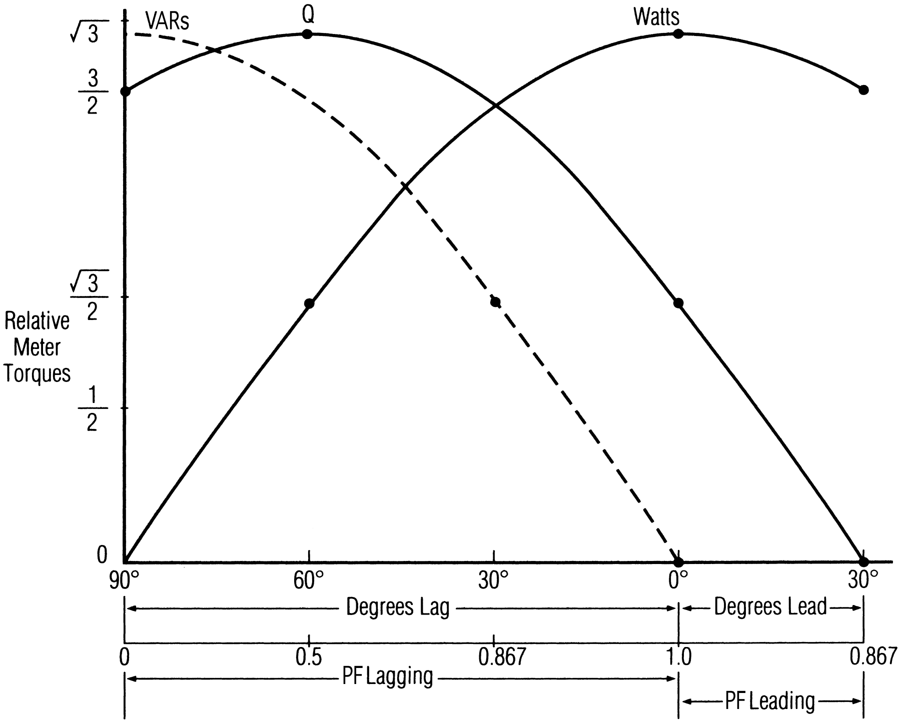


Figure 9-20. Useful Range of Q-hour Meter with 60° Lag of Voltages.

Relative measurements (torques) for the watthour meter and corresponding power factor angles are also shown. Note that the watthour meter also has forward torque over PF range equal to that of the Q-hour meter. If the Q-hour meter is to provide measurement for both leading and lagging power factor, how is the distinction between leading and lagging VARhours to be made when the meter gives positive (forward) readings for both? Note from Figure 9-20 that the calculated VAR are positive between 0° power factor and 90° lagging power factor angle. The relationships may be used to determine whether VAR are leading or lagging:

If (2Q − Watts) is positive, PF is lagging.

If (2Q − Watts) is zero, PF is 1.0.

If (2Q − Watts) is negative, PF is leading.

Other relationships are:

If Q/W > 0.5, PF is lagging.

If Q/W = 0.5, PF is 1.0.

If Q/W < 0.5, PF is leading.

When power factors are leading more than 30° (86.7% PF), the 60° lagged Q-hour meter cannot be used since it reverses at that point. In such cases, either a Q-hour meter lagged by some appropriate angle less than 60° or separate leading and lagging reactive meters are required. Also, at locations where power flow may be in either direction, conventional reactive meters rather than Q-meters should be used.

ELECTRONIC MULTIQUADRANT METERING

Electronic multiple-quadrant meters can measure active quantities such as watt demand and watthours, reactive quantities such as VAR demand and VARhours, and apparent quantities such as VA demand and VAhours. These measurements can be for unidirectional or bidirectional applications.

Figure 9-21 shows a diagram which illustrates relationships between active power (watts), reactive power (VAR), and vector apparent power (voltamperes). The familiar Power Triangle has been incorporated into Figure 9-21 in each of the four quadrants.

Quadrant	Power Factor	Watts		VARs	
I	Lag	Delivered	(+)	Delivered	(+)
II	Lead	Received	(−)	Delivered	(+)
III	Lag	Received	(−)	Received	(−)
IV	Lead	Delivered	(+)	Received	(−)

Energy sold by the source may be defined as delivered. Energy purchased may be defined as received.

For any given voltage and current, VA is constant and an unsigned absolute quantity. For any given phase angle θ

$$\text{Watts} = EI \cos \theta$$

$$\text{VAR} = EI \sin \theta$$

The signs, plus, minus, and directions, delivered, received, are for conventionally polarized instrument transformer connections with respect to the power source.

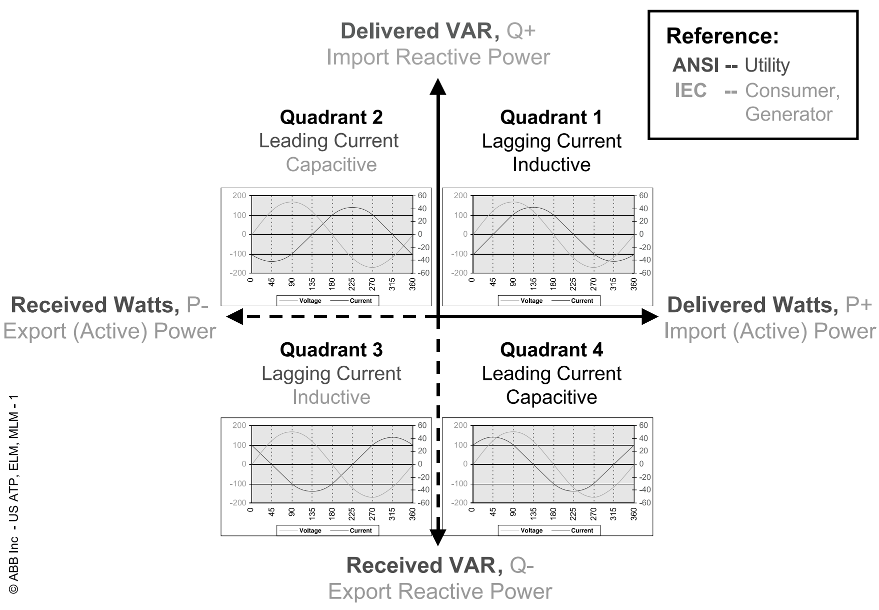


Figure 9-21. Four Quadrant Power: Normal Conventions.

Electronic multiple-function meters can measure the following quantities, or combinations of quantities:

kWh, kW demand delivered	Quadrants I and IV
kWh, kW demand received	Quadrants II and III
kVAh, kVA demand delivered	Quadrants I and IV
kVAh, kVA demand received	Quadrants II and III
kVARh, kVAR demand active quantities delivered, PF lagging	Quadrant I
kVARh, kVAR demand active quantities received, PF leading	Quadrant II
kVARh, kVAR demand active quantities received, PF lagging	Quadrant III
kVARh, kVAR demand active quantities delivered, PF leading	Quadrant IV

The following combinations of reactive quantities are available on some meters as displayed quantities or as non-displayed outputs. Consult the specifications of individual meter manufacturers.

kVARh and kVAR demand delivered	Quadrant I plus II
kVARh and kVAR demand received	Quadrant III plus IV

These two combined quadrant VAR quantities are equivalent to the performance of a rotating detented VAR meter.

kVARh and kVAR demand delivered, net	Quadrant I minus IV
kVARh and kVAR demand received, net	Quadrant III – II

These two combined quadrant VAR quantities are equivalent to the performance of a rotating undetented VAR meter.

Figure 9-22 illustrates the relationships between active power (watts), reactive power (VAR), and the quantity, Q. Notice that Q is delivered (is positive) when the phase angle is between 0° and 90°, or between 330° and 360°. Q is received (is negative) when the phase angle is between 150° and 270°. Q is not defined when the phase angle is between 90° and 150° or between 270° and 330°.

Electronic Reactive Metering

Modern electronic reactive meters may provide both real and reactive quantities without the use of external phase shifting transformers or special element wiring. In general, the overall reactive measurement is greatly improved over the electromechanical meter (again with some cautions about harmonic measurement of VAR if phase shifting circuits are used). Electronic meters incorporate one of the following four methods of metering reactive power.

The most common method employed by simple electronic meters, is to phase shift each phase current or voltage by 90° prior to the multiplication process. This is usually accomplished by incorporating either an integrator or differentiator for each phase. These circuits affect any harmonics making them either too small or too large, respectively. The error is directly proportional to the harmonic number, thus the third harmonic is three times too large in the case of the differentiator.

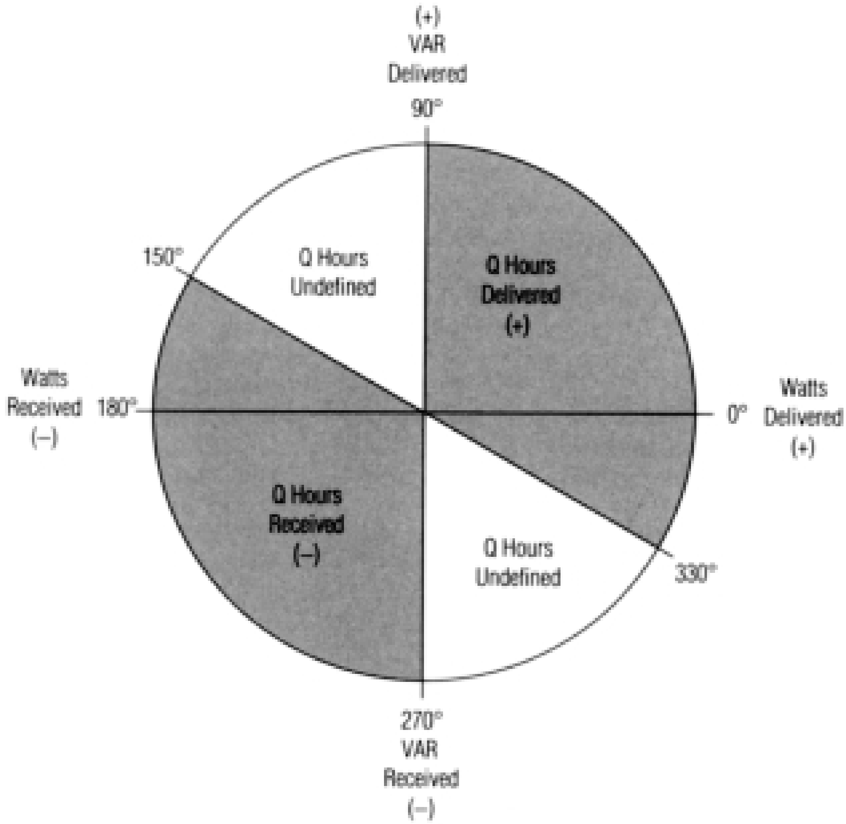


Figure 9-22. Relationships Between Watts, VAR, and Q.

A second compromise method is to employ a fixed time delay that is equivalent to 90° of the fixed fundamental frequency prior to the multiplication. This method is inaccurate as the power line frequency varies about its average value. It also does not allow for the accurate delaying of the harmonics. For example, on a 60 Hz system, all signals would be delayed by 4.166 ms; however, the 3rd harmonic should only be delayed by 1.388 ms to get the correct 90° phase shift. As the delay is incorrect, the magnitude of the harmonic thus measured also will be significantly in error and/or the sign will be incorrect.

A third method employs a time delay. However the time delay tracks the actual power line fundamental frequency. This greatly improves the accuracy of measurement, but does not address the inaccuracy issue with harmonics.

A fourth method of measuring reactive energy more accurately addresses the issue of harmonic performance. This requires the measurement of apparent power VA, along with real power watts, with the VAR reactive quantities arithmetically derived from these two. This method was discussed in conjunction with apparent power measurement earlier in this chapter.

Electronic Q Metering

The electronic Q meter is based on principles described in Chapter 7 for electronic multipliers. For time-division multipliers, Hall-effect multipliers, and multipliers using transconductance amplifiers, the 60E voltage phase shift is accomplished by internal cross phasing of the connections. For digital multipliers using microprocessors, a digital phase shifter accomplishes the 60° phase shift, or Q is calculated from

$$Q = \frac{\text{Real Power}}{2} + \frac{\sqrt{3} \times \text{Reactive Power}}{2}$$

For multipliers not using microprocessors, the 60° phase shift is accomplished through internal cross phasing of the connections. Phase sequence must be taken into consideration when the multiplier chosen produces the 60E phase shift by internal cross phasing of connections.

Impact of Non-fundamental Frequencies on VAR and VA

When power is generated by the utility, the voltage and current waveform have only one frequency present, typically 60Hz in North America. If a spectrum or harmonic analyzer did an analysis, only one frequency would be detected. However, as more sophisticated electronic and industrial loads are being added to the system, current drawn from the line is not linear with the voltage.

A good example is a power supply in a desktop computer. The power supply only pulls current when the line voltage exceeds the voltage on the internal storage capacitors so the current waveform is close to zero until the voltage nears its peak. Suddenly, the current surges to fill the capacitors once the threshold is exceeded. This gives a nonlinear waveform similar to that shown in Figure 9-23.

Because of resistance in the circuit wiring, this sudden surge of current causes the voltage to drop slightly near the peak, both positively and negatively. As a result the voltage waveform becomes distorted. It is no longer a single frequency but now has a small amount of distortion that can be expressed as a higher frequency waveform. This higher frequency now present on the line is called an harmonic. In this case, that is the third harmonic or three times the line frequency, 180 Hz. Any other equipment, including electricity meters, will be affected by the added frequency components. Other sources of non-fundamental signals also have characteristic harmonics patterns.

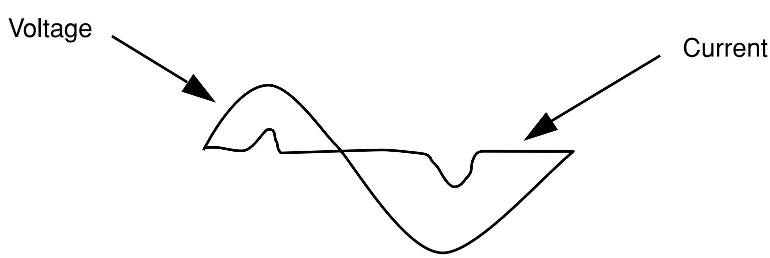


Figure 9-23. Non-sinusoidal Current Waveform.

Harmonics and VA Definitions

With the advent of more complex loads or when the system is not balanced, the difference between vector generated VA and rms generated VA becomes larger. What is the difference that adds to vector VA to total to rms VA?

There are many labels and definitions currently under discussion to help provide meaning to these values. Some in the industry refer to VA that is caused by harmonics as distortion VA and VA that is caused by asymmetry in a polyphase system as imbalance VA.

For some, the discussion about how to define the various VA quantities involves finding definitions that are understandable and useful for field application. The emphasis is placed on finding quantities that actually help the utility to operate the power distribution system.

Harmonics and Watts and VARs Definitions

The calculations of harmonic watts and VAR also involve definition issues. There is general agreement that the definition for watts is simply:

$$\textit{Watthours} = \sum (v_\mathrm{i} \times i_\mathrm{i}), \text{ where } v_\mathrm{i} \text{ and } i_\mathrm{i} \text{ are the instantaneous values}$$

This equation is correct in AC and DC circuits and with or without harmonics.

$$\text{Watts at an harmonic} = \text{volts at that harmonic} \times \text{current at that harmonic} \times \cos(\text{phase angle at that harmonic})$$

When it comes to VAR, no definition has been agreed upon yet in the metering industry. It is presently only defined for single frequency systems.

Importance of Harmonics on Accuracy

Generally speaking, as the harmonic values increase, the relative magnitude of the harmonics tends to fall off, but there are many types of loads in which this general statement is not true. Only when the harmonic value is small on both voltage and current, is the product of the two very small. The example below gives the details when the harmonic values are small and thus the harmonically caused watt values will be small compared to the watt values at the main frequency. Other examples could be given when the harmonic values cause significant changes to the resultant calculations.

For example, there is a 5% third harmonic on the current (i.e., the fundamental current is 10 amps at 60 Hz, the harmonic current is $0.05 \times 10 = 0.5$A at 180 Hz) and there is a resulting 1% third harmonic on the voltage (i.e., if the fundamental voltage is 120 V at 60 Hz, the harmonic voltage is $0.01 \times 120 = 1.2$ V at 180 Hz) and assuming that they are in phase (phase displacement of the third harmonic is 0°), then:

$$\text{Watts at third harmonic} = V_3 \times I_3 \times \cos\theta = 1.2 \times 0.5 \times 1 = 0.6 \text{ watts}$$

While the fundamental has, assuming a unity power factor,

$$\text{Watts at first harmonic} = V_1 \times I_1 \times \cos\theta = 120 \times 10 = 1200 \text{ watts}$$

If you measure this with a meter of 0.1% accuracy, the accuracy of the fundamental measurement is 1200 +/–1% or $0.001 \times 1200 = 1.2$ watts or 2.0 times greater than the third harmonic watts! In this example if the accuracy of the third harmonic is off slightly, it will not "be seen" in the accuracy band of the meter's fundamental accuracy.

There have been studies reported in the literature where harmonics in the current exceeded 30% and the harmonics in the voltage exceeded 10%. In such cases it is necessary to include harmonics to get a true measurement of the conditions on the electrical system. The harmonics measurements are useful as diagnostic tools and do catch significant power at higher harmonic levels. Any measurement of harmonics done in an electronic meter must not compromise the basic function of metering power at the fundamental frequency.

CHAPTER 10

SPECIAL METERING

COMPENSATION METERING FOR TRANSFORMER AND LINE LOSSES

WHY IS COMPENSATION DESIRED?

SOMETIMES IT IS IMPRACTICAL, either for physical or cost reasons, to install metering equipment at the contractual billing point. As a solution, the metering equipment can be installed at a location which is more economical or more accessible, and then compensate the meter for losses which occur between the metering point and the billing point.

For example, instead of measuring power consumption on the high voltage side of a power transformer with high voltage meters, it is less costly to use lower voltage meters and measure the power on the low voltage side of the customer's transformer. In some cases, supply power can be measured more accurately at the lower usage voltage rather than at the supply voltage. Compensation metering is needed if the billing point is located at an inaccessible point, such as a remote boundary between two utilities or the mid-span of a river crossing. For these conditions, where transformer losses or line losses between the metering equipment and the billing point are significant, compensation metering for the losses should be considered. The decision to use compensation metering can be influenced by local regulations and practices, the layout of the substation, and the ability to obtain contractual agreements with the customers.

Because compensation is based on mathematical formulas, errors are introduced when the formulas do not accurately describe actual physical conditions. For example, the formulas may assume temperature and frequency are constants and always 75°C and 60 Hz, when actually both parameters are variables. Imbalanced voltages and currents can effect the accuracy of loss measurements. The different electrical characteristics of power transformer steels are usually ignored in the loss calculations. In general, transformer losses represent less than 2% of the capacity of a transformer bank, and errors due to loss compensation have a negligible effect on the measurements of total kilowatthours and total revenue.

WHAT IS COMPENSATION METERING?

The objective of compensation metering is to determine unmetered losses which occur between the billing and metering points, and then record the losses on a loss meter or combine the losses with the metered portion of the load on a single meter. The common practice is to combine the losses with the metered portion which duplicates values which the meter would have recorded had it been located at the billing point.

Energy dissipated between the billing and metering points cannot be measured directly. The losses are calculated indirectly using transformer theory, circuit theory, and currents and voltages at the meter test switch or meter socket.

Commercially available compensation meters operate with formulas approved by meter engineers and regulatory agencies. These formulas add or subtract simulated losses to the metered load and record compensated meter readings, or uncompensated readings with simulated losses directed to a separate loss meter.

TRANSFORMER LOSSES

Losses in the transformer are caused by hysteresis, eddy currents, and load currents. Hysteresis losses are derived from energy expended as the magnetic field within the transformer continually changes intensity and direction. Hysteresis losses are a function of the metallurgical properties of the core material. Eddy current losses are caused by energy expended by current, induced by the magnetic field, and circulating within the transformer core. Eddy current losses are minimized by building the transformer core from electrically resistive steel formed into thin, insulated laminations. Load losses, or I^2R losses, are caused by current passing through the transformer windings and the resistance of those windings.

Transformer losses are either no-load losses, also called core losses or iron losses, and load losses, also called copper losses.

LINE LOSS COMPENSATIONS

Lines are considered to be resistive and have I^2R losses. The lengths, spacings, and configurations of lines are usually such that inductive and capacitive effects can be ignored. Bus losses are treated the same as line losses. If line and bus losses are to be compensated, they are included as part of the transformer load losses. Most solid-state meters can compensate for both resistive and reactive losses.

TRANSFORMER LOSS TESTS

Power transformers are tested for losses by the manufacturer prior to shipping. Characteristics of individual transformers vary, and for accurate compensation it is important to obtain actual test results for each power transformer involved. *Real* losses are given in the test results. *Reactive* losses are generally not given but can be calculated based on real losses, magnetizing current, and transformer impedance.

An open circuit test at rated voltage measures no-load (core) losses, at rated voltage.

A short circuit test at base current measures load (copper) losses, at rated load. Base current is the current at rated kVA and rated voltage.

Magnetizing current and transformer impedance are determined by other tests and are included with the transformer test results.

TRANSFORMER LOSS MODEL

The transformer loss model for loss compensation is based on mathematical relationships with metered voltage and current as the variables.

> No-load (core) loss watts are proportional to V^2.
> Load (copper) loss watts are proportional to I^2.
>
> No-load (core) loss VAR are proportional to V^4.
> Load (copper) loss VAR are proportional to I^2.

The first pair of relationships, no-load loss watts and load loss watts, for rated current and voltage are given in the manufacturer's test results. The second pair of relationships, no-load loss VAR and load loss VAR, must be derived from the respective loss kVA and the power factor angles of the losses.

No-load loss kVA equals rated transformer kVA times per-unit magnetizing current. Load loss kVA equals rated transformer kVA times per-unit impedance.

The power factor angle for no-load loss is the angle whose cosine equals the ratio of no-load loss watts to no-load kVA. The power factor angle for load loss is the angle whose cosine equals the ratio of load loss watts to kVA.

No-load loss VAR and load loss VAR are the products of their respective kVAs times the sines of their respective power factor angles.

The Power Triangle may also be used to determine VAR. VAR equals the square root of kVA^2 minus watts^2.

BIDIRECTIONAL ENERGY FLOW

Usually, if energy is delivered by a high voltage line to a customer, it passes through the customer's transformer for use at a lower voltage. Compensation for losses between the high voltage billing point and the low voltage metering point is calculated by the meter and can be added to the metered (i.e., measured) data. Different meters may provide uncompensated meter data, compensated meter data, or both at the same time.

If energy flow is from a low voltage circuit to a high voltage circuit (e.g., a generation plant metering point), compensation is subtracted from the metered (i.e., measured) data to represent the net energy flowing into the transmission system.

Normally transformer loss compensators are wired additively but they can be ordered wired as subtractive. A pair of compensators, one additive and one subtractive, and a pair of detented watthour meters can meter and compensate bidirectional energy flow.

Bidirectional energy flow and compensation can be accomplished with one solid-state meter with a compensation option. Watthours and VAhour quantities can be metered and compensated by one solid-state meter. Some advanced meters can also compensate Q-hour.

METER LOCATION

The transformer-loss meter, or any meter compensating for transformer losses, should be connected to the low-voltage side of the circuit ahead of the disconnection device, so that the core losses may be registered even though the load is disconnected. For most types of construction the metering point is the point where the voltage circuit (or metering voltage transformer) is connected to the low-voltage bus.

Conductor copper losses on the low-voltage side between the billing point and the metering point should be included in the compensation calculations. These losses may be negligible, but in some cases it is desirable to include conductor losses in calibrating calculations if these losses assume appreciable proportions. Conductor copper losses are added to the copper losses of the transformer since both vary with the square of the current.

TRANSFORMERS WITH TAPS

Usually transformers are provided with taps to permit adjustment of utilization voltages. The loss data for transformers supplied by the manufacturers is generally based on the rated voltage. Iron losses in watts at rated voltage are the same as those existing when connection is made to a tap and its rated voltage applied. For copper losses of transformers it is sufficiently close to consider that the losses are divided equally between the high-voltage and the low-voltage sides and that the site of the conductor is the same throughout each of the windings. Taps on the high-voltage side are the most common. When metering on the low-voltage side, if copper loss is given for the rated voltage V_R and tap voltage V_T is used, the multiplying factor M_T to be applied to the copper loss at rated voltage will be:

$$M_T = \frac{V_R}{2V_T + 0.5}$$

For taps on the low-voltage side with metering also on the low-voltage side:

$$M_T = \frac{V_T}{2V_R} + \frac{1}{2}\left(\frac{V_T}{V_R}\right)^2$$

Multipliers calculated for most common taps are shown in Table 10-1. Where taps are used in both windings, both multipliers are required. Where taps might be changed rather frequently, or for use with automatic tap changers, the best performance is obtained by basing the adjustment on the median tap.

Table 10-1. Copper-Loss Multipliers for Common Transformer Taps with Low-Voltage Metering.

Percent Tap	Tap on High-Voltage Winding	Tap on Low-Voltage Winding
86.6	1.077	0.808
90.0	1.056	0.855
92.5	1.041	0.890
95.0	1.026	0.926
97.5	1.013	0.963
100.0*	1.000*	1.000*
102.5	0.988	1.038
105.0	0.976	1.076
107.5	0.965	1.115
110.0	0.955	1.155

*Tap on which copper loss data is based.

TRANSFORMER CONNECTIONS

Consideration must be given to the relationship existing between the load current through the power transformer winding and the current through the metering current transformer. The connections of the power transformers may affect the copper-loss calculations for determination of the meter calibrations. This will apply to the calibration of both the transformer-loss meter and the transformer-loss compensator.

Open-Delta Connections

For open-delta connections, full-load losses occur when the transformers are supplying 86.6% of the sum of the kVA ratings of the two transformers. Therefore, if an open delta bank was used, the value of the full-load line current would be multiplied by 0.866 to determine the current in the transformer windings at full-load transformer losses. This will apply to both the loss-meter and the loss-compensator calculations.

Scott Connections

In Scott connections used for three-phase to two-phase transformation, the teaser transformer is connected to the 86.6% tap. The copper-loss multiplier for the teaser transformer is 1.077 or 0.808 as shown in Table 10-1, depending on whether the metering is on the two-phase or three-phase side. For the main transformer, the copper-loss multiplier is 0.875 for metering on the three-phase side and 1.167 for metering on the two-phase side. This applies to both the loss-meter and loss-compensator calculations.

Three-Phase, Four-Wire Delta Connections

Three-phase, four-wire delta connections with a two-stator meter involve a special feature. When final tests of the meters are made with stators in series, the percent loss to which the transformer-loss compensator is adjusted applies to the stator connected to the two-wire current transformer. The stator connected to the three-wire current transformer measures the vector sum of the two currents displaced by 120°. For this stator, the percent of copper loss is multiplied by 1.155. For operation in service, the loss increment will then be divided equally between the two stators. Similarly, with the transformer-loss meter the speed of the stator connected to the three-wire current transformer should be increased by the relation:

$$1 \text{ to } \frac{5^2}{4.33^2} = 1 \text{ to } 1.333 \text{ or } 33.3\%$$

LOSS COMPENSATION METHODS

Electromechanical Transformer-Loss Meters

The basic measurement requirements for transformer losses call for a meter having one voltage-squared stator and one or more current-squared stators, depending on the number of metering current circuits. All stators are combined on the same shaft which drives a register of proper ratio to record the losses in kilowatthours or kiloVARhours. The E^2 stator consists of a standard watthour meter voltage coil and a low-current (possibly 50 mA) winding, which is connected in series with an adjustable resistor that serves as a core-loss adjustment. Registration is proportional to E^2. An I^2 stator consists of a standard current coil and a low-voltage voltage coil connected across the current coil and a series resistor in the current circuit. Registration, therefore, is proportional to I^2.

Standard transformer-loss meters equipped with two or three stators are supplied by the manufacturer and are designed for 3.6 seconds per revolution of the disk with five amperes flowing through each of the I^2 stators. Four-stator meters with five amperes flowing through each of the three I^2 stators are designed for 2.4 seconds per revolution of the disk. These values are for basic timing only; the meters are to be adjusted for each specific application. Calibration of heavy load is accomplished by adjusting the permanent magnets and light load by the light-load adjustment associated with the voltage coil of the E^2 stator. The watthour constant K_H, and the register ratio R_R, are selected so that the loss registration is in kilowatthours and the desired register constant K_R, obtained. If a demand register is used, the loss increment of maximum demand will be in kilowatts. Since the maximum loss demand will be coincident with the maximum load demand, except under very rare load conditions, the loss demand may be added to the load demand for billing purposes. Figure 10-1 shows the basic principles employed in the transformer-loss meter. Figure 10-2 shows the connections of a typical three-phase, three-wire, transformer-loss meter installation.

In all of the following descriptions of methods to be used for recording losses it must be remembered that any change in the original set of conditions will have an effect on the results. Should losses be calculated for paralleled lines, paralleled transformers, or for individual transformers, any changes in the connections or the methods of operation will call for a new set of calculations. The compensation meter has been generally superseded by the transformer-loss compensator because of the greater simplicity of the latter for the combined load-plus-loss measurement in a single meter. However, it remains as a useful instrument in those cases where separate loss measurements are required.

Transformer-Loss Compensator

In compensation for losses using the transformer-loss compensator, losses are added into the registration of the standard watthour meter that is used to measure the customer's load on the low-voltage side of the transformer bank. The transformer-loss compensator is connected into the current and the voltage circuits and, when properly calibrated, the losses will be included in the watthour meter registration.

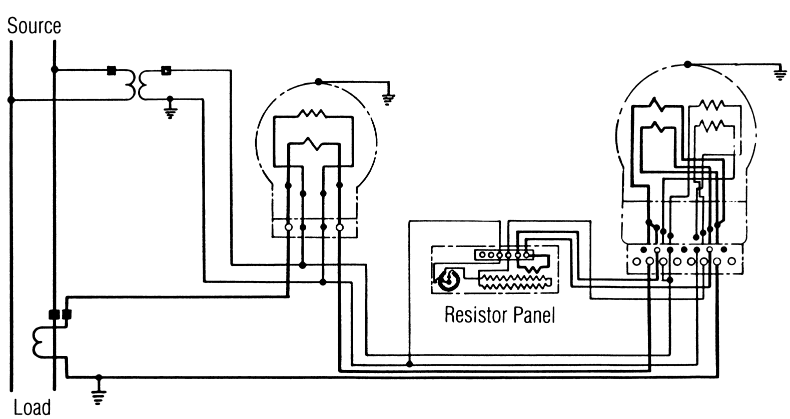


Figure 10-1. Principle of Loss Meter.

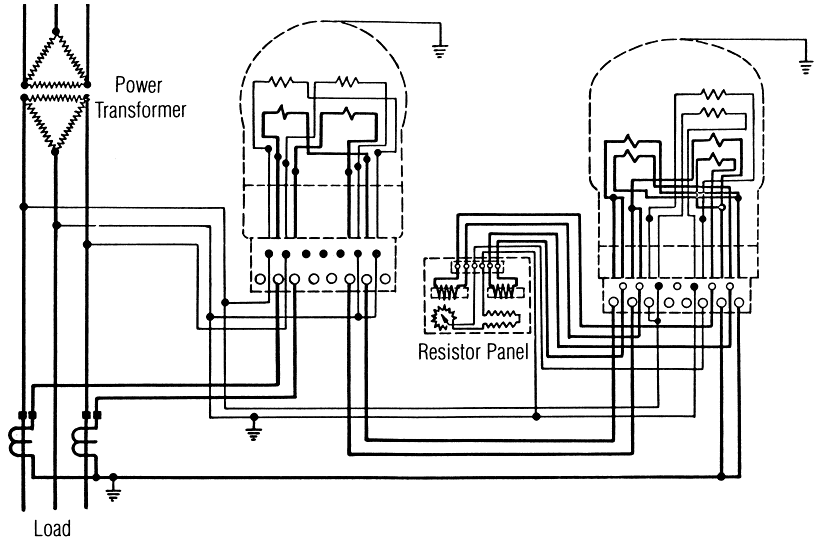


Figure 10-2. Connections for a Three-Phase, Three-Wire Loss Meter Installation.

For iron-loss compensation a 115/230:3 volt transformer, with its primary connected to the metering voltage supply and the three volt secondary connected in series with an adjustable resistor, provides a current which is passed through the current coil of the meter and is equivalent to the iron loss. As the iron-loss current so produced is proportional to the voltage, the iron-loss increment as measured by the meter is proportional to the square of the voltage.

To include the copper-loss increment, a small current transformer has its primary connected in series with the current coil of the watthour meter and an adjustable resistor connected to its secondary. The connections are such that the drop across the resistor is added to the voltage applied to the voltage coil of the meter. As the copper-loss component so produced is proportional to the current, the copper-loss increment as registered by the meter is proportional to the square of the current. Compensation for the flow of voltage-circuit current through the copper-loss element is provided. Figure 10-3 shows the principle of operation. Figure 10-4 shows the connection of a transformer-loss compensator for a typical three-wire, three-phase circuit. Three-element compensators suitable for connection to three-stator meters differ only in the addition of the third element. Figure 10-5 illustrates a two-element transformer-loss compensator.

In applying this method, the losses are determined in percent of the load at the light-, heavy-, and inductive-load test points of the meter. The meter normally used to measure the customer's load remains a standard measuring instrument and the compensator is calibrated by tests on the meter with and without the compensator. A switch is provided on the compensator for this purpose.

Resistor Method

The resistor method of loss compensation uses standard metering equipment which has been especially adapted to measure losses. No-load losses are compensated by a resistor which is energized by the meter voltage and with its watts-loss

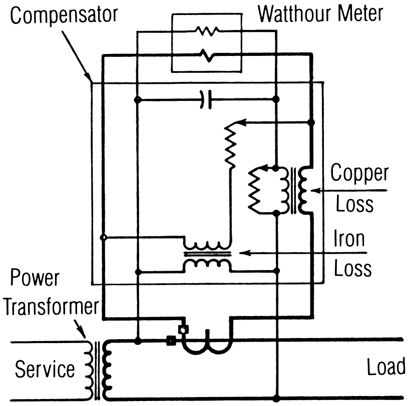


Figure 10-3. Principle of Transformer-Loss Compensator.

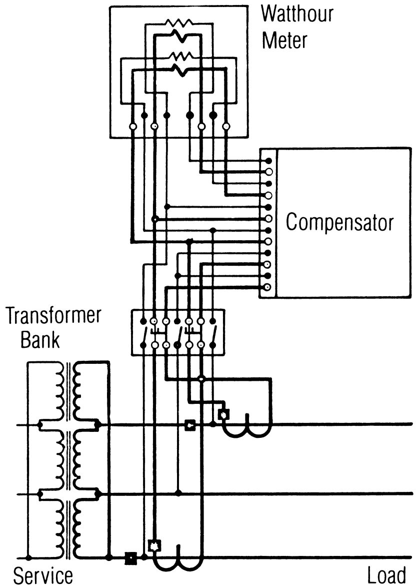


Figure 10-4. Connections of Meter and Transformer-Loss Compensator on a Three-Phase, Three-Wire Circuit.

measured by one stator of the watthour meter. Compensation for load losses is accomplished by setting the meter full-load adjustment and light-load adjustment to include the percent losses in meter percent registrations.

The resistor can be in the meter or in the meter enclosure. A resistor located in the enclosure is easier to install, replace, and calibrate than a resistor in the meter.

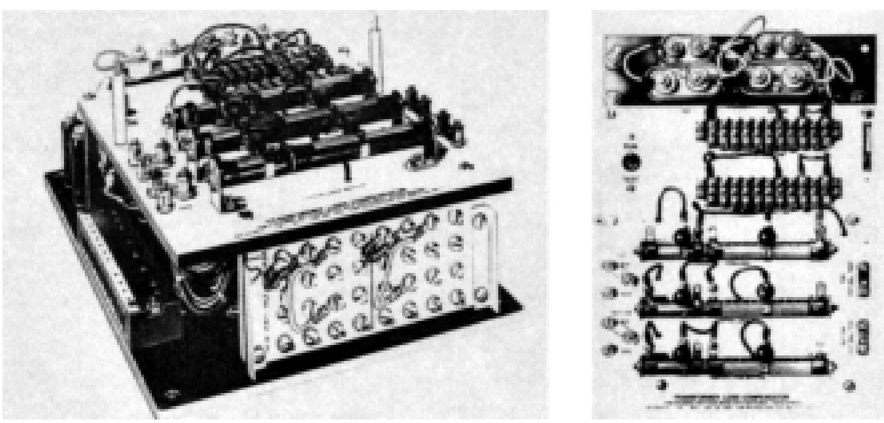


Figure 10-5. Front and Bottom Views of a Two-Element Transformer-Loss Compensator.

Solid-State Compensation Meter

A complete compensation meter combines transformer and line loss compensation with meter functions within the meter package. Modern compensation meters are solid-state with several optional compensation provisions.

Although solid-state meters compensate using the same mathematics as electromechanical meters combined with transformer loss compensators, they differ markedly in their method of operation. Instead of using resistances, tapped transformers, and capacitors to modify currents and voltages, solid-state compensation meters convert the current and voltage to digital inputs for microprocessor circuits, which then performs the mathematical operations to compute metered quantities (i.e., watts, VARs, VA, Q, etc.). Using the measured voltage and current, the microprocessor circuits also calculates the losses and adds (or subtracts) these losses to the metered quantities. Some meters are capable of measuring and displaying both compensated and uncompensated metered quantities at the same time.

LOSS CALCULATIONS

Determination of Losses

For both methods of metering losses the following information is requested from the manufacturer of the transformers: kVA rating, iron loss at rated voltage, copper loss at 75°C at rated full-load current, rated voltage, and voltage taps provided in the high-voltage and/or low-voltage side. If power factor tests are to be made on the low-voltage side or if VARhour losses need compensation, the following additional information is required: percent exciting current at rated voltage and percent impedance at 75°C. From a field inspection of the installation, data are obtained relative to transformer connections, taps in use, and the length, size, and material of conductors from the low-voltage terminals of the transformers to the metering point.

Application

The first step in applying loss compensation on any specific service, as pointed out before, is the collection from the manufacturer of certain data concerning the individual transformers and the securing of certain field data. It is recommended that forms be provided with which the average meter employee can become familiar. By filling in the data secured from these various sources, the procedures can more easily be followed. The application of the loss compensation meter or transformer-loss compensator may be better understood by the following steps, applied to a specific installation.

Typical Example

A 9,999 kVA transformer bank, consisting of three 115,000:2,520 volt, 3,333 kVA transformers, is connected delta-delta. Metering at 2,520 volts will be by a two-stator watthour meter connected to two 3,000:5 ampere current transformers and two 2,400:120 volt voltage transformers. It is desired to compensate the metering to record, in effect, the load on the 115,000 volt side of the power transformer using (a) a transformer-loss meter, and (b) a transformer-loss compensator. A field inspection indicates that the connection from the low-voltage terminals of the transformer to the metering point (where voltage transformers are connected) consists of the following conductors:

Carrying Phase Current: 96 ft. of 500 kcmil copper conductor and 69 ft. of square copper ventilated tubing, 4 in. × 4 in. × 5/16 in. thick.

Carrying Line Current: 54 ft. of 4 in. × 4 in. × 5/16 in. square ventilated copper tubing.

Figure 10-6 shows a suggested field-data form on which the information obtained in the field has been entered. This data serves as a basis for requesting loss information from the manufacturer and for loss calculations.

LOSS COMPENSATING METER INSTALLATION
FIELD DATA

Customer's Name or Station JOHN DOE MFG. CO

Address 1000 MARKET STREET

Transformer Data (From Name Plate)

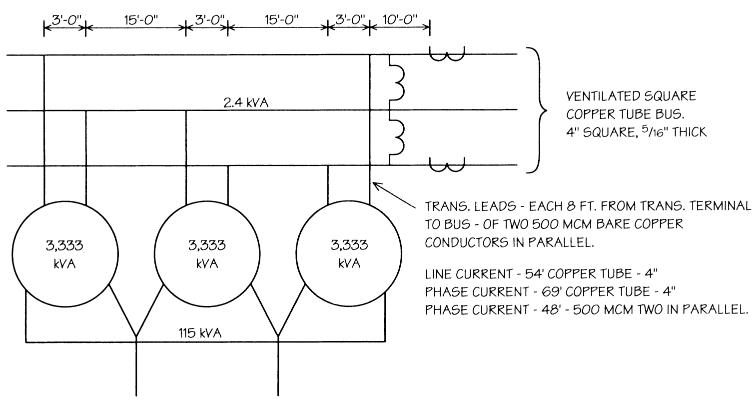
Make	Type	Serial No.	KVA Rating	Rated Voltage	Tap Voltage In Use	% Imp. 75° C.
WESTG	SL-OA	6530499	3,333	115,000/2,520	115,000/2520	8.16
WESTG	SL-OA	6530500	3,333	115,000/2,520	115,000/2520	8.03
WESTG	SL-OA	6530501	3,333	115,000/2,520	115,000/2520	8.12

Available Taps: H. V. 115,000; 112,125; 109,250; 106,375; 103,500 **L. V.** 2,520

Connections: Hi V: Delta ✗ **Wye** **Wire** 3 **Low V: Delta** ✗ **Wye** **Wire** 3

Current Transformer Ratio 3,000:5 **Voltage Transformer Ratio** 2,400:120

Secondary conductor data: Show size, length, and kind of secondary conductor from power transformer terminals to potential transformer connections. Make sketch below showing power transformer connections, secondary conductors, and ground connections.



By __________

Date __________

Figure 10-6. Field Sheet for Obtaining Loss Data on Power Transformers.

Calculation Methods

Figures 10-7 and 10-8 show suggested forms for making loss calculations. The loss data received from the manufacturer and the secondary conductor data obtained from the field have been entered and the iron and copper losses have been calculated. Total iron loss and total copper loss results will be used later for determining calibrations for transformer-loss meters and transformer-loss compensators.

LOSS CALCULATIONS (WATTS)

Customer's Name or Station JOHN DOE MFG. CO

Address 1000 MARKET STREET

Power Transformer Data (Furnished By: WESTINGHOUSE ELECTRIC CORP. **)**

Make	Type	Serial No.	Rated KVA	Rated Voltage	Tap Voltage In Use	Fe Loss At Rated Voltage	Cu Loss At Rated Voltage
WESTG	SL-OA	6530499	3,333	115,000/2,520	115,000/2,520	9,650	18,935
WESTG	SL-OA	6530500	3,333	115,000/2,520	115,000/2,520	9,690	18,400
WESTG	SL-OA	6530501	3,333	115,000/2,520	115,000/2,520	9,340	18,692

Connections: PRIMARY Delta ✗ **Wye** **Wire** 3 **SECONDARY Delta** ✗ **Wye** **Wire** 3

Instrument Transformer Ratio: CT 3,000:5 **VT** 2,400:120

Fe Loss Calculations:

Total Fe losses at power transformer at rated voltage:

9,650 + 9,690 + 9,340 = 28,680 WATTS

Total Fe losses at 120 volts (voltage transformer secondary):

$$\left(\frac{2{,}400}{2{,}520}\right)^2 \times 28{,}680 = 26{,}013.6 \text{ WATTS}$$

Cu Loss Calculations:

Transformer coil current (secondary) at full load:

$$\frac{3{,}333{,}000}{2{,}520} = 1{,}322.6 \text{ AMPS}$$

Line current at transformer <u>bank</u> (secondary) at full load:

$$1{,}322.6 \times \sqrt{3} = 2{,}290.9 \text{ AMPS}$$

Total transformer Cu losses at rated voltage and kVA:

18,935 + 18,400 + 18,962 = 56,027 WATTS

Total transformer Cu losses at voltage tap other than rated:

____

Transformer Cu losses at current transformer full load:

$$\left(\frac{3{,}000}{2{,}290.9}\right)^2 \times 56{,}027 = 96{,}078.8 \text{ WATTS}$$

Secondary conductor losses at current transformer full load:

$$\text{LINE CURRENT} = \frac{3{,}000^2 \times 54 \times .00275}{1{,}000} = 1{,}336.5 \text{ WATTS}$$

$$\text{PHASE CURRENT} = \frac{1{,}732^2 \times 69 \times .00275}{1{,}000} = 569.2 \text{ WATTS}$$

$$\text{PHASE CURRENT} = \frac{1{,}732^2 \times 48 \times .01099}{1{,}000} = 1{,}582.5 \text{ WATTS}$$

Total Watts Cu loss at current transformer at full load:

96,078.8 + 1,336.5 + 569.2 + 1,582.5 = 99,567.0 WATTS

Calculated By: ________ **Date:** ________ **Checked By:** ________ **Date:** ________

Figure 10-7. Calculations for Transformer Watt Losses.

LOSS CALCULATIONS (VARS)

Customer's Name or Station JOHN DOE MFG. CO

Address 1000 MARKET STREET

Power Transformer Data (Furnished By: WESTINGHOUSE ELECTRIC CORP. **)**

Make	WESTG	WESTG	WESTG	
Type	SL-OA	SL-OA	SL-OA	
Serial Number	6530499	6530500	6530501	
Rated kVA	3,333	3,333	3,333	
Rated Voltage	115,000/2,520	115,000/2,520	115,000/2,520	
Tap Voltage in Use	115,000/2,520	115,000/2,520	115,000/2,520	
Fe Loss Rated Voltage	9,650	9,690	9,340	
Cu Loss at Full Load	18,935	18,400	18,692	
% Imp. at 75°	8.16	8.03	8.12	
% Exciting Current	1.00	1.06	0.91	

Instrument Transformer Ratio: CT 3,000:5 **VT** 2,400:120

Core Loss

$$VA = 3{,}333{,}000 \times .01 = 33{,}330$$
$$\cos\theta = \frac{9{,}650}{33{,}330} = .2895$$
$$\sin\theta = .9571$$
$$VARs = 33{,}330 \times .9571 = 31{,}900$$

$$VA = 3{,}333{,}000 \times .0106 = 35{,}329$$
$$\cos\theta = \frac{9{,}690}{35{,}329} = .2742$$
$$\sin\theta = .9617$$
$$VARs = 35{,}329 \times .9617 = 33{,}975$$

$$VA = 3{,}333{,}000 \times .0091 = 30{,}330$$
$$\cos\theta = \frac{9{,}340}{30{,}330} = .3079$$
$$\sin\theta = .9514$$
$$VARs = 30{,}330 \times .9514 = 28{,}855$$

TOTAL VARs = 94,730

AT RATED VOLTAGE $= \left(\frac{2400}{2520}\right)^4 \times 94{,}730$

$= 77{,}934.2$ VARs

Copper Loss

$$VA = 3{,}333{,}000 \times .0816 = 271{,}972$$
$$\cos\theta = \frac{18{,}935}{271{,}972} = .06962$$
$$\sin\theta = .9975$$
$$VARs = 271{,}972 \times .9975 = 271{,}292$$

$$VA = 3{,}333{,}000 \times .0803 = 267{,}639$$
$$\cos\theta = \frac{18{,}400}{267{,}639} = .06874$$
$$\sin\theta = .9976$$
$$VARs = 267{,}639 \times .9976 = 266{,}996$$

$$VA = 3{,}333{,}000 \times .0812 = 270{,}639$$
$$\cos\theta = \frac{18{,}692}{270{,}639} = .06906$$
$$\sin\theta = .9976$$
$$VARs = 270{,}639 \times .9976 = 269{,}989$$

TOTAL VARs = 808,277

AT CURRENT TRANSF. FULL LOAD $= \left(\frac{3000}{2290.9}\right)^4 \times 808{,}277$

$= 1{,}386{,}086$ VARs

Calculated By: ______ **Date:** ______ **Checked By:** ______ **Date:** ______

Figure 10-8. Calculations for Transformer VAR Losses.

Thus far, the procedure is identical for both transformer-loss meters and transformer-loss compensators. Throughout the calculations an empirical assumption is made that within small variations of the rated voltage, iron watt losses vary as the square of the voltage and the iron VAR losses vary approximately as the fourth power of the voltage.

Loss Compensation Formulas

Calculations should be referred to the high voltage circuit or to the low voltage circuit. Once the choice is made, the convention should be followed for all subsequent calculations to avoid confusion. The formulas which follow all refer to the high voltage circuit.

Note: VTR = Voltage Transformer Ratio
CTR = Current Transformer Ratio

$$\text{LWFe} = \text{Watt losses due to iron (core-loss watts)}$$

$$\text{LWFe} = \text{No-load Test Watts} \times \frac{(\text{Meter Voltage} \times \text{VTR})^2}{(\text{Rated Transformer Volts})^2}$$

$$\text{LWCu} = \text{Watt losses due to copper}$$

$$\text{LWCu} = \text{Load Test Watts} \times \frac{(\text{Meter Test Current} \times \text{CTR})^2}{(\text{Transformer Test Amps})^2}$$

$$\text{LVFe} = \text{VAR losses due to iron (core-loss VAR)}$$

$$\text{LVFe} = \text{No-load VAR} \times \frac{(\text{Meter Voltage} \times \text{VTR})^4}{(\text{Rated Transformer Volts})^4}$$

With No-load VAR being calculated as follows:

$$\text{No-load VA} = (\text{Transformer Percent Exciting Current}/100) \times (\text{Transformer kVA Rating} \times 1000)$$

$$\text{No-Load VAR} = \text{SQRT}((\text{No-load VA Loss})\text{\^{}}2 - (\text{No-Load Watts})\text{\^{}}2)$$

$$\text{LVCu} = \text{VAR losses due to copper}$$

$$\text{LVCu} = \text{Load VAR} \times \frac{(\text{Meter Test Current} \times \text{CTR})^2}{(\text{Transformer Test Amps})^2}$$

With Load VAR being calculated as follows:

$$\text{Transformer Load VA Loss} = (\text{Transformer Percent Impedance}/100) \times (\text{Transformer kVA Rating} \times 1000)$$

$$\text{Load VAR} = \text{SQRT}((\text{Load VA Loss})\text{\^{}}2 - (\text{Load Watts Loss})\text{\^{}}2)$$

$$\%\text{LWFe} = \text{Percent Iron Watt Loss (Core Loss)}$$

$$\%\text{LWFe} = \frac{\text{LWFe} \times 100}{\text{Meter Test Current} \times \text{Meter Voltage} \times \text{CTR} \times \text{VTR}}$$

$$\%\text{LWCu} = \text{Percent Copper Watt Loss (Load Loss)}$$

$$\%\text{LWCu} = \frac{\text{LWCu} \times 100}{\text{Meter Test Current} \times \text{Meter Voltage} \times \text{CTR} \times \text{VTR}}$$

$$\%\text{LVCu} = \text{Percent Copper VAR Loss (Load VAR)}$$

$$\%\text{LVCu} = \frac{\text{LVCu} \times 100}{\text{Meter Test Current} \times \text{Meter Voltage} \times \text{CTR} \times \text{VTR}}$$

$$\%LVFe = \text{Percent Iron VAR Loss (Core VAR)}$$

$$\%LVFe = \frac{LVFe \times 100}{\text{Meter Test Current} \times \text{Meter Voltage} \times CTR \times VTR}$$

Meter test current is test current with metered current elements (coils) in series, and with unity power factor. Meter test voltage is test voltage with meter voltage elements (coils) in parallel, and with unity power factor.

$$\begin{aligned}
\text{Meter test current} &= \text{Meter TA} \times K \\
\text{Meter test current} &= \text{5.0 amperes (transformer rated)} \times K \\
\text{Meter test current} &= \text{50\% Class (JEMTECH)} \times K \\
\text{Where } K &= \text{3 (three-element meter)} \\
K &= \text{2 (two-element meter)} \\
K &= 4\ (2^1\!/\!_2\text{-element meter})
\end{aligned}$$

$$\text{Transformer Test Amps} = \frac{\text{Transformer Test kVA}}{\sqrt{3} \times \text{Transformer Rated kV}}$$

Calculate %LWFe, %LWCu, %LVFe, and %LVCu for full load, single phase, and with unity power factor.

If the test voltage remains constant:

%LWCu is proportional to test load (test amps)
%LWCu is inversely proportional to power factor

%LWFe is inversely proportional to test load (test amps)
%LWFe is inversely proportional to power factor

%LVCu is proportional to test load (test amps)
%LVCu is inversely proportional to power factor

%LVFe is inversely proportional to test load (test amps)
%LVFe is inversely proportional to power factor

These relationships permit light-load test and 50% power-factor-load test values which are derived from full-load test values.

Percent Watthour Losses

Percent watthour losses, calculated at full-load meter test, can be used to determine the percent watthour losses at light load and at 50% lag load. For example, the percent *copper* loss for the meter light-load (10%) test is one-tenth the *copper* loss for the meter full-load (100%) test. The percent *iron* loss at meter light-load test is 10 times the *copper* loss at meter full-load. The percent *copper* loss at a meter lag load (50% power factor) is twice the *copper* loss of the meter full-load test. The percent *iron* loss at meter lag load is twice the *iron* loss of the meter full-load test.

The percent losses are added to the percent registration of the uncompensated meter to obtain the calibration percent registrations of the compensated meter.

TRANSFORMER-LOSS METER

Calibrations

Figure 10-9 is a suggested form to be used for transformer-loss meters. This form lists the calculations necessary for calibration of the transformer-loss meter to be used with the typical installation that has been selected for this example.

LOSS METER CALIBRATIONS

Customer's Name or Station JOHN DOE MFG. CO

Address 1000 MARKET STREET

Loss Meter Calibration Data:

Co. No. 68480 **Serial No.** 27891397 **Make** G. E.

Type V-21-A **Amps.** 5 **Volts** 120 **Phase** 3 **Wire** 3 **Stators** 2

K_h 100 R_r 100 R_g 10,000 **Reg. Type** M-30 K_r 100 **Demand K** 100

Connections: PRIMARY Delta ✗ **Wye** **Wire** 3 **SECONDARY:** ✗ **Wye** **Wire** 3

Cu Element Calibration:

Cu loss at full load of current transformer 99,567 **(watts).**

Seconds / disk revolution with 5 amperes through meter coils connected series 3.6156 **seconds.**

Fe Element Calibration:

Fe loss at 120 volts 26,013.6 **(watts).**

Seconds / disk revolution 13.839 **seconds.**

The above information from calculations below:

K_h **(Basic):** $\frac{99{,}567 \times 3.6}{3{,}600} = 99.57$

Selected — K_h 100 R_r 100 K_r 100 **Demand K** 100

Cu Loss — Sec / disk revolution at 5 amperes:

$\frac{100 \times 3{,}600}{99{,}567} = 3.6156$ seconds

Fe Loss — Sec / disk revolutuion at 120 volts:

$\frac{100 \times 3{,}600}{26{,}013.6} = 13.839$ seconds

Calculated By: ______ **Date:** ______ **Checked By:** ______ **Date:** ______

Figure 10-9. Calculations for Determining Loss Meter Calibrations.

The final calibrating data is listed in seconds per revolution at 120 V for the iron-loss element and at five amperes for the copper-loss element. These quantities are selected in order that testing values for all loss installations will be uniform. Also, 120 V is the normal rated secondary voltage of most voltage transformers and five amperes is the secondary current of the current transformer operating at its full rating. The calculations for VAR losses are needed only if power-factor determinations or VARhour measurements are to be made on the low-voltage side. If VAR losses are required, the form shown in Figure 10-9 would be used in the same manner as described for watt losses.

Meter Test

Transformer-loss meters usually are calibrated and tested using an ammeter, a voltmeter, a stop watch, a variable supply of voltage and current, and applying the revolutions per second as determined from calculations. If the number of meter installations warrants, a portable standard transformer-loss meter may be used. This consists of an E^2 and an I^2 element which can be operated separately. The E^2 element operates at 3.6 seconds per revolution for 120 V and the I^2 element at 3.6 seconds per revolution for five amperes. Service meters can be tested by comparison with this test meter using the ratio of the meter to the standard revolutions. In such cases, variations in current or voltage during the test would be compensated for automatically.

Initial adjustment of a transformer-loss meter consists of balancing the individual stator torques. For this test, voltage only is applied to the E^2 stator. Five amperes of current is passed through each I^2 stator individually and the separate torques adjusted by the torque balance adjustments until they are equal. An arbitrary current of 45 to 60 mA is then passed through the current coil of the E^2 stator and the torque adjusted to equal that produced by each of the I^2 stators.

Full-load calibration is accomplished by applying rated voltage only to the E^2 stator and passing five amperes through the I^2 stators in series. The meter speed is adjusted using the braking magnets until the calculated copper-loss speed is obtained. Following the full-load test, with voltage only still applied to the E^2 stator, the current in the I^2 stators is reduced to an arbitrary light-load value and the meter speed is adjusted to the correct value using the light-load adjustment on the E^2 stator. If a value of $1^1/_2$ amperes is selected for the light-load test, the correct meter speed will be 9% of the value at full load since speed varies with the square of the current in the I^2 stators, and the time per revolution will be $11^1/_9$ times that at full load.

The final calibration test consists of removing all current from the I^2 stators and connecting the external resistors to supply current to the E^2 stator. The E^2 stator current is then adjusted by the resistors to produce the calculated speed value for transformer-core-loss measurement at rated voltage.

TRANSFORMER-LOSS COMPENSATOR

Calibrations

Should a transformer-loss compensator be used, Figure 10-10 shows a form that may be used for calculations and calibration data. The losses at light-load, full-load, and inductive-load test points are calculated in terms of the watt loads at

DETERMINATION OF METER CALIBRATIONS AND COMPENSATOR SETTINGS

KWH Meter:

Co. No. 67614 **Ser. No.** 19022727 **Make** WESTG **Type** R1-2

Amps 5 **Volts** 120 **Phase** 3 **Wire** 3

K_h 2/3 **R_r** 3,000 **R_g** 15,000 **K_r** 12,000 **Demand K** 12,000

Current Transformer Ratio 3,000:5 **Voltage Transformer Ratio** 2,400:120

Demand Element:

Co. No. ________ **Ser. No.** ________ **Make** ________ **Type** ________ **Volts** ________

Demand Interval 30 Minutes **Demand Constant** 12,000

Loss Compensator:

Co. No. 164 **Ser. No.** 15409 **Make** E. S. **Type** 1014 **Volts** 120

Phase 3 **Wire** 3 **Delta or Wye** D **Elements** 2

DETERMINATION OF METER CALIBRATIONS:
Full load meter rating for series test:

2 **EI Cos θ =** 2 × 2400 × 3000 = 14,400,000 WATTS

Percent Iron Loss: $\frac{26{,}013.6 \times 100}{14{,}400{,}000} = .180\%$

Percent Copper Loss: $\frac{99{,}567 \times 100}{14{,}400{,}000} = .691\%$

Percent Meter Calibration with Compensator:

Load	Stator	Meter Calibration	% Fe Loss	% Cu Loss	% Total Loss	Final % Registration
Light	Series	100.0	1.80	.0691	1.869	101.9
	Top or Right					
	Mid or Split					
	Bot or Left					
Full	Series	100.0	.180	.691	.871	100.9
	Top or Right					
	Mid or Split					
	Bot or Left					
Inductive	Series	100.0	.360	1.382	1.742	101.7
	Top or Right					
	Mid or Split					
	Bot or Left					

Calculated By: ________ **Date:** ________ **Checked By:** ________ **Date:** ________

Figure 10-10. Calculations for Determining Transformer Compensator Calibration.

which the meter is tested. For a polyphase meter at the full-load test point, this is the product of the number of meter stators and the voltampere rating of each stator. The percent loss at any other load may be calculated by proportion. While copper losses vary as the square of the load current, percent copper losses vary directly with the percent load on the meter. Similarly, percent iron losses vary inversely with the percent load on the meter. Therefore, for any load a percent loss can be determined. For meter test loads at power factors other than 1, it is necessary to divide the percent iron and percent copper losses at power factor 1.0 by the desired power factor. Thus, calibrations for percentage losses need be made only for the full-load test point. Other loads are determined by proportion as shown in Figure 10-10. As in the case of the compensation meter installation, the calculation of VAR losses is made only if power factor determinations or VARhour measurement on the low-voltage side are to be compensated to the high-voltage side. The VAR-loss calculations are performed similar to the watt-loss calculations shown in Figure 10-10.

Test

A transformer-loss compensator and a watthour meter are connected for test in the same manner as a watthour meter. With the compensator test switch in the test position, thus disconnecting the compensator from the watthour meter, the watthour meter is tested in the usual way. When all of the tests on the watthour meter are completed, the compensator test switch is opened which will place the copper-loss elements in the circuit. Current is applied to each stator separately with the appropriate copper-loss resistor in the circuit in each case. In Figure 10-10 the percent copper loss at full load was calculated as 0.691%. With five amperes in each stator, one at a time, the performance is adjusted by the compensator loss resistors to give single-stator performance values 0.7% faster than the values obtained in the final meter calibration. (For three-phase, four-wire delta meters, see comments earlier in this chapter under “Transformer Connections”.) After this check, the compensator test switch is closed in the normal position, which includes the iron-loss element in the circuit, and meter test onnections are made for the series test. With light-load current, the iron-loss element is adjusted to the calculated light-load setting point. Since the copper-loss units are also in the circuit, the value for this test, shown in Figure 10-10, is the total final percent registration of 101.9. A final check should then be made with the compensator at all loads. It must be remembered that inductive-load tests are for check purposes only since it is not possible to make any compensator adjustments under this condition. If the compensator adjustments are correct under the other test conditions, the meter performance with inductive load should agree with the calculated value. In making inductive-load tests it must be remembered that any deviation in power factor from the nominal value of 0.5 lagging will result in differences from the desired performance. For inductive load tests, therefore, it is important that the test results be compared with the desired values for the power factor at which the test is made.

Tests in service follow the same general principles. A test on the meter with and without the compensator determines the accuracy of either the meter or the compensator. The compensator’s performance is indicated by the difference between the results of the test with and without the compensator.

If the compensator requires adjustment, errors on the heavy-load test are corrected with the copper-loss adjustment; those at light load with the iron-loss adjustment. If inductive-load tests are desired in the field, it is important to establish and correct for the true power factor of the test load. The phase angle of the loading devices and possible variations in the three-phase line voltages all have an effect on the true power factor of the test load.

RESISTOR METHOD

There are other methods being used to measure transformer losses that employ standard metering equipment especially adapted to measure losses. One such method uses a standard watthour meter connected to the secondary side of the transformer bank in the usual manner.

Copper-loss compensation is effected by applying corrections to the observed meter registration at heavy load and at light load in a manner similar to the application of instrument transformer corrections. In general, the loss is added to the load kilowatthour registration by applying a negative correction equal in value to:

$$100\left[\frac{\text{kW bank losses}}{\text{kW load}}\right]$$

so that the observed meter registration is correct at the test load employed. These corrections are computed from the known copper loss of the transformer bank at rated load and take into account the power factor of the customer's load.

Since copper losses vary as the square of the load current, the required adjustment at any load point, I, is equal to I^2/I, or is in direct proportion to the load current I. For example, the adjustment at 10% meter load will be one-tenth of that required at 100% load. In this manner, the performance curve of the watthour meter so adjusted, will closely follow the copper-loss curve of the power transformer throughout its load range.

Core-loss compensation is obtained by adding a single-phase load to the watthour meter in the form of a fixed resistor mounted within the meter. The resistor is connected so that it is energized by the meter voltage and its watts loss is measured by one stator of the watthour meter. The actual watts load added to the meter is equal to the bank core loss divided by the product of the instrument transformer ratios used.

Since the resistance is fixed, the watts loss varies as the square of the voltage and the measurement of this watts loss is equivalent to direct measurement of the core loss of the power-transformer bank which also varies approximately with the square of the voltage.

Formula for Calculating Resistance

The value of the resistance to be used for this resistor is determined by the following equation:

$$R = \frac{E_{mo}^2 \times N_v \times N_c}{1000 L_i \dfrac{E_{mo}^2}{E_m^2}} = \frac{E_m^2 \times N_v \times N_c}{L_i \times 1000}$$

Where

R = Resistance in ohms

E_m = Calculated meter voltage

$= \dfrac{\text{Rated secondary voltage of transformer bank}}{N_v}$

E_{mo} = Meter operating voltage

N_v = Ratio of instrument voltage transformers

N_C = Ratio of instrument current transformers

L_i = kW core loss of transformer bank at rated voltage

= kW core loss at calculated meter voltage E_m

Formula for Computing Compensation Corrections

The percentage registration for a compensated meter should be as follows:

1. Percentage Registration $= 100 \left[\dfrac{\text{kW load} + \text{kW bank losses}}{\text{kW load}}\right]$

2. Percentage Registration $= 100 \left[\dfrac{\text{kW load}}{\text{kW load}}\right] + 100 \left[\dfrac{\text{kW bank losses}}{\text{kW load}}\right]$

The first component, $100 \left[\dfrac{\text{kW load}}{\text{kW load}}\right]$, represents the meter registration due to the load.

The second component, $100 \left[\dfrac{\text{kW bank losses}}{\text{kW load}}\right]$, represents the meter registration due to the losses in the transformer bank.

As it is desirable that an overall correction be applied which includes the compensation required for both the core loss and the copper loss, the watthour meter is tested with the compensation resistor current added to the test-load current in the meter but not in the portable standard watthour meter. The following formulas are derived on this basis.

Copper-Loss Correction

From formula 2 above, the correction for copper loss may be stated as:

3. Copper-loss correction $= -100 \left[\dfrac{\text{kW bank losses}}{\text{kW load}}\right] \%$

Let L_c = kW copper loss of transformer bank at rated kVA load
$\cos\theta$ = Average power factor of customer's load
T = Transformer bank kVA rating at full load
A = kW load in percent of rated kW load of transformer bank

Then formula 3 becomes:

4. Copper-loss correction at rated load of bank $= -100 \dfrac{L_c}{T\cos\theta} \%$

Since copper losses vary as the square of the load current, the kW = 100 copper loss at any load A is equal to

$\left[\left(\dfrac{A}{100}\right)^2 L_c\right]$ and since the kW load at A is equal to $\left(\dfrac{A}{100}\right)$T $\cos\theta$, then

Copper-loss correction at any load A is:

5. $A = -\left[\dfrac{100\left(\dfrac{A}{100}\right)^2 L_c}{\left(\dfrac{A}{100}\right) T\cos\theta}\right] = -100 \left[\dfrac{\left(\dfrac{A}{100}\right) L_c}{T\cos\theta}\right] \%$

To convert load A to test load

Let S = Test load in percent of meter rating

$F = \dfrac{\text{Meter capacity [See note below]}}{\text{Rated kVA of transformer bank} \times 1{,}000}$

whence $A = SF$. Substituting SF for A, formula 5 may be expressed as:

6. Copper-loss correction at test load $S = -100 \left[\dfrac{\left(\dfrac{SF}{100}\right) L_c}{T\cos\theta}\right] \%$

Core-Loss Correction

From Formula 2, the correction for core loss may be stated as:

7. Core-loss correction $= -100 \left[\dfrac{\text{kW bank core loss}}{\text{kW load}}\right]\%$

Let L_i = kW core loss of transformer bank at rated secondary voltage. Then core-loss correction at rated kVA load is

8. $= -100 \left[\dfrac{L_i}{T\cos\theta}\right]\%$

Since core losses do not change with load current, the kW core loss is

9. $= -100 \left[\dfrac{L_i}{\left(\dfrac{A}{100}\right)T\cos\theta}\right]\%$

Since $A = SF$, then core-loss correction at test load S

10. $= -100 \left[\dfrac{L_i}{\left(\dfrac{SF}{100}\right)T\cos\theta}\right]\%$

Since the kW core loss of the transformer bank is given at rated voltage and since at the time of the meter test the operating voltage of the bank may differ from the rated voltage, the value of core loss for the operating voltage is determined as follows:

Let E = Rated secondary voltage of the transformer bank
E_o = Operating voltage of the transformer bank

11. Then kW core loss at $E_o = \left(\dfrac{E_o}{E}\right)^2 \times L_i$

Since voltage measurements are taken at the meter terminals, let:

E_m = Calculated meter voltage

$= \dfrac{\text{Rated secondary voltage of transformer bank}}{\text{Voltage transformer ratio}}$

$= \dfrac{E}{N_v}$

E_{mo} = Meter operating voltage at time of test $= \dfrac{E_o}{N_v}$

From which $E = E_m \times N_v$ and $E_o = E_{mo} \times N_v$

Formula 1 then becomes:

12. kW core loss at $E_o = \left(\dfrac{E_{mo} \times N_v}{E_m \times N_v}\right)^2 L_i = \left(\dfrac{E_{mo}}{E_m}\right)^2 L_i$

Formula 10 may be restated:
Core-loss correction at test load S and any meter voltage

13. $E_{mo} = -100 \left[\dfrac{L_i\left(\dfrac{E_{mo}}{E_m}\right)^2}{\left(\dfrac{SF}{100}\right)T\cos\theta}\right]\%$

Combined Copper- and Core-Loss Correction

Combining formulas 6 and 13, the combined copper-loss and core-loss correction becomes:

Compensated metering correction at test load S and meter operating voltage can be expressed as:

$$14.\ E_{mo} = -\frac{100}{T\cos\theta} \times \left[\frac{SF\,L_c}{100} + \frac{100L_i\left(\frac{E_{mo}}{E_m}\right)^2}{SF}\right]\%$$

Where

L_c = kW copper loss of transformer bank at rated kVA load
L_i = kW core loss of transformer bank at rated voltage
T = Transformer bank kVA rating at full load
$\cos\theta$ = Average power factor of customer's load
E_{mo} = Meter operating voltage at time of test
E_m = Calculated meter voltage

$$= \frac{\text{Rated secondary voltage of transformer bank}}{\text{Voltage transformer ratio}}$$

S = Test load in percent of meter kVA rating
= 100% for heavy-load test = 10% for light-load test

$$F = \frac{\text{Meter capacity (See Note below)}}{\text{Rated kVA of transformer bank} \times 1{,}000}$$

Note: Meter capacity is defined as (meter primary amperes) × (meter primary volts) × (number of stators), except for three-phase, three-wire, two-stator meters, for which meter capacity is (meter primary amperes) × (meter primary volts) × $\sqrt{3}$.

An example of the data necessary in calculating settings for resistor-type compensated meters follows.

Transformer Bank Rating (T)	1,500 kVA
Rated Primary Voltage of Transformer Bank	26,400 volts
Rated Secondary Voltage of Transformer Bank (E)	2,400 volts
Service Characteristic of Transformer Bank Secondary	three-phase, three-wire, delta
Ratio of Metering Voltage Transformers (N_v)	2,400:120 volts
Ratio of Metering Current Transformers (N_c)	400:5 amperes
Calculated Meter Voltage ($E_m = E/N_v$)	120 volts
Core Loss of Transformer Bank (L_i at E)	3.680 kW
Copper Loss of Transformer Bank (L_c at T)	13.130 kW
Customer's Average Power Factor ($\cos\theta$)	1.0

$$\text{Ratio Factor } (F) = \frac{\text{Primary Meter Volts} \times \text{Primary Meter Amps} \times \sqrt{3}}{T \times 1{,}000} = 1.11$$

Using this data, compensation resistance can be computed:

$$\text{Compensation Resistance} = R = \frac{E_m^{\,2} \times N_v \times N_c}{L_i \times 1000} = 6{,}261 \text{ ohms}$$

Compensated meter correction, for assumed values of Emo (meter operating voltage at time of test), and with S (test load, in percent), assumed to be 100% and then 10%, can be computed and are shown in the table below.

$$\text{Compensated Metering Correction} = -\frac{100}{T\cos\theta}\left[\frac{SF \times L_c}{100} + \frac{100\ L_i}{SF}\left(\frac{E_{mo}}{E_m}\right)^2\right]\%$$

Table 10-2. Compensated Meter Correction.

E_{mo} (Volts)	S = 100%	S = 10%
110	–1.2%	–2.0%
112	–1.2%	–2.0%
114	–1.2%	–2.1%
116	–1.2%	–2.2%
118	–1.2%	–2.2%
120	–1.2%	–2.3%
122	–1.2%	–2.4%
124	–1.2%	–2.5%
126	–1.2%	–2.5%

Figure 10-11 gives the connections for the testing of a watthour meter with its compensation resistor.

Occasionally situations arise when it is necessary to subtract the transformer losses from the kilowatthour registration. To accomplish this, the fixed resistor is connected so that its watts loss is subtractive, the sign before the formula is reversed, and the meter speed adjusted with a positive correction applied.

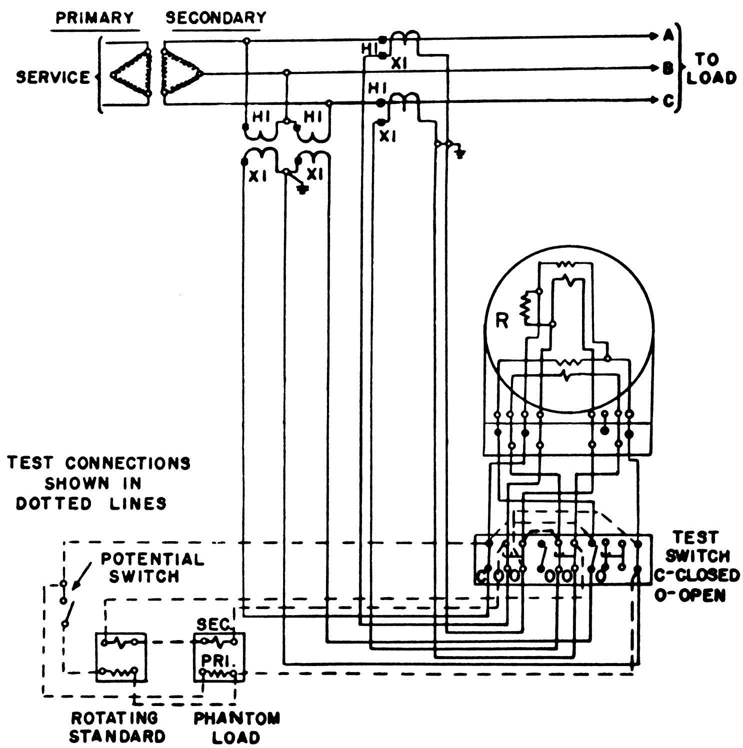


Figure 10-11. Test Connections for Three-Phase, Three-Wire, Two-Stator Watthour Meter with Compensating Resistor.

SOLID-STATE COMPENSATION METERS

Derivation of Coefficients

Solid-state meters with transformer loss compensation (TLC) options are sometimes programmed by the manufacturer using loss data provided by the meter purchaser, but are most often programmed by the user for each metering site. Since transformers and bus wiring are site specific, loss compensation parameters are usually unique to each site.

The meter performs internal calculations to generate compensation values and adds those values to measured quantities. When the meter is programmed, coefficients based on TLC percentages and other meter-specific information are stored by the meter and accessed each time a loss calculation is performed.

The compensated metered quantities can then be stored as part of typical billing data (energy, demand, load profile data, etc.) can be displayed, generate an energy pulse output, and can be used as triggers or alarms.

SUMMARY

The methods described in this section are useful as compared to metering on the high-voltage side:

1. When the metering cost is appreciably lower than for metering on the high-voltage side,
2. For exposed locations on the system, where high-voltage instrument transformer equipment may be expected to be troublesome because of lightning or other disturbances,
3. When the limited available space makes the installation of high voltage metering equipment difficult, hence more expensive,
4. When a customer with a rate for low-voltage service is changed to a high-voltage service rate.

Generally speaking, metering on the high-voltage side should be preferred when:

1. The cost of high-voltage metering is lower than for methods with loss compensation,
2. Multiple low-voltage metering installations are necessary in place of one metering equipment on the high-voltage side,
3. Primary metering is necessary because a part of the load is used or distributed at the supply voltage.

Comparing the compensation meter with the transformer-loss compensator, the advantages of the compensation meter are:

1. Iron losses are registered at no load, regardless of how small they are,
2. The load measurement on the low-voltage side by the conventional watthour meter is available as a separate quantity from the losses.

The disadvantages of the compensation meter are:

1. Two meters are used which complicates the determination of maximum demand,
2. Special test equipment, not ordinarily carried by meter testers, is required.

TOTALIZATION

Introduction

Totalization is the combining the metering of two or more electrical circuits. Revenue metering of a customer who is served by two or more lines and is billed on coincident demand must be totalized. Totalization is done in real time, addition of the individual meter readings does not suffice.

Often totalization is not necessary but is used to simplify meter reading and the subsequent accounting procedures. Monthly kilowatthour usage, for example, can be the addition of the individual meter readings or one totalized meter reading.

Totalization is the algebraic addition of like electrical quantities, done on a real time basis. The addition can be as simple as combining the kilowatthour usage of two circuits, or as complicated as solving an algebraic algorithm to determine the net usage for an installation with multiple internal and external sources and loads.

Several methods to totalize the metering of multiple circuits are available.

Parallel Current-Transformer Secondaries

Totalization before measurement, such as paralleling the secondaries of the current transformers in two or more circuits having a common voltage source, is shown in Figure 10-12. Here the secondaries of the current transformers on Line 1, of circuits A and B, have been connected in parallel at the coil of the meter. A similar arrangement would be used on Line 3. Precautions must be taken because of the difficulties arising from the increased effects of burden and the flow of exciting current from one transformer to the other during imbalanced load conditions. The following precautions are important:

1. All of the transformers must have the same nominal ratio regardless of the ratings of the circuits in which they are connected,
2. All transformers which have their secondaries in parallel must be connected in the same phase of the primary circuits,
3. The secondaries must be paralleled at the meter and not at the current transformers,
4. There should be only one ground on the secondaries of all transformers at their common point at the meter,
5. Use modern current transformers with low exciting currents and, therefore, little shunting effect when one or more current transformers are floating at no load. (Three or more floating current transformers might have an effect that should be investigated),
6. The secondary circuits must be so designed that the maximum possible burden on any transformer will not exceed its rating. The burden should be kept as low as possible as its effects are increased in direct proportion to the square of the total secondary current,
7. A common voltage must be available for the meter. This condition is met if the circuits share a common bus that is normally operated with closed bus ties,
8. A common voltage must be available for the meter,
9. Burdens and accuracies must be carefully calculated,

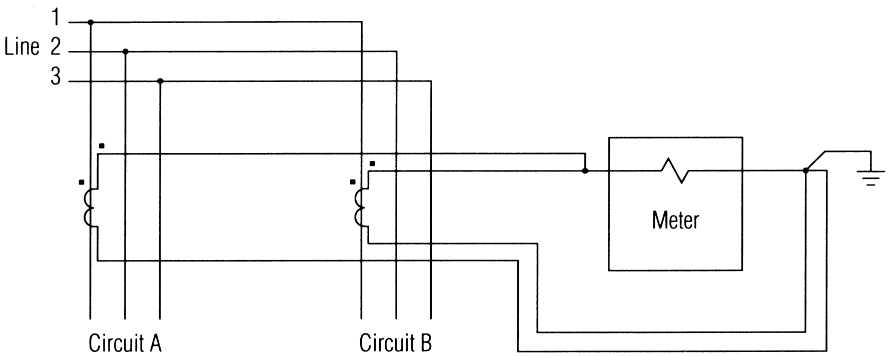


Figure 10-12. Simplified Connection Diagram for Parallel-Connected, Current-Transformer Secondaries.

10. If adjustments are made at the meter to compensate for ratio and phase angle errors, the ratio and phase angle error corrections used must represent the entire combination of transformers connected as a unit,
11. The watthour meter must be of sufficient current capacity to carry without overload errors, the combined currents from all the transformers to which it is connected,
12. Low-voltage, low-burden-capability current transformers are not suited to this application since the burden imposed on parallel secondaries may be very high,
13. Meter voltage usually is equipped with a throw-over relay to avoid loss of meter voltage in the event the normal supply is de-energized.

Parallel Current-Transformer Primaries

Under certain conditions, particularly with window-type transformers, primaries may be paralleled. With the proper precautions, acceptable commercial metering may be obtained with this method. Without proper consideration of all factors involved, the errors may be excessive particularly at low current values.

Multi-Stator Meters

Mechanical totalization is accomplished by combining on one watthour meter shaft the number of stators necessary to properly meter the circuits involved.

Mechanical totalizing is in common use for the totalization of power and lighting circuits. A three-stator meter for example, is available for the totalization of one three-wire, three-phase power circuit plus one single-phase lighting circuit, either three- or two-wire.

Mechanical totalization can be extended to include other combinations within the scope of multistator watthour meters. In determining the suitability of such meters, consideration must be given not only to the number of stators required for the totalization, but also to the practical space limitation for the required number of meter terminals.

Although it is not necessary to have circuits of identical ratings for this method of totalization, the circuits must be such as to give the same watthour constant to each meter stator. For instance, if one circuit has voltage transformers of 24,000:120 and current transformers of 100:5, while the second circuit has voltage transformers of 2,400:120 and current transformers of 1,000:5, the transformer multiplying factors are the same for both circuits, 24,000:120 $\times$ 100:5 = 2,400:120 $\times$ 1,000:5, and totalization through a totalizing meter is feasible.

PULSE TOTALIZATION

Pulse totalization is the algebraic addition or subtraction of pulses from two or more pulse generating meters. This method may be accomplished using an external totalizer or, in some meters, using pulse inputs and totalization abilities internal to the meter. Pulses are available in two-wire form A (KY) and three-wire form C (KYZ) versions.

PULSE INITIATORS

A pulse initiator is the mechanism, either mechanical or electrical, within the meter which generates a pulse for each discrete amount of a metered quantity.

The pulse initiator can be a small switch or pair of switches mounted within the meter. It may also be an electronic device. The pulse initiator may consist of a light-sensitive device positioned so as to receive reflections directly from the bottom of the disk or from reflective vanes on a shaft driven from the disk. Whether the pulse initiator assembly is commonly geared to the disk shaft or receives reflections from the disk itself, the number of pulses is directly proportional to the number of disk revolutions.

The output pulses are normally Form C closures, commonly known as KYZ or double-throw, single-pole, or their electrical equivalent. Each closure is one pulse.

In some applications, Form A closures are used. These can be obtained from a Form C by using only KY or KZ. Obtaining a Form A from a Form C doubles the value of each pulse.

Since the pulses are directly proportional to disk revolutions, a definite watthour value can be assigned to each pulse. If the ratio between pulses and disk revolutions is 1:1, the watthour value of a pulse must be, and is, equal to the primary watthour constant of the meter. Thus, in a receiving instrument which counts the number of pulses, this count, multiplied by the primary watthour constant gives the value of the energy measured. It is important to note that in certain mechanical pulse receivers one pulse is a latching and the next an advancing pulse. There may be confusion regarding this type of device since only half the pulses are recorded. Regardless of the action of the receiver, this chapter considers one closure of the pulse initiator as one pulse transmitted.

The pulses are initiated by disk revolutions of a watthour meter. Hence, the value of the pulse is in terms of energy and not of power. Before any time factor is introduced, the pulse has a value in watthours rather than watts. In a magnetic tape recorder the time channel, in effect, divides the quantity received by time and permits a reading in watts over the time period. This does not change the character of the value of the pulse as received. In this type of device the interval pulses, when multiplied by the appropriate constant, yield demands in kilowatts; the total, when multiplied by the appropriate constant yields kilowatthours.

There are certain requirements in the design and operation of pulse initiators that should be kept in mind when employing this type of telemetering. In any pulse system the initiator is the only source of information transmitted. Therefore, particularly when used for billing, the performance of the mechanism generating the pulses must match the accuracy of the requirement. A pulse initiator, free from faults, has the accuracy of the watthour meter in which it is installed. The final answer given by the receiver cannot be more accurate than the initiating pulse.

To achieve the desired accuracy, good design of the pulse initiator, proper application, and a high order of maintenance are necessary. The good design must be provided by the manufacturers. Proper application means matching the capabilities of the pulse initiator, the communication channel, and the receiver.

It must be remembered that as the value in kilowatthours of each pulse is increased, the possible dollar error in the demand determination by a miscount of even one pulse becomes correspondingly greater. The lower limit of pulse value and correspondingly greater rate of sending pulses is determined by pulse initiator design and receiver capabilities.

Characteristics of Pulse Initiators

There are two basic output circuits of pulse initiators used for telemetering of kilowatthours, the two wire and the more common three wire.

The pulse initiator output circuit may be energized with AC or DC. Direct current, in conjunction with polarized relays, or electronic type demand devices, is used where transmission over telephone lines is necessary. The polarized relay permits true three-wire operation over a two-wire circuit. It is also used on long circuits to avoid the attenuation due to the capacity effect of some communication cables.

Electronic pulse initiators of the mercury wetted relay or transistor switch types provide quick-make, quick-break action in delivering pulses to the transmitting circuit and obtain all of the advantages of this construction with none of the disadvantages associated with the mechanical types.

The output pulse circuits of pulse initiators are usually low power circuits. Most receivers, totalizers, and pulse equipment designed for meter pulse applications are also low power devices and therefore require no intermediary device. However, the installation must have interposing relays, impedance correcting circuits, or a combination thereof to protect the pulse initiator where there are long runs of connecting wire, multiple devices activated by one initiator, or devices having inductive or capacitive input characteristics.

Types of Pulse Initiators

Mechanical pulse initiators with cam-and-leaf construction depend upon the meter disk for their driving force.

Electronic pulse initiators may have a shuttered disk, an output shaft with reflective vanes or reflective spots on the rotor of the meter, that work in conjunction with a light source to furnish an input signal to an amplifier whose output is connected to the pulse transmitting circuit. Electronic pulse initiators can be designed to permit a much greater number of output pulses per meter disk revolution than cam-and-leaf devices.

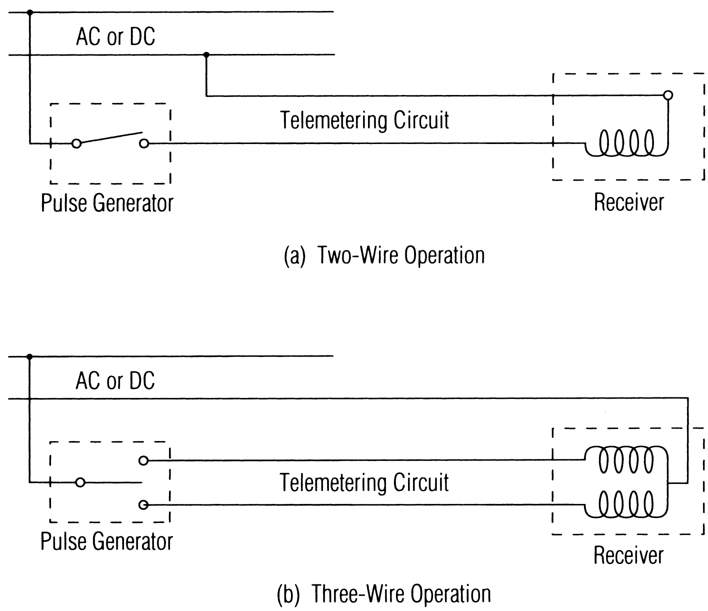


Figure 10-13. Simplified Diagrams Illustrating Basic Two- and Three-Wire Pulse Circuits.

Pulse initiators of meters with electronic registers are sometimes integral with these registers. The registers are driven, not by direct gearing as with a mechanical device, but by light or infrared reflections off the meter disk. The pulse initiator supplies output pulses which are an integral number of the pulses driving the register. Normally the register input is 12 pulses per revolution. Output pulses can therefore be 12, 6, 4, 3, 2, or 1 pulse per revolution. The reciprocals 1/12, 1/6, 1/4, 1/3, 1/2, and 1/1 are known as the M_p or R/I of the initiator. The choice of M_p or R/I is made when programming the register.

Some meters with electronic registers have no provision for supplying output pulses. These meters must be equipped with a separate pulse initiator. Having a separate initiator has the advantage of providing a redundant revolution-counting circuit which can serve as a check against the meter registration.

Electronic meters which do not have a rotating disk may be programmed to generate pulses based on the quantity selected and the pulse weight entered. These pulse outputs may be configured to indicate a quantity of energy which is identical to that quantity metered by one revolution of the disk of an equivalent mechanical meter. This equivalent revolution pulse permits testing the meter using conventional test procedures. The output pulse is usually programmable in terms of K_e, where K_e is a discrete amount of the metered quantity per pulse, for example, kilowatthours/pulse.

Maintenance of Pulse Initiators

Proper maintenance of mechanical pulse initiators requires correct adjustment of contacts for maximum tension, minimum resistance when closed, adequate clearance with contacts open, and low friction loading on the meter rotor.

If the contact points become discolored or pitted, the points should be dressed with a burnishing tool and then with paper until they are bright but not necessarily flat. If employed with discretion, fine crocus cloth is sometimes useful. The use of a file on these points is bad practice and should be avoided. If contacts require filing, they should be replaced because their service life will be limited. Small pits in the contact points will not impair operation as long as the points are clean.

The same mesh conditions required for mechanical pulse initiators must be obtained for electronics pulse initiators. However, friction due to mechanical make and break of contacts has been eliminated in solid-state pulse initiators.

Kilowatthour and Kilowatt Constants

Meter pulse initiators normally have a three-wire pulse output. The wires are designated K, Y, and Z. The pulse output is a series of alternating KY and KZ closures. Contact closure between K and Y is a pulse as is closure between K and Z. Most initiators have break-before-make closures. The output can be thought of as a single-pole, double-throw switch. Described in relay terms which are relevant because many initiators have mechanical relay outputs, although the trend is toward solid-state switches, the output is dry, Form C contacts.

Each pulse represents a distinct quantity of kilowatthour energy. The kilowatthour value of each pulse is K_e.

Meter K_d is programmable in most solid-state meters and electronic registers which have KYZ pulse outputs. It is derivable for pulse initiators on electromechanical meters using constants listed in manufacturers' literature as Pulses/Disk Revolution (P/DR), Revolutions/Impulse (R/I), or Revolutions per pulse (M_p). All of these constants are either equivalents or reciprocals of the particular constant depending on the preference of the meter manufacturer. Depending on the model and type, these constants are either programmable or must be specified when purchased. Meter K_e equals K_h (watthours per revolution) $\times$ R/I (revolutions per pulse), divided by 1,000.

Overall K_e, that is the effective K_e of pulses delivered to an end device by the output of the pulse totalizer or relay, may be different from meter K_e. If the totalizer or any interposed relay has an input/output ratio other than 1:1 the output K_e will equal the meter K_e times the product of the input/output ratios.

If a two-wire device is operated by a three-wire pulse system, the value of each two-wire pulse will be double the three-wire value.

For a particular demand interval, each pulse represents a distinct quantity of kilowatt demand. The demand interval is programmed into the pulse receiver, a demand indicator, pulse recorder, translation system, and other devices. The value of the demand pulse K_d, is equal to the overall K_e divided by the demand interval expresses in hours.

Meter pulse systems determine demand by counting the total quantity of pulses accumulated over a complete demand interval. Devices that operate on pulse rate, duration, or the times between pulses, might be erroneous, especially when pulse totalization is being performed.

The following gives the nomenclature, equations, and method of calculating the application of pulse initiators.

Required data:

Maximum kW demand expected, e.g., kilowatts.
Demand interval in hours.
Pulse receiving capacity of demand meter per interval.

Nomenclature:

kWh = kW × demand interval in hours.
Pulse = The closing and opening of the circuit of a two-wire pulse system. The alternate closing and opening of one side and then the other of a three-wire system is equal to two pulses.
K_e = kWh/pulse, i.e., the energy.
M_p = Meter disk revolutions per pulse.
T_i = Demand interval in hours.
R_p = Ratio of input pulses to output pulses for totalizing relay(s).
N_p = Number of pulses required to advance receiver.
K_d = Kilowatts per incoming pulse at receiver $= \dfrac{K_e \times R_p}{T_i}$
K_h = Secondary watthour constant.

Kilowatts divided by the pulse receiving capacity of the demand meter gives a possible value of K_d. Obviously no demand meter would intentionally be run to exactly full scale at the demand peak. Usually a choice of one-half to three-quarters of the maximum pulse capacity per interval of the receiver is reasonable and will allow for load growth. Also, the choice should be such as to obtain convenient values of K_e and K_d.

If revolutions per pulse is too small a fraction, the value of K_e must be increased and a lower scale reading on the demand meter accepted.

kW Constants

Where K_d is the kilowatt value of the incoming pulse and where T_i = the incoming demand interval in hours,

$$\frac{K_e\ (\text{final})}{T_i}$$

Kilowatt dial, chart, or tape multiplier = K_d × kW ratio where the kW ratio equals the number of incoming pulses to give a reading of 1 on the demand dial, chart, or tape.

Available *R/I*, M_p, and other ratios are generally in the range of 1:10 to 10:1. Indicators which operate on reflections off the meter disk are normally 2, 4, 6, or 8 pulses per revolution. Questions concerning the availability of specific ratios should be referred to the meter manufacturer.

TOTALIZING RELAYS

Where the totalization of more than two circuits is required, an intermediate totalizing relay is generally necessary. This relay must be capable of adding pulses and, when required, subtracting other pulses from the positive sum and retransmitting the algebraic sum to a receiving device. When a totalizing relay with an input to output ratio other than 1:1 is used it must be considered in adjusting the pulse value of the meter.

If, for example, a relay is used which has a 4:1 ratio, it is necessary to furnish four pulses to the relay for every one that is retransmitted to the receiver. Pulse values for the meter must be in a 1:4 ratio the values for the receiver. As an example, if the receiver pulse value was 38.4 kWh, it would be $38.4/4 = 9.6$ kWh at the meter.

Totalizing relays serve to combine pulses produced by two or more meters and to retransmit the total over a single channel. Electronic types eliminate most of the problems of maintenance associated with the older electromechanical mechanisms but in no way relieve the situation of limiting pulse rates to prevent "overrun" of the relays. Attention to pulse rates (pulses per minute) is especially important if several relays are operated in cascade to accommodate a large number of meters in a single totalizing network.

The maximum pulse rate at which any relay can be operated is often limited by the receiver. Electronic data logging receivers are capable of accepting very high pulse rates with very short time duration per pulse, but many electromechanical receivers require relatively low rates and relatively long pulses.

In electronic totalizing relays all input circuits of a relay must be interrogated (scanned) in turn and all pulses present must be outputted to the receiver before any channel can be again interrogated. A limiting condition is pulses on all channels simultaneously (burst condition).

For a multi-channel relay the maximum input rate must be no greater than output rate divided by the number of channels. For example, a seven-channel relay with a relay ratio of 1:1 and an output rate of 56 pulses per minute has an input rate of 8 pulses per minute per channel ($56/7=8$). In order to provide some safety margin, a rate of 7 pulses per minute is published.

If the relay ratio is other than 1:1, this factor must be considered. The formula used is output rate times the ratio factor divided by the number of channels ($56 \times 4/7 = 32$ for a four to one relay).

It must be kept in mind that the higher the output rate of the relay, the shorter the duration of the pulses. This, too, can be a limiting factor for some receivers.

A general discussion of the electromagnetic type totalizing relays can be found in the 7th edition of this *Handbook* in Chapter 10. For specific operating characteristics of modern totalizing relays, the manufacturer's literature should be consulted.

MULTI-CHANNEL PULSE RECORDERS

Many applications which previously required a totalizing relay and a single-channel pulse counter can now be performed by a multi-channel pulse recorder used in conjunction with a "smart" translation device. Normally, the recorder stores pulse counts from one to four meters. Periodically, the recorder is interrogated and the information is transferred to a computer which performs the translation. The computer is programmed to combine those channels which are to be totalized, and to produce reports for revenue billing, load survey, market research, and other applications.

Typical recorders store at least 35 days of data in 15 minute increments. New electronic meters can record substantially more data before filling up their memories. The time base is usually programmed to be that of the demand interval. A smaller increment would fill the recorder memory in proportionally less time, perhaps 11 or 12 days. Similarly, a larger increment would permit more days of data to be stored; if the increment were one hour, 140 days of data could be stored. Most meters allow at least 16 bit resolution or 65,535 pulses per interval. The resolution of the data (per pulse) is controlled by this maximum pulses per interval and the interval length or duration.

One useful memory design is the wrap-around type. Wrap-around memory overwrites the most current data over the oldest data. Another useful property is the data is not erased when the recorder is interrogated. These properties permit redundancy in data storage. The recorder always retains the most recent 35 days of data. The database at the translation site has all data up through the last interrogation. The field data can be reread if the communications channel introduced errors or if data stored at the central computer is corrupted.

Data transmission can be by telephone, frame relay, fiber optic cable, packet radio, cable TV lines, power line carrier, microwave, or other communication medium with the ability to transmit data accurately. In the event the communication system fails, most solid-state recorders can be interrogated by a portable reader or computer coupled to the recorder via an optical port.

Each time there is communication between an individual recorder and the central computer, the central computer runs a time check and corrects the individual unit to the system time. Each unit keeps time using the 60 hertz power system as reference. In addition, each unit has a backup source for keeping time during power outages.

When the communication system is telephone, packet radio, or other medium which is constantly available, individual units can call or be called at frequent intervals, such as once a day. By frequent interrogation, problems can be discovered and solved promptly. Additionally, the units can be self-diagnostic, including tamper detectors which initiate calls to report alarms.

PULSE ACCESSORIES

Auxiliary Relays

In some cases of totalization it may be found necessary to operate more than one device from the same watthour meter pulse initiator or to operate an AC device and a DC circuit from the same pulse source. Auxiliary relays may be used for this purpose. In general such relays have a single three-wire input and two or three similar isolated three-wire output circuits. Relays are available to convert two-wire pulses to three-wire and three-wire pulses to two-wire.

Another auxiliary relay often used for this and other purposes is the polarized relay. A polarized relay is a direct current operated relay. It permits the use of the two-wire circuit to transmit three-wire pulses. This is done by reversing the polarity of the direct current applied to the relay coil. It is equivalent to using a positive pulse for one side of the three-wire circuit and a negative pulse for the other.

Polarized relays are found to be necessary in the totalization and telemetering of pulses over some distance. The features of these relays are the low current at which they operate, 1 to 20 mA DC; the positive action upon polarity change, preventing stray currents from causing incorrect operation; and the fact that the contacts for retransmitting consist of two sets which can be paralleled or used to drive separate circuits. The polarized relay maintains a closed transmitting contact until the opposite polarity is received. Polarized relays require only two wires between the source of pulses and the relay, an obvious advantage for distance metering.

PULSE-COUNTING DEMAND METERS

Pulse-counting demand meters, as their name implies, are the receiving devices which count the pulses transmitted by the telemetering system. By counting for a time interval such as 15 minutes, and then resetting, a block-interval demand measurement is obtained.

The final read-out may be a demand register, a round chart, a strip chart, a printed figure, a punched tape, or a magnetic tape. Limitations in regard to the rate at which pulses can be received, and also to the total number of pulses accepted in any demand interval, are characteristic of all pulse-counting demand meters. Manufacturers' publications should be consulted for details of individual demand meters.

NOTES ON PULSE TOTALIZATION

When selecting or designing a pulse-totalization system there are a number of practical considerations that must not be ignored.

The pulse-receiving capability of the totalizing recorder is a case in point. Here are four factors to be considered:

1. Total number of pulses that can be recorded during any one demand interval;
2. Ability to record clusters of pulses at a much higher rate than capability over entire demand interval. Cascaded intermediate relays may result in transmission of two to eight almost simultaneous pulses. If the receiver fails under these conditions, the intermediate relay circuits must be redesigned to space pulses;
3. Sensitivity to pulse duration. When pulse duration may be less than one-quarter of a second, it is futile to employ a receiver requiring pulses of a minimum duration of three-quarters of a second;
4. Pulse-receiving mechanisms which fail to respond to less than perfect contact closures will require excessive maintenance. Receivers should tolerate some variation in pulse current as well as in pulse duration.

In any complex pulse-totalization system pulse values must be established for both transmitting and receiving instruments. If it is desired to retain the same pulse value at the initiator and at the receiver, it may be necessary to cascade totalizing relays rather than combine all pulses in one relay. For example, certain types of six- or eight-circuit totalizing relays cannot be operated with any degree of reliability with a 1:1 ratio of incoming to outgoing pulses. A 2:1 ratio doubles the value of the pulse. It is often possible to employ, in such a case, two four-element relays with 1:1 pulse ratios, the outputs of which are combined on a two-element relay again with a 1:1 pulse ratio. In this manner pulse values at the receiver can be kept at the same values as when initiated.

METERING TIME-CONTROLLED LOADS

Certain loads that lend themselves readily to control as to time of usage (TOU) are sometimes served by utilities under a special TOU rate schedule. Sometimes a watthour meter in conjunction with a time switch is employed in order that the load may be disconnected during the time of peak system demands. In other cases, the meter can be configured to store the metered quantities in a register based on the time of day and the TOU rate schedule. Registration of metered quantities can be stored based on the TOU schedule. Most meters that are capable of TOU metering support at least four rate registers, subdividing the total billing data for each metered quantity. The TOU rates are used in many ways from monitoring some loads at a residential account like a water heater or a pool pump to monitoring whole plant loads at a large industrial account. Rate structures vary from utility to utility and TOU metering is designed to allow the user to fit the various rate schedules that have been devised.

Water Heater Loads

Perhaps the most frequently used method in the past has employed a regular watthour meter for the house load and a separate meter and time switch combination for the water heater load. The time switch is operated by a synchronous motor and its contacts open the water heater circuit during the on-peak periods specified within the special rate schedules provided. Combination single-phase watthour meters and time switches are available in a single case. The combination watthour meter and the time switch may be equipped either with the conventional four- or five-dial register or it may be equipped with a two-rate register having two sets of dials so that the off-peak and on-peak energy can be indicated on separate dials. Such devices have a number of varied applications. In some instances it may be desirable to register the on-peak load of the entire service on one set of dials or, if the rate schedule so provides, the house load might be recorded during on-peak periods with the water heater disconnected.

The connection of the combination meter and time switch for control of off-peak water heater load with a separate meter for the house load is illustrated in Figure 10-14. This combination is applicable where the water heater load is supplied at a completely different rate than the house load.

Figure 10-15 shows a combination meter and time switch with a single rate register and double-pole contacts controlling the off-peak water heater load. The meter registers both the house load and the water heater load, the latter being disconnected during predetermined on-peak periods. This arrangement is suitable when the regular domestic rate applies also to the water heater load or a fixed block of kilowatthours during the billing period is assigned to the water heater load by the tariff.

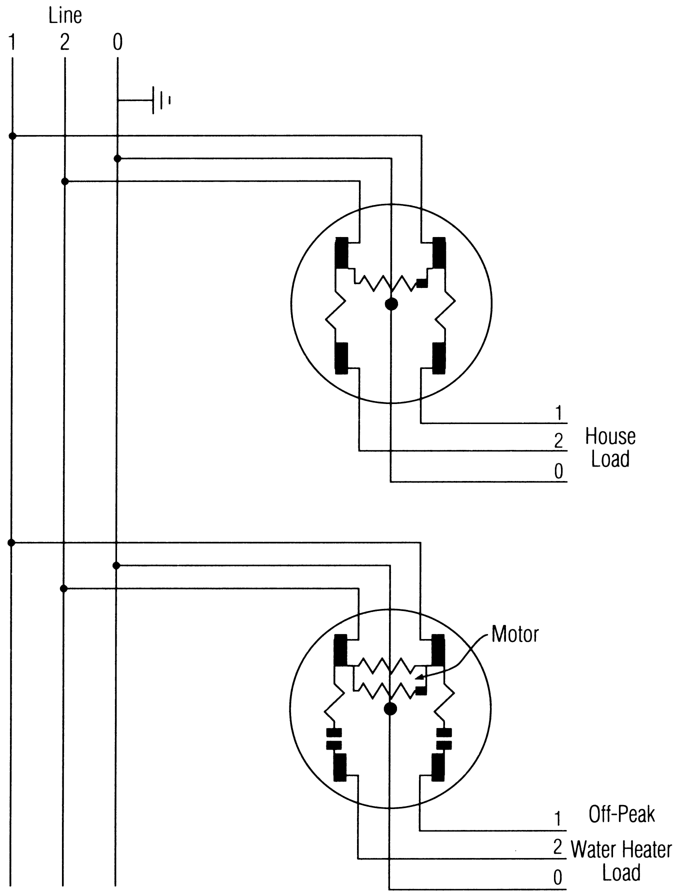


Figure 10-14. Connection for Combination Watthour Meter and Time Switch and Separate Meter for Residential Load.

Figure 10-16 shows a combination meter and time switch with a two-rate register and double-pole contacts for disconnecting the water heater during on-peak periods. This arrangement might be applied where the house load used during off-peak periods is charged at the same rate as the water heater load. The connections are the same as shown in Figure 10-15.

There is also a combination meter and time device available with a two-rate register but without contacts for the water heater load. The water heater remains connected to the service at all times. The time device serves to control only the two sets of register dials. In this case the water heater load may be billed at the regular domestic rate during peak periods and all loads billed at a different rate during off-peak periods or a specified number of kilowatthours during the billing period may be assigned by the tariff to the water heater load.

A number of the arrangements provided by two-rate registers and time switch combinations may also be obtained by separate meters and time switches.

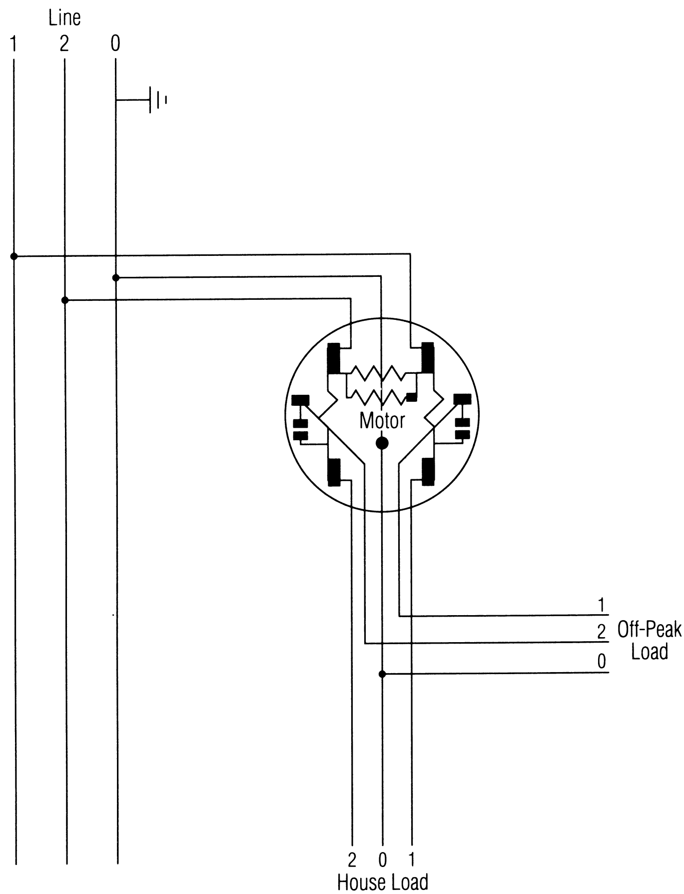


Figure 10-15. Connection for Combination Watthour Meter and Time Switch.

The use of time switches and similar methods of control have been replaced in some measure by a so called fixed block or floating block in the rate schedule. Under this method the water heater load is supplied at a lower rate than the domestic load and a fixed number or a variable number of kilowatthours are assigned to the water heater during the billing period. This method requires only one single-dial meter without a time switch for the entire water heater and domestic load.

ELECTRONIC REGISTERS

In the late 1970s and early 1980s, manufacturers began taking advantage of the miniaturization of electronic components introduced standard in watthour meters with sophisticated registers which could record the customer's usage on several registers apportioned as to time of day, and, where applicable, day of the week. One such demand meter, shown in Figure 10-17, records total kilowatthours on a continuously cumulative basis similar to standard kilowatthour meters. In addition, the register can record energy and maximum demand for each of the three daily time periods.

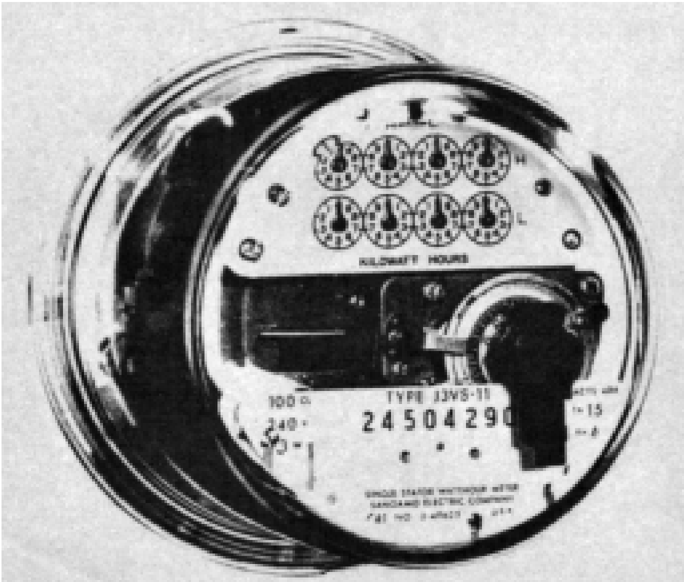


Figure 10-16. Combination Time Switch and Two-Rate Register.

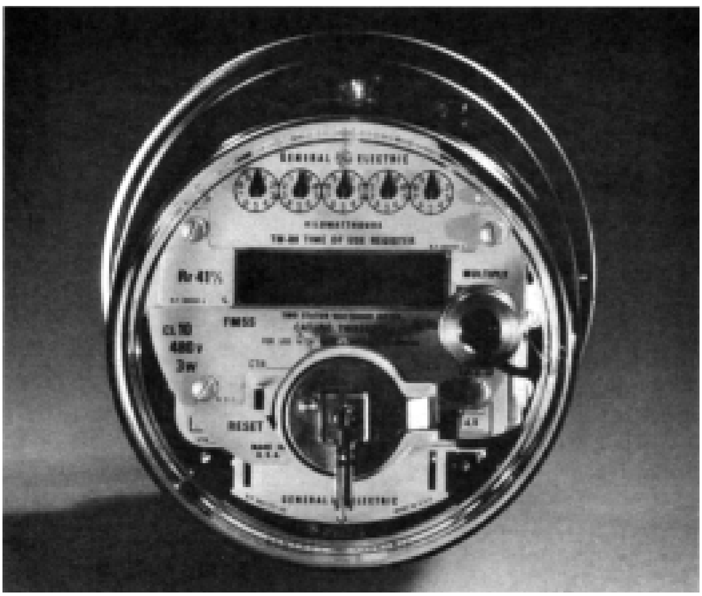


Figure 10-17. Demand Meter with Cover Removed.

The electronic register shown in Figure 10-17 allows program selection of up to three possible demand presentations. The three demand presentations are cumulative, continuously calculated, and indicating. The register may be programmed to display any or all of the three demand formats. Demand is calculated as kilowatthours divided by the demand interval, which is program selectable. Intervals of 15, 30, 60, 120, 240 minutes or the entire TOU may be selected. In addition, rolling demand measurements can be program selected, with rolling demand calculations occurring at programmed subintervals. The register display verifies demand reset by a continuous "all eights" display. The all eights display can also be used to verify that the display segments are operating properly. Many solid-state registers have timed load control outputs which can operate a contactor. The contactor, sized to make and break the water heater load, controls the appliance.

KILOWATTHOUR MEASUREMENTS ABOVE PREDETERMINED DEMAND LEVELS

For load studies, rate studies, or other special applications, a differential register is available which will register the total kilowatthours on a service as well as the number of kilowatthours consumed during a period when the demand is in excess of a predetermined kilowatt demand level. This is accomplished with a differential gear, one side of which is driven at a speed proportional to a given kilowatthour load by a synchronous motor and the other side from the watthour meter disk. A ratchet prevents reverse rotation when the speed of the meter-driven gear is less than that of the motor-driven gearing. The result is a reading on one set of dials of the total kilowatthours and, on another set of dials, the kilowatthours used during the period when the demand is greater than the preset level. The application of this device is illustrated for an actual load curve in Figure 10-18. The shaded area indicated above the horizontal line represents the energy used at the higher demand level.

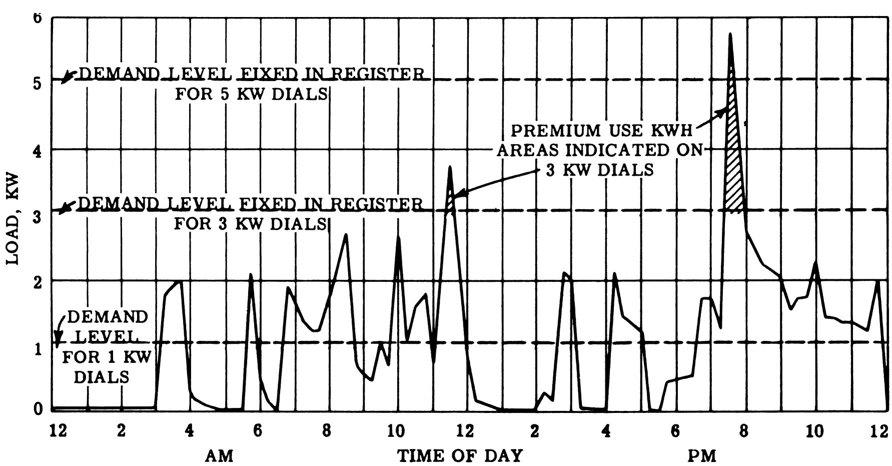


Figure 10-18. Load Curve Showing Measurement by Differential Register.

There is also another special meter available to record the so-called excess energy above a predetermined set point or, in effect, a predetermined demand point. Such a meter consists of a watthour meter having an extra stator rated at 120 V and 50 mA and connected for reverse torque. Also provided are an external adjustable resistor panel and a standard voltage transformer to supply all of the power for the negative torque stator. The meter torque is negative up to the point of excess so no registration results until the excess set point is passed. Below and at the excess point the meter will not register and a detent will prevent reverse rotation of the shaft. When the excess point is passed, the meter shaft rotates and the registration of kilowatthours above the preset limits will occur. This meter may have certain applications for specially designed rate schedules. It has some slight advantage over the register employing the differential gearing because it can be more easily calibrated for a change in the excess point without requiring mechanical gear changes.

LOAD-STUDY METERS

Load study implies load profile. Most major meter manufacturers offer solid-state registers with load profile capabilities. Meters capable of load profile typically store at least 35 days of 15-minute data, where the interval length and total number of days are configurable. Depending on the software, translation of the data is usually done on a mainframe computer or a personal computer. Various software packages are available. The reports are typically graphical plots of 15-minute average demands (or the demands averaged over the programmed interval), and tabular presentations of kilowatt demand, kilowatthours, and meter revolutions.

Temporary studies of installations, that is installations where the study is for a short time, are often read with a handheld device or computer to avoid the costs of installing a remote communications capability. Load studies of longer duration are usually linked for remote access via a communications network such as the telephone network or packet radio.

CHAPTER 11

INSTRUMENT TRANSFORMERS

IT WOULD BE DIFFICULT AND IMPRACTICAL to build self-contained meters to measure the energy in high-voltage or high-current circuits. To provide adequate insulation and current-carrying capacity the physical size of the meters would have to be enormously increased. Such meters would be costly to build and would expose the meter technician to the hazards of high voltage. The use of instrument transformers makes the construction of such high-voltage or high-current meters unnecessary.

Instrument transformers are used primarily for the following reasons:

1. To insulate, and thereby isolate, the meters from the high-voltage circuits;
2. To reduce the primary voltages and currents to usable sizes and standard values that are easily metered with meters having a common secondary rating;

The instrument transformers deliver accurately known fractions of the primary voltages and currents to the meters. With proper register ratios and multipliers the readings of the meters can be made to indicate the primary kilowatthours.

CONVENTIONAL INSTRUMENT TRANSFORMERS

DEFINITIONS

Definitions which relate mainly to instrument transformers are listed below. Other general definitions are included in Chapter 2 of this *Handbook* and in IEEE Std 100, *The Authoritative Dictionary of IEEE Standards Terms*.

Bar-Type Current Transformer—A transformer with a fixed and straight single primary turn which passes through the magnetic circuit. The primary and secondary(s) are insulated from each other and from the core(s) and are assembled as an integrated structure.

Burden of an Instrument Transformer—The active and reactive power consumed by the load on the secondary winding. Burden is expressed either as impedance with the effective resistance and reactive components, or as voltamperes and power factor at a specified current or voltage and frequency.

Bushing-Type Current Transformer—A transformer with an annular core, no primary winding, and a secondary winding insulated from and permanently assembled on the core which can fit on the bushing of a power transformer or power circuit breaker.

Grounded-Neutral Terminal-Type Voltage Transformer—A transformer with the neutral line of the primary permanently connected to the case or mounting base.

Hazardous CT Open-Circuiting—An energized current transformer (CT) with the secondary open-circuited can result in a high voltage across the secondary terminals or conductors which may be hazardous to personnel or damaging to equipment.

Indoor Transformer—A transformer which must be protected from weather.

Insulated-Neutral Terminal-Type Voltage Transformer—A transformer with the neutral line of the primary insulated from the case or base and connected to a terminal with insulation for a lower voltage than required by the line terminal. The neutral line may be connected to the case or mounting base in a manner which allows temporary disconnection for dielectric testing.

Leakage Flux—Magnetic flux, produced by current in a transformer winding which flows outside the windings.

Low Remanence Current Transformer—A transformer with a remanence less than 10% of maximum flux.

Multiple-Secondary Current Transformer—A transformer with one primary and two or more secondaries, each on separate magnetic circuits.

Multi-Ratio Current Transformer—A transformer with three or more ratios obtained by taps on the secondary winding.

Rated Current—The current in the primary upon which the performance specifications are based.

Rated Secondary Current—Rated current divided by the marked ratio.

Rated Secondary Voltage—Rated voltage divided by the marked ratio.

Rated Voltage—The primary voltage upon which the performance specifications of a voltage transformer are based.

Series-Parallel Primary Current Transformer—A transformer with two insulated primaries which can be connected in series or in parallel, and provides different rated currents.

Tapped-Secondary Current (Voltage) Transformer—A transformer with two ratios, obtained by a tap on the secondary winding.

Window-Type Current Transformer—A transformer with no primary winding, and a secondary winding insulated from, and permanently assembled on, the core providing a window through which the primary line conductor can pass.

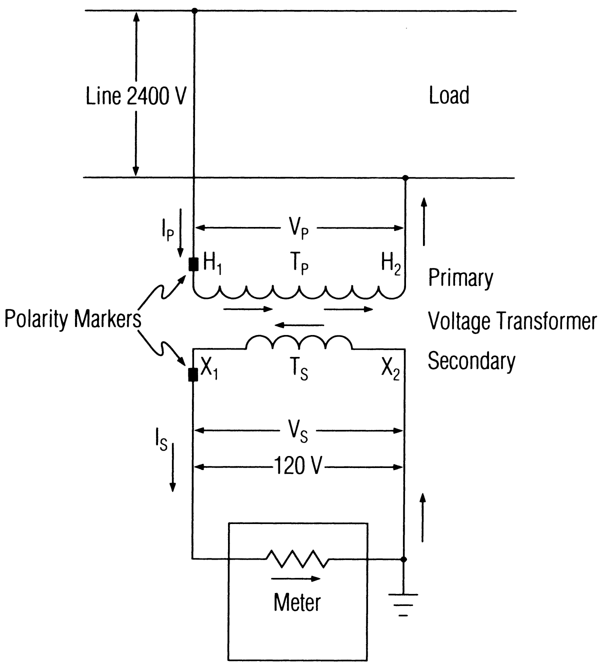
Wound-Type Current Transformer—A transformer with a primary with one or more turns mechanically encircling the core. The primary and secondary windings are insulated from each other and from the core and are assembled as an integrated structure.

BASIC THEORY OF INSTRUMENT TRANSFORMERS

The Voltage Transformer

The Ideal Voltage Transformer Connection Diagram

Figure 11-1 shows the connection diagram for an ideal voltage transformer. Note that the primary winding is connected across the high-voltage line and the secondary winding is connected to the voltage coil of the meter. When 2,400 volts are applied to the primary of this voltage transformer, 120 volts are developed in the



Marked Primary Voltage = 2400 V
Marked Secondary Voltage = 120 V
Marked Ratio = 2400:120 = 20:1

$$\text{Turn Ratio} = \frac{T_P}{T_S}$$

$$\text{True Ratio} = \frac{V_P}{V_S}$$

Figure 11-1. The Ideal Voltage Transformer.

secondary by transformer action. This secondary voltage is applied to the voltage coil of the meter. Since there is no direct connection between the primary and secondary windings, the insulation between these windings isolates the meter from the primary voltage. One side of the secondary circuit is connected to ground to provide protection from static charges and insulation failure.

Polarity

In Figure 11-1 the polarity markers are used to show the instantaneous direction of current flow in the primary and secondary windings of the voltage transformer. They are so placed that when the primary current I_P is flowing into the marked primary terminal H_1, the secondary current I_s is at the same instant flowing out of the marked secondary terminal X_1. These markings enable the secondaries of the voltage and current transformers to be connected to the meter with the proper phase relationships. For example, in the case of a single-stator meter installed with a voltage and a current transformer, reversal of the secondaries from either transformer would cause the meter to run backward .

Secondary Burden

In Figure 11-1 the voltage coil of the meter draws a small current from the secondary winding. It is therefore a burden on the secondary winding. The burden of an instrument transformer is defined by IEEE Standard C57.13 as follows:

> "That property of the circuit connected to the secondary winding that determines the active and reactive power at its secondary terminals."

The burden on a voltage transformer is usually expressed as the total volt-amperes and power factor of the secondary devices and leads, at a specified voltage and frequency (normally 120 volts at 25 KV and below and 115 volts above 25 KV, 60 Hz).

The burden imposed by the voltage sensors of an electronic (solid-state) meter is typically less than 0.1 VA and may be considered insignificant. However, the solid-state meter's power supply, which is typically connected to phase A, may be significant enough for consideration as a voltage transformer secondary burden.

Marked Ratio, Turn Ratio, True Ratio

The marked ratio of a voltage transformer is the ratio of primary voltage to secondary voltage as given on the rating plate.

The turn ratio of a voltage transformer is the ratio of the number of turns in the primary winding to that in the secondary winding.

The true ratio of a voltage transformer is the ratio of the root-mean-square (rms) primary voltage to the rms secondary voltage under specified conditions.

In an ideal voltage transformer, the marked ratio, the turn ratio, and the true ratio would always be equal and the reversed secondary voltage would always be in phase with the impressed primary voltage. It must be strongly emphasized that this ideal voltage transformer does not exist. It has been assumed that the ideal voltage transformer is 100% efficient, has no losses, and requires no magnetizing current. This assumption is not true for any actual voltage transformer.

The concept of the ideal voltage transformer is, however, a useful fiction. Modern voltage transformers, when supplying burdens which do not exceed their accuracy ratings, approach the fictional ideal very closely. Most metering installations involving instrument transformers are set up on this ideal basis and in most cases no corrections need be applied. Thus, in the example shown in Figure 11-1 it would normally be assumed that the meter voltage coil is always supplied with 1/20th of the primary voltage. If this assumption is to be valid, the limitations of actual voltage transformers must be clearly understood and care taken to see that they are used within these limitations.

The Actual Voltage Transformer—The Phasor Diagram

In the ideal voltage transformer the secondary voltage is directly proportional to the ratio of turns and opposite in phase to the impressed primary voltage. In an actual transformer an exact proportionality and phase relation is not possible because:

1. The exciting current that is necessary to magnetize the magnetic core causes an impedance drop in the primary winding;
2. The load current that is drawn by the burden causes an impedance drop in both the primary and secondary windings.

Both of these produce an overall voltage drop in the transformer and introduce errors in both ratio and phase angle. The net result is that the secondary voltage is slightly different from that which the ratio of turns would indicate and there is a slight shift in the phase relationship. This results in the introduction of ratio and phase angle errors as compared to the performance of the ideal voltage transformer.

Figures 11-2 and 11-3 are the schematic and phasor diagrams of an actual voltage transformer. The phasor diagram (Figure 11-3) is drawn for a transformer having a 1:1 turn ratio and the voltage-drop and loss phasors have been greatly exaggerated so that they can be clearly separated on the diagram. These are normal conventions used when drawing phasor diagrams for transformers and do not invalidate any of the results to be derived.

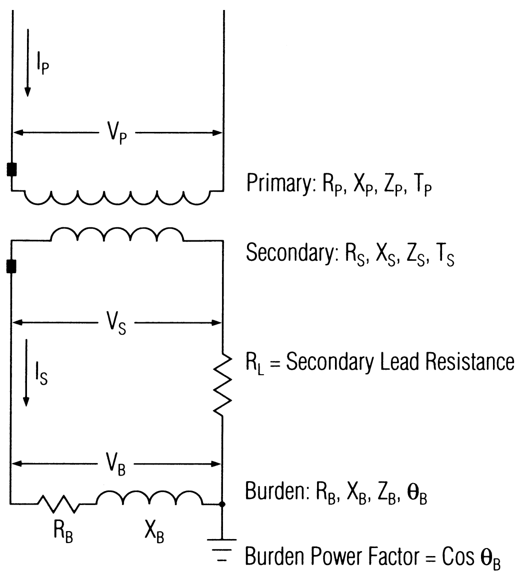
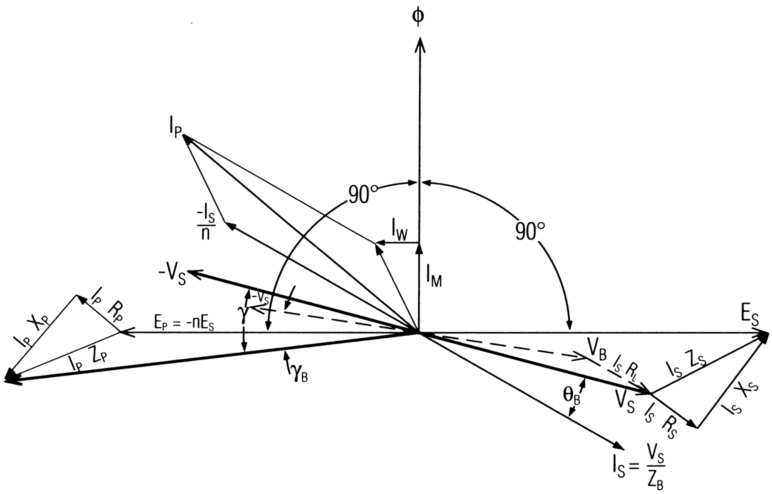


Figure 11-2. The Actual Voltage Transformer with Burden and Lead Resistance.

The operation of the voltage transformer may be explained briefly by means of the phasor diagrams, Figure 11-3, as follows:

The flux ϕ in the core induces a voltage E_S, in the secondary winding lagging the flux by 90°. A voltage equal to nE_S (where n is the turn ratio) is also induced in the primary winding lagging ϕ by 90°. To overcome this induced voltage a voltage $E_P = -nE_S$ must be supplied in the primary. Thus, nE_S must lead E_S by 180° and therefore leads the flux ϕ by 90°.



ϕ = Flux in Core
I_M = Magnetizing Current
I_W = Core Loss Current
I_E = Exciting Current
V_P = Impressed Primary (Terminal) Voltage
E_P = Voltage Required to Overcome Induced Primary Voltage
I_P = Primary Current
R_P = Resistance of Primary
X_P = Reactance of Primary
Z_P = Impedance of Primary
E_S = Induced Secondary Voltage
V_S = Secondary Terminal Voltage
I_S = Secondary Current
R_S = Resistance of Secondary
X_S = Reactance of Secondary
Z_S = Impedance of Secondary
R_L = Resistance of Secondary Leads
V_B = Voltage at Terminals of Burden
R_B = Resistance of Burden
X_B = Reactance of Burden
Z_B = Impedance of Burden
θ_B = Phase Angle of Burden
$\cos \theta_B$ = Power Factor of Burden
γ_B = Apparent Phase Angle of Voltage Transformer at Burden Terminals
T_P = Turns on Primary
T_S = Turns on Secondary
N = Turns Ratio = T_P / T_S
V_P / V_S = True Ratio of Voltage Transformer
V_P / V_B = Apparent Ratio of Voltage Transformer at Burden Terminals
γ = Phase Angle of Voltage Transformer

Figure 11-3. Phasor Diagram of Voltage Transformer.

The secondary current I_S is determined by the secondary terminal voltage V_S and the impedance of the burden Z_B. Theoretically, the true burden "seen" by a voltage transformer includes the leads R_L in series with the connected instruments. In practice the effect of the leads on the total burden is very small and is neglected. I_S is equal to $\frac{V_S}{Z_B}$ and lags V_S by a phase angle θ_B, where cos θ_B, is the power factor of the burden. (This burden power factor should not be confused with the power factor of the load being supplied by the primary circuit.)

The voltage drop in the secondary winding is equal to $I_S Z_S$ where Z_S is the impedance of this winding. This drop is the phasor sum of two components $I_S R_S$ and $I_S X_S$, where R_S and X_S are the resistance and reactance of the secondary winding. The voltage drop $I_S R_S$ must be in phase with I_S and the voltage drop $I_S X_S$ must lead I_S by 90°. The induced secondary voltage E_S is equal to the phasor sum of $V_S + I_S Z_S$ and V_S is the phasor difference $E_S - I_S Z_S$.

I_M is the magnetizing current required to supply the flux ϕ and is in phase with the flux. I_W is the current required to supply the hysteresis and eddy current losses in the core and leads I_M by 90°. The phasor sum of $I_M + I_W$ is the exciting current I_E. This would be the total primary current if there were no burden on the secondary.

When a burden is connected to the secondary, the primary must also supply the reflected secondary current, $\frac{I_S}{n}$. The total primary current I_P is therefore the phasor sum of I_E and $-\frac{I_S}{n}$.

The voltage drop in the primary winding is equal to $I_P Z_P$ where Z_P is the impedance of the primary winding. This drop is the phasor sum of the two components $I_P R_P$ and $I_P X_P$ where R_P and X_P are the resistance and the reactance of the primary winding. The voltage drop $I_P R_P$ must be in phase with I_P and the drop $I_P X_P$ must lead I_P by 90°. The primary terminal voltage V_P is equal to the phasor sum of $E_P + I_P Z_P$.

The phasor $-V_S$ is obtained by reversing the secondary voltage phasor V_S. In practice this simply amounts to reversing the connections to the secondary terminals. This reversal is automatically done by the polarity markings and, if these are followed, the terminal voltage from the marked to the unmarked secondary lead will be $-V_S$.

In Figure 11-3 note that the reversed secondary voltage phasor $-V_S$ is not equal in magnitude to the impressed primary voltage V_P and that $-V_S$ is out of phase with V_P by the angle γ. In an ideal voltage transformer of 1:1 ratio, $-V_S$ would be equal to and in phase with V_P. In the actual voltage transformer this difference represents errors in both ratio and phase angle.

True Ratio and Ratio Correction Factor

The true ratio of a voltage transformer is the ratio of the rms primary voltage to the rms secondary voltage under specified conditions.

In the phasor diagram, Figure 11-3, the true ratio is $\frac{V_P}{V_S}$. It is apparent that this is not equal to the 1:1 turn ratio $\frac{T_P}{T_S}$ upon which this diagram was based. In this case V_S is smaller in magnitude than V_P as a result of the voltage drops in the transformer.

The turn ratio of a voltage transformer $\frac{T_P}{T_S}$ is built in at the time of construction and the marked ratio is indicated on the nameplate by the manufacturer. These ratios are fixed and permanent values for a given transformer.

The true ratio of a voltage transformer is not a single fixed value since it depends upon the specified conditions of use. These conditions are secondary burden, primary voltage, frequency, and waveform. Under ordinary conditions primary voltage, frequency, and waveform are practically constant so that the true ratio is primarily dependent upon the secondary burden and the characteristics of the particular voltage transformer.

The true ratio of a voltage transformer cannot be marked on the nameplate since it is not a constant value but a variable which is affected by external conditions. The true ratio is determined by test for the specified conditions under which the voltage transformer is to be used. For most practical applications, where no corrections are to be applied, the true ratio is considered to be equal to the marked ratio under specified IEEE standard accuracy tolerances and burdens.

Thus it might be found that the true ratio of a voltage transformer having a marked ratio of 20:1 was 20.034:1 under the specified conditions. However, the true ratio is not usually written in this way because this form is difficult to evaluate and inconvenient to use. The figure 20.034 may be broken into two factors and written 20×1.0017. Note that 20 is the marked or nominal ratio of the voltage transformer which is multiplied by the factor 1.0017.

This factor, by which the marked ratio must be multiplied to obtain the true ratio, is called the ratio correction factor (RCF). True Ratio = Marked Ratio $\times$ RCF.

$$\text{RCF} = \frac{\text{True Ratio}}{\text{Marked Ratio}}$$

Phase Angle

Figure 11-3 shows that the reversed secondary voltage $-V_S$ is not in phase with the impressed primary voltage V_P. The angle γ between these two phasors is known as the phase angle of the voltage transformer and is usually expressed in minutes of arc. (Sixty minutes of arc is equal to one degree.)

In the ideal voltage transformer the secondary voltage V_S would be exactly 180° out of phase with the impressed primary voltage V_P . The polarity markings automatically correct for this 180° reversal. The reversed secondary voltage $-V_S$, would therefore be in phase with the impressed primary V_P and the phase angle γ would be zero.

In the actual voltage transformer the phase angle γ represents a phase shift between the primary and secondary voltages in addition to the normal 180° shift. The 180° shift is corrected by the reversal that occurs when the polarity markings are followed, but the phase angle γ remains. This uncorrected phase shift can cause errors in measurements when exact phase relations must be maintained.

The phase angle of an instrument transformer is defined by IEEE Std. C57.13 as the phase displacement, in minutes, between the primary and secondary values. The phase angle of a voltage transformer is designated by the Greek letter gamma (γ) and is positive when the secondary voltage from the identified to the unidentified terminal leads the corresponding primary voltage.

The phase angle of a voltage transformer is not a single fixed value but varies with burden, primary voltage, frequency, and waveform. It results from the voltage drops within the transformer as shown in Figure 11-3. Under ordinary conditions, where voltage, frequency, and waveform are practically constant, the phase angle is primarily dependent upon the secondary burden and the characteristics of the particular voltage transformer.

Effects of Secondary Burden on Ratio and Phase Angle

It is apparent from Figure 11-3 that any change in the secondary current I_S will change the relative magnitudes and phase relations of the primary terminal voltage V_P and the secondary terminal voltage V_S. Since the secondary current I_S is a function of the burden impedance Z_B the true ratio $\frac{V_P}{V_S}$ and the phase angle γ are affected by any change in burden. Figure 11-5 shows the metering accuracy curve of a voltage transformer referenced to connected burden.

Effects of Primary Voltage on Ratio and Phase Angle

A change in primary voltage causes a nearly proportional increase or decrease in all of the other voltages and currents shown in the phasor diagram, Figure 11-3. If this proportionality were exact, no change in true ratio or phase angle would result from a change in voltage. However, the exciting current I_E is not strictly proportional to the primary voltage V_P but varies according to the saturation curve of the magnetic core as shown in Figure 11-4. Note that the change in exciting current for the normal operating range of 90 to 110% of rated primary voltage is very nearly linear. Above 110% rated voltage the core is rapidly approaching saturation and the exciting current I_E increases more rapidly than the primary voltage V_P. This could result in a change in true ratio and phase angle with voltage if the transformer is operated at more than 110% of its rated voltage. The exact point of saturation depends upon the particular design. Some voltage transformers may show greater changes with voltage than others.

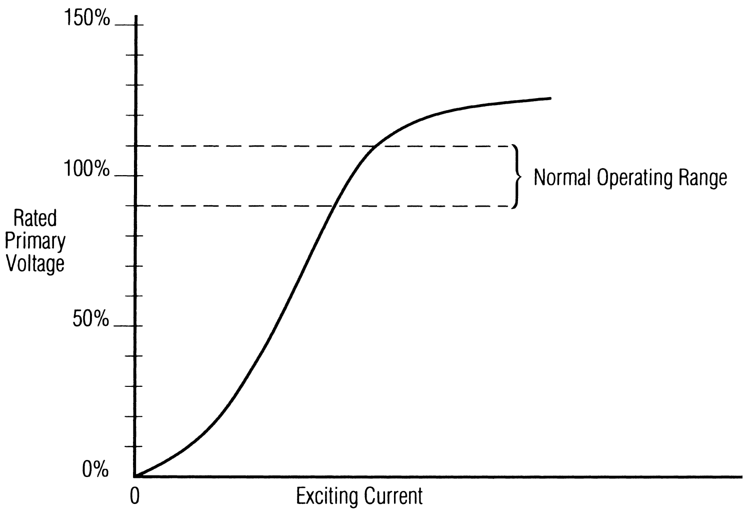


Figure 11-4. Typical Saturation Curve for a Voltage Transformer.

In the normal operating range, and even well below this range, the change of true ratio and phase angle with voltage is very small with modern well-designed voltage transformers.

Effects of Frequency on Ratio and Phase Angle

A change in frequency changes the impedance of the voltage transformer and the burden. Increasing frequency increases the reactance of the transformer X_P and X_S and would increase the voltage drops $I_P X_P$ and $I_S X_S$ were it not for the fact that the secondary current I_S would decrease because of an increase in the burden reactance X_B. (See Figure 11-3.) These two effects tend to cancel each other to some extent, but depend upon the ratio of resistance to reactance in the transformer and the burden. In addition, the exciting current I_E decreases rapidly at higher frequencies and increases at lower frequencies. At lower frequencies the core will saturate at voltages below the normal rating and large changes in ratio and phase angle could occur.

Thus a small increase in frequency may have little effect, whereas a small decrease may result in appreciable change in true ratio and phase angle. A drastic decrease in frequency results in excessive exciting current and overheating of the voltage transformer.

Voltage transformers are normally designed for a single frequency though they can be designed to work satisfactorily for a small range of frequencies such as 50 to 60 hertz. In utility work this frequency is usually 60 hertz. Since power system frequency is closely regulated, the problem of varying frequency does not normally arise.

Effects of Waveform on Ratio and Phase Angle

Since any distorted waveform of the impressed primary voltage may be considered equivalent to a mixture of a sinusoidal voltage at the fundamental frequency and sinusoidal voltages at higher harmonic frequencies, waveform distortion would also have an effect on the true ratio and phase angle.

If the burden is a magnetic core device requiring a large exciting current, this may result in a waveform distortion in the secondary current I_S. However, this error is included if the transformer is tested with this burden. In testing voltage transformers, care must be used to avoid overloading the primary voltage supply which could produce a distorted primary voltage waveform.

Effects of Temperature on Ratio and Phase Angle

A change in temperature changes the resistance of the primary and secondary windings of the voltage transformer. This results in only slight changes of ratio and phase angle as the voltage drops in the transformers are primarily reactive and the secondary current is determined by the impedance of the burden. The change in accuracy is usually less than 0.1% for a 55°C change in temperature.

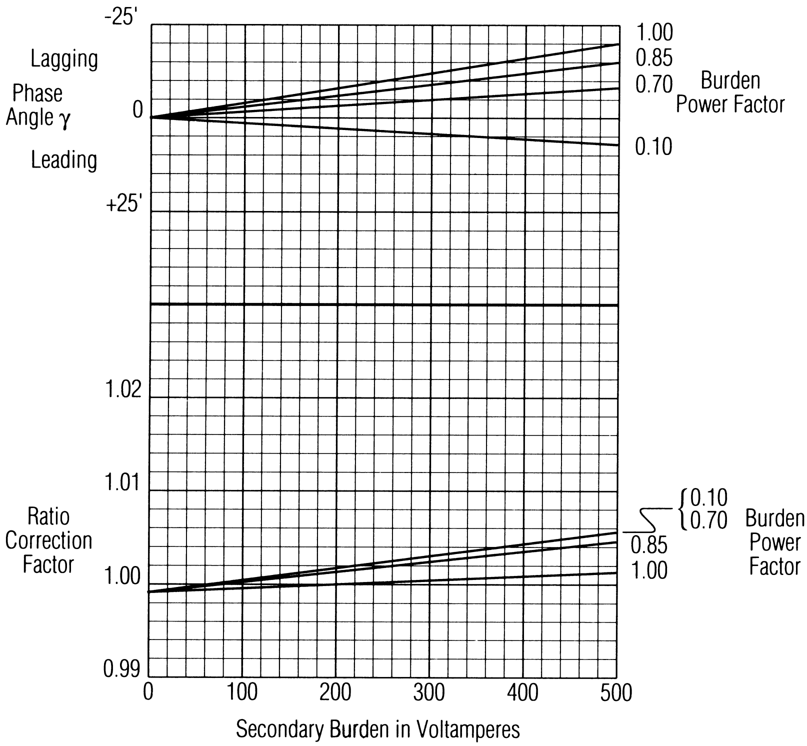


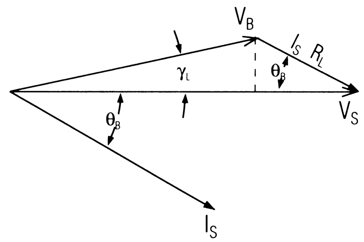
Figure 11-5. Characteristic Ratio and Phase Angle Curves for a Voltage Transformer at 60 Hertz, 120 Volts.

Effects of Secondary Lead Resistance on the Ratio and Phase Angle as Seen by the Meter

The true ratio and phase angle of a voltage transformer are defined in terms of the terminal voltages V_P and V_S. The true secondary burden is defined in terms of the impedance connected to the secondary terminals and therefore includes the secondary lead resistance R_L as shown in Figure 11-2. The resistance of the secondary leads R_L is small compared to the impedance of the burden Z_B so that ordinarily the lead resistance does not change the secondary burden sufficiently to make any appreciable difference in the ratio and phase angle at the voltage transformer terminals.

However, the meter is not connected directly to the secondary terminals, but at the end of the secondary leads. The voltage at the meter terminals is the burden voltage V_B as shown in Figure 11-2 and not the secondary terminal voltage V_S; V_B differs from V_S by the phasor drop $I_S R_L$ that occurs in the leads. (See Figures 11-3 and 11-6.)

This voltage drop is in phase with the secondary current I_S and therefore causes the burden voltage V_B to be slightly different in magnitude and slightly shifted in phase relation with respect to the secondary terminal voltage V_S.



V_S = Secondary Terminal Voltage (Example: 120 Volts)
V_B = Voltage at Terminals of Burden (Example, Calculated: 119.896 Volts)
I_S = Secondary Current (Example: 0.24 Amperes)
θ_B = Phase Angle of Burden (Example: 30°)
$\cos\theta_B$ = Power Factor of Burden (Example: .866)
R_L = Resistance of Secondary Leads (Example: 0.50 Ohms)

RCF_L = Ratio Correction Factor (Caused by Secondary Leads Only)

Example:

$$RCF_L = \frac{V_S}{V_B} \approx \frac{V_S}{V_S - I_S R_L \cos\theta_B} = \frac{120}{120-(0.24)(0.5)(.866)} = 1.0009$$

γ_L = Phase Angle in Minutes (Caused by Secondary Lead Resistance Only)

Example:

$$\gamma_{L\,(\text{min.})} \approx \frac{I_S R_L \sin\theta_B}{V_S}\,3438 = \frac{(0.24)(0.5)(0.5)(3438)}{120} = +1.7 \text{ Minutes}$$

Note: The constant 3438 is the number of minutes in a radian.
The above formulas are approximations based on small angles.

Figure 11-6. Phasor Diagram and Calculation of the Ratio Correction Factor and Phase Angle Due to the Secondary Lead Resistance Only (Applies to Voltage Transformer Secondary Leads).

The effect of this line drop in terms of ratio correction factor and phase angle may be calculated as shown in Figure 11-6. Values for a typical example have also been given to illustrate the use of these equations. In this example, the ratio correction factor 1.0009 and the phase angle +1.7 minutes due to the secondary lead resistance were small and could be ignored in all but the most exacting applications. If a greater lead resistance or a heavier secondary burden had been assumed, then this effect would be much greater. For example, if the lead resistance R_L was increased to one ohm and the secondary current I_S to one ampere at 0.866 burden power factor (θ_B) then the ratio correction factor and phase angle due to the leads would rise to 1.0073 and +14.3 minutes. Such an error should not be ignored.

It should be emphasized that the effect of the secondary lead resistance, in causing a change in apparent ratio and phase angle at the meter terminals, is a straight lead-drop problem and is not due to the voltage transformer in any way. The effect would be exactly the same if an ideal voltage transformer were used.

In spite of the fact that this lead-drop effect is not due to the voltage transformer, it is sometimes convenient to include this drop during the test of a voltage transformer by determining the apparent ratio and phase angle between the primary terminals of the transformer and the terminals of the burden of the end of the actual or simulated secondary leads. This apparent ratio $\frac{V_P}{V_B}$ and apparent phase angle (γ_B) are indicated by the dashed-line phasors V_B, $-V_B$, and $I_S R_L$ on the phasor diagram, Figure 11-3. This is the total RCF and phase angle that must be used to correct the readings of the meter as both the transformer and lead-drop errors are included. In making acceptance tests to determine if the transformers meet specifications, the tests must be made at the transformer secondary terminals as the lead drop is not caused by the transformer.

In actual practice the ratio and phase angle errors due to secondary lead drop are usually limited to small values by strict limitations of allowable lead resistance and secondary burden. This lead drop is troublesome only in exceptional cases where long leads and heavy burdens are required. In case of doubt, a calculation, using the formulas given in Figure 11-6, will quickly indicate the magnitude of the error involved.

Effects of Common Secondary Leads on Ratio and Phase Angle as Seen by the Meter

In a polyphase circuit where two or three voltage transformers are used it is the normal practice to use one wire as the common neutral secondary lead for all of the voltage transformers.

This fact must be taken into account when measuring or calculating the effect of the lead drop on the ratio and phase angle at the meter. If three voltage transformers are connected in wye as shown in Figure 11-20, the neutral secondary lead carries no current with a balanced burden. If two voltage transformers are connected in open delta as shown in Figure 11-18, the neutral secondary carries $\sqrt{3}$ times the current of the other leads for a balanced burden on phases 1-2 and 2-3.

If, because of long secondary leads or heavy burdens, the lead-drop effect causes significant error, then the use of a common secondary lead increases the difficulties of determining this effect by test or calculation. Calculations must be made phasorially, taking into account the magnitude and phase relation of the current in each secondary lead.

Polyphase Burdens

When the secondaries of two or three voltage transformers are used to supply interconnected polyphase burdens, it becomes difficult to determine the actual burden in each transformer. Calculations of burden must be made phasorially and become exceedingly complex when several polyphase and single-phase burdens are involved. Such calculations can be avoided by testing at the burden under actual or simulated three-phase conditions. This is required only in the most exacting applications where corrections based on the actual burden must be applied. In most cases burdens are kept within the ratings of the voltage transformers and no corrections are applied.

Methods of Compensating Voltage Transformers to Reduce Ratio and Phase Angle Errors

Voltage transformers are designed to have low exciting current and low internal impedance. This reduces the ratio and phase angle errors. In addition, the turn ratio may be made slightly different than the marked ratio. This is done to compensate the transformer for minimum error at a specific burden instead of at zero burden. If the transformer is used with a burden approximating the design burden, errors may be greatly reduced.

Permanence of Accuracy

The accuracy of a voltage transformer does not change appreciably with age. It may change due to mechanical damage or to electrical stresses beyond those for which the transformer was designed.

The Current Transformer

The Ideal Current Transformer Connection Diagram

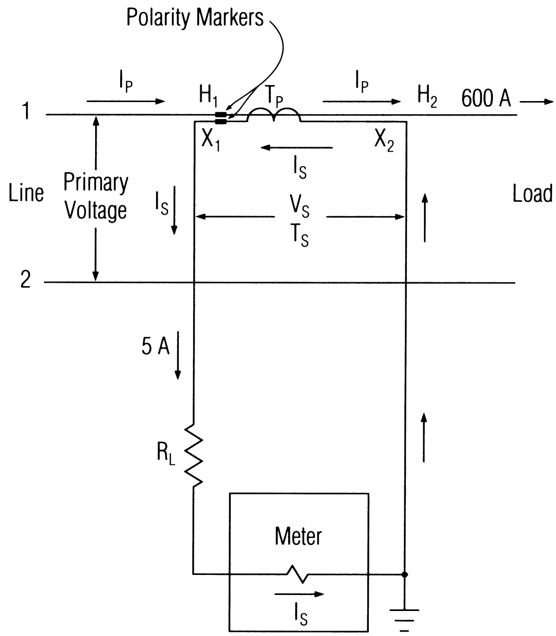
Figure 11-7 shows the connection diagram for an ideal current transformer. Note that the primary winding is connected in series with one of the high-voltage leads carrying the primary current, and the secondary winding is connected to the current coil of the meter. When 600 amperes flow through the primary winding of this current transformer, 5 amperes are developed in the secondary winding by transformer action. This secondary current is passed through the current coil of the meter. Since there is no direct connection between the primary and secondary windings, the insulation between these windings isolates the meter from the voltage of the primary. One side of the secondary circuit is connected to ground to provide protection from static charges and insulation failure.

Polarity

In Figure 11-7 the polarity markers are used to show the instantaneous direction of current flow in the primary and secondary windings of the current transformer. They are so placed that when the primary current I_P is flowing into the marked primary terminal H_1, the secondary current I_S is at the same instant flowing out of the marked secondary terminal X_1. These markings enable the secondaries of the current and voltage transformers to be connected to the meter with the proper phase relationships. For example, in the case of a single-stator meter installed with a current and a voltage transformer, reversal of the secondaries from either transformer would cause the meter to run backward.

Secondary Burden

In Figure 11-7 the impedance of the current coil of the meter and the resistance of the secondary leads causes a small voltage drop across the secondary terminals of the current transformer when the secondary current I_S is flowing. The current transformer must develop a small terminal voltage V_S to overcome this voltage drop in order to maintain the secondary current. The impedance of the meter and resistance of the secondary leads is therefore a burden on the secondary winding.



Marked Primary Current = 600 A

Marked Secondary Current = 5 A

Marked Ratio = 120:1

Turn Ratio = $\frac{T_S}{T_P}$

True Ratio = $\frac{I_P}{I_S}$

Figure 11-7. The Ideal Current Transformer.

This burden may be expressed as the total voltamperes and power factor of the secondary devices and leads at a specified current and frequency (normally, 5 amperes and 60 hertz). It is often more convenient to express current transformer burdens in terms of their total resistance in ohms and inductance in millihenries, or as total ohms impedance at a given power factor and frequency.

While the basic definition of burden for a current transformer and voltage transformer is the same in terms of active and reactive power supplied by the instrument transformer, the effect of burden impedance is the reverse in the two cases. Zero burden on a voltage transformer is an open-circuit or infinite impedance, while zero burden on a current transformer is a short-circuit or zero impedance.

The impedance of the current coil of the meter in Figure 11-7 is very low so that the current transformer is operated with what amounts to a short circuit on its secondary winding. This is the normal condition of operation for a current transformer.

Marked Ratio, Turn Ratio, and True Ratio

The marked ratio of a current transformer is the ratio of primary current to secondary current as given on the rating plate.

The turn ratio of a current transformer is the ratio of the number of turns in the secondary winding to the number of turns in the primary winding. (*Note*: This is just the opposite of a voltage transformer. A voltage transformer that steps down the voltage has more turns on the primary than the secondary. A current transformer that steps down the current has more turns on the secondary than on the primary.)

The true ratio of a current transformer is the ratio of rms primary current to the rms secondary current under specified conditions.

In an ideal current transformer, the marked ratio, the turn ratio, and the true ratio would always be equal and the reversed secondary current would always be in phase with the impressed primary current. It must be strongly emphasized that this ideal current transformer does not exist.

The concept of the ideal current transformer is a useful fiction. Modern current transformers when supplying burdens which do not exceed their accuracy ratings, approach this fictional ideal very closely. Most metering installations involving instrument transformers are set up on this ideal basis and, in most cases, no corrections need be applied. In the example shown in Figure 11-7 it would normally be assumed that the meter current coil is always supplied with 1/120 of the primary current. If this assumption is to be valid, the limitations of actual current transformers must be clearly understood and care taken to see that they are used within these limitations.

The Actual Current Transformer—The Phasor Diagram

In the ideal current transformer the secondary current is inversely proportional to the ratio of turns and opposite in phase to the impressed primary current. In reality an exact inverse proportionality and phase relation is not possible because part of the primary current must be used to excite the core. The exciting current may be subtracted phasorially from the primary current to find the amount remaining to supply secondary current. Therefore, the secondary current will be slightly different from the value that the ratio of turns would indicate and there is a slight shift in the phase relationship. This results in the introduction of ratio and phase angle errors as compared to the performance of the "ideal" current transformer.

Figures 11-8 and 11-9 are the schematic and phasor diagrams of an actual current transformer. The phasor diagram, Figure 11-9, is drawn for a transformer having a 1:1 turn ratio and the voltage drop and loss phasors have been greatly exaggerated so that they can be clearly separated on the diagram.

Basically, the phasor diagram for a current transformer is similar to that for the voltage transformer. However, in the current transformer the important phasors are the primary and secondary current rather than the voltages.

The operation of the current transformer may be explained briefly by means of the phasor diagram, Figure 11-9, as follows:

The flux ϕ in the core induces a voltage E_S in the secondary winding lagging the flux by 90°. A voltage equal to $\frac{E_S}{n}$, where n is the turn ratio $\left(\frac{T_S}{T_P}\right)$, is also induced in the primary winding lagging ϕ by 90°. To overcome this induced voltage, a voltage $E_P = \frac{E_S}{n}$ must be supplied in the primary. Thus, E_P must lead E_S by 180° and therefore leads the flux by 90°.

The secondary current I_S is determined by the secondary terminal voltage V_S and the impedance of the burden Z_B. I_S is equal to $\frac{V_S}{Z_B}$ and lags V_S by a phase angle θ_B where cos θ_B is the power factor of the burden. (This burden power factor should not be confused with the power factor of the load being supplied by the primary circuit.) The burden impedance Z_B is made up of the burden resistance R_B and the burden reactance X_B. (See Figure 11-8.) Note particularly that the burden resistance R_B is equal to the sum of the meter resistance R_M and the secondary lead resistance R_L. Since the total impedance of current transformer burdens is very low, usually less than one ohm, the lead resistance R_L is an appreciable part of the burden and cannot be neglected. In many cases the resistance of the secondary leads may constitute the greater part of the burden impedance.

The voltage drop in the secondary winding is equal to I_SZ_S, where Z_S is the impedance of this winding. This drop is the phasor sum of the two components I_SR_S and I_SX_S, where R_S and X_S are the resistance and reactance of the secondary winding. The voltage drop I_SR_S must be in phase with I_S and the voltage drop I_SX_S must lead I_S by 90°. The induced secondary voltage E_S is equal to the phasor sum of $V_S + I_SZ_S$ and V_S is the phasor difference $E_S - I_SZ_S$.

I_M is the magnetizing current required to supply the flux ϕ and is in phase with the flux. I_W is the current required to supply the hysteresis and eddy current losses in the core, and leads I_M by 90°. The phasor sum of $I_M + I_W$ is the exciting current I_E.

The primary must supply the reflected secondary current $-nI_S$. The total primary current I_P is therefore the phasor sum of I_E and $-nI_S$.

With a low-impedance burden connected to the secondary winding, the impedance of the primary winding is extremely low, since the reflected impedance of the secondary is approximately proportional to the square of the turn ratio, and the primary winding of a step-down current transformer has fewer turns than the secondary.

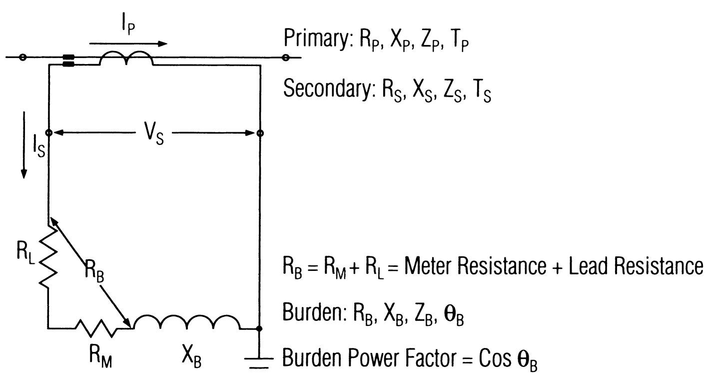
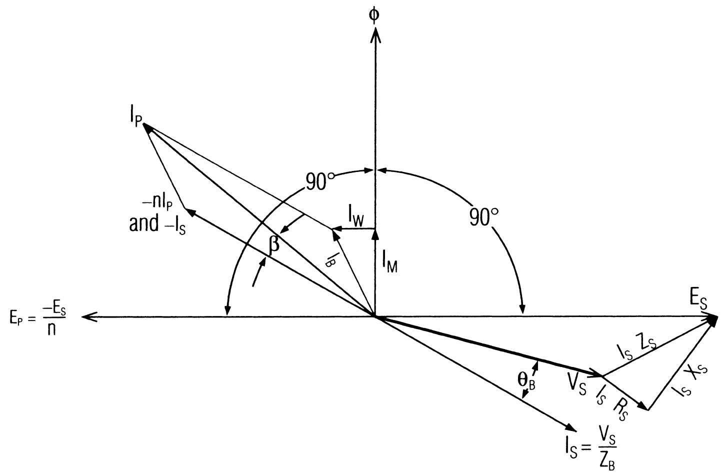


Figure 11-8. The Actual Current Transformer with Burden.



ϕ	=	Flux in Core	R_B	=	Resistance of Burden
I_M	=	Magnetizing Current	X_B	=	Reactance of Burden
I_W	=	Core Loss Current	Z_B	=	Impedance of Burden
I_E	=	Exciting Current	θ_B	=	Phase Angle of Burden
E_P	=	Voltage Required to Overcome Induced Primary Voltage	$\cos\theta_B$	=	Power Factor of Burden
I_P	=	Primary Current	T_P	=	Turns on Primary
E_S	=	Induced Secondary Voltage	T_S	=	Turns on Secondary
V_S	=	Secondary Terminal Voltage	n	=	Turns Ratio = T_S/T_P
I_S	=	Secondary Current	I_P/I_S	=	True Ratio of Current Transformer
R_S	=	Resistance of Secondary	β	=	Phase Angle of Current Transformer
X_S	=	Reactance of Secondary			

Figure 11-9. Phasor Diagram of Current Transformer.

The primary current in the current transformer is determined by the load on the primary circuit of the installation. The voltage drop in the primary winding is therefore very small, even with full-rated current in the primary line, because of the low impedance of this winding. The induced secondary voltage E_S and the secondary terminal voltage V_S are both small because the transformer is essentially short circuited by the low-impedance burden. Therefore, the voltage E_P required to overcome the voltage $\frac{E_S}{n}$ induced in the primary is also very small.

Since the true ratio of a current transformer is $\frac{I_P}{I_S}$, it is not ordinarily necessary to consider the primary voltage or the voltage drops in the primary, since they do not affect the value of either the primary or secondary currents.

The phasor $-I_S$ is obtained by reversing the secondary current phasor I_S. In Figure 11-9, which is for a 1:1 transformer, $-I_S$ is coincident with $-nI_S$. This reversal is automatically done if the polarity markings are followed.

In Figure 11-9 note that the reversed secondary current phasor $-I_S$ is not equal in magnitude to the impressed primary current phasor I_P and that $-I_S$ is out of phase with I_P by the angle beta, β. In an ideal current transformer of 1:1 ratio, $-I_S$ would be equal to and in phase with I_P. In the actual current transformer, this difference represents errors in both ratio and phase angle.

True Ratio and Ratio Correction Factor

The true ratio of a current transformer is the ratio of the rms primary current to the rms secondary current under specified conditions.

In the phasor diagram, Figure 11-9, the true ratio is $\frac{I_P}{I_S}$. It is apparent that this is not equal to the 1:1 turn ratio $\left(\frac{T_S}{T_P}\right)$ upon which the diagram was based. I_S in this case is smaller in magnitude than I_P because part of the primary current I_P is required to supply the exciting current I_E.

The turn ratio of a current transformer $\left(\frac{T_S}{T_P}\right)$ is built in at the time of construction and the marked ratio is indicated on the nameplate by the manufacturer. These ratios are fixed and permanent values for a given transformer.

The true ratio of a current transformer is not a single fixed value since it depends upon the specified conditions of use. These conditions are secondary burden, primary current, frequency, and waveform. Under ordinary conditions, frequency and waveform are practically constant so that the true ratio is primarily dependent upon the secondary burden, the primary current, and the characteristics of the particular current transformer.

The true ratio of a current transformer cannot be marked on the nameplate since it is not a constant value but a variable which is affected by external conditions. The true ratio is determined by test for the specified conditions under which the current transformer is to be used. (For most practical applications, where no corrections are to be applied, the true ratio is considered to be equal to the marked ratio under specified IEEE standard accuracy tolerances and burdens.)

Thus, it might be found that the true ratio of a current transformer having the marked ratio of 120:1 was 119.796:1 under the specified conditions. However, the true ratio is not usually written in this way because this form is difficult to evaluate and inconvenient to use. The figure 119.796 may be broken into two factors and written 120×0.9983. Note that 120 is the marked or nominal ratio of the current transformer which is multiplied by the factor 0.9983.

This factor, by which the marked ratio must be multiplied to obtain the true ratio, is called the ratio correction factor (RCF). It has exactly the same meaning when applied to the current transformer as previously given for the voltage transformer. True Ratio = Marked Ratio × RCF.

$$\text{RCF} = \frac{\text{True Ratio}}{\text{Marked Ratio}}$$

Phase Angle

Figure 11-9 shows that the reversed secondary current I_S is not in phase with the impressed primary current I_P. The angle beta (β) between these phasors is known as the phase angle of the current transformer and is usually expressed in minutes of arc (60 minutes of arc is equal to one degree).

In the ideal current transformer the secondary current I_S would be exactly 180° out of phase with the impressed primary current I_P. The polarity markings automatically correct for this 180° reversal. The reversed secondary current $-I_S$ would therefore be in phase with the impressed primary current I_P and the phase angle β would be zero.

In the actual current transformer the phase angle β represents a phase shift between the primary and secondary currents in addition to the normal 180° phase shift. The 180° shift is corrected by the reversal that occurs when the polarity markings are followed, but the phase angle β remains. This uncorrected phase shift can cause errors in measurements when exact phase relations must be maintained.

The phase angle of a current transformer is designated by the Greek letter beta (β) and is positive when the current leaving the identified secondary terminal leads the current entering the identified primary terminal.

The phase angle of a current transformer is not a single fixed value, but varies with burden, primary current, frequency, and waveform. It results from the component of the primary current required to supply the exciting current I_E as shown in Figure 11-9. Under ordinary conditions where frequency and waveform are practically constant, the phase angle is primarily dependent upon the secondary burden, the primary current, and the characteristics of the particular current transformer.

Effects of Secondary Burden on Ratio and Phase Angle

An increase of secondary burden, which for a current transformer means an increase in the burden impedance Z_B, requires an increase in the secondary voltage V_S if the secondary current I_S is to remain the same. See Figure 11-9. (Note that in a voltage transformer an increase of secondary burden requires an increase in the secondary current if the secondary voltage is to remain the same.) Increasing the secondary current requires an increase in the induced secondary voltage E_S which can only be produced by an increase in the flux ϕ.

To provide an increased flux, the magnetizing current I_M must increase and the core loss current I_W also increases. This results in an increase in the exciting current I_E. Thus, increasing the burden causes an increase in the exciting current. Since the exciting current is the primary cause of the ratio and phase angle errors in the current transformer, these errors are affected by any change in the secondary burden.

Effect of Primary Current on Ratio and Phase Angle

Unlike the voltage transformer which operates at a practically constant primary voltage, the current transformer must operate over a wide range of primary currents from zero to rated current, and above rated current in special cases, such as the operation of protective relays. This means that with a constant secondary burden the flux in the core must vary over a wide range as the primary current is changed. To produce this varying flux, the exciting current must also vary over a wide range. If the flux ϕ varied in exact proportion with the exciting current I_E then the changes in primary current would not affect the ratio and phase angle. However, current transformers are designed to operate at low flux densities in the core and under these conditions the flux is not directly proportional to the exciting current. Figure 11-10 shows a typical exciting current curve for the magnetic core of a current transformer.

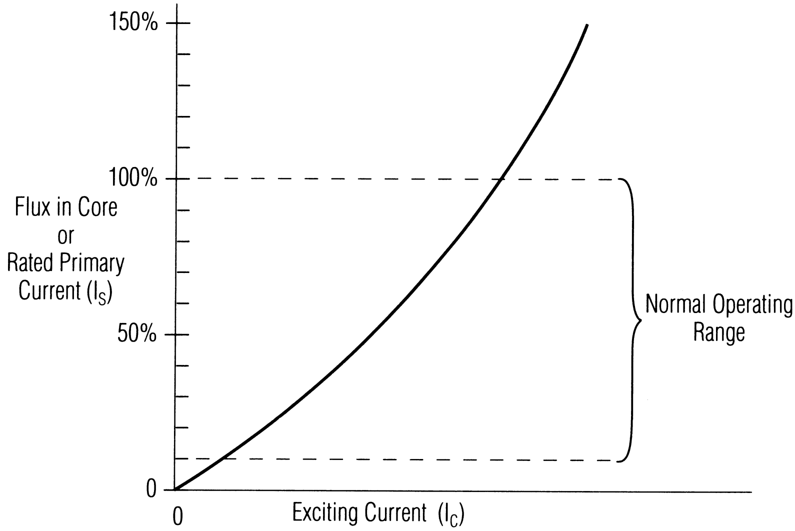


Figure 11-10. Typical Exciting Current Curve for a Current Transformer.

Note that the change of exciting current over the normal operating range from 10 to 100% rated primary current is not a linear function of the primary current. The shape of the saturation curve for the current transformer is actually similar to the curve for the voltage transformer, as seen in Figure 11-4, but only an expanded portion of the lower end of the curve is shown in Figure 11-10. With normal secondary burdens, saturation does not occur until the primary current reaches 5 to 20 times the rated value. Thus, the saturation point is not shown in Figure 11-10.

Since the exciting current does not change in exact proportion to the primary current, the true ratio and phase angle vary to some extent with the primary current. The ratio and phase angle errors are usually greater at 10% primary current than at 100% primary current, though this depends upon the burden and the compensation of the particular current transformer. Figure 11-11 shows typical metering accuracy curves for a 0.3 Accuracy Class current transformer at IEEE standard burdens and rated current ranging from 5 to 160%. Note that the typical current transformer ratio and phase angle errors are very small at the lower burdens. Also, the current transformers are typically much more accurate over a wider current range than is required by IEEE Accuracy Class 0.3 (at these lower burdens), i.e., 0.3% maximum error at 100% rated current and 0.6% maximum error at 10% rated current. See discussions later in this chapter on IEEE Accuracy Classes.

Effects of Frequency on Ratio and Phase Angle

The effect of frequency variation on the ratio and phase angle of a current transformer is less than that on a voltage transformer primarily because of the low flux density. Current transformers may be designed to have reasonable accuracy over a range from 25 to 133 hertz. There will, however, be some slight variation with frequency in this range.

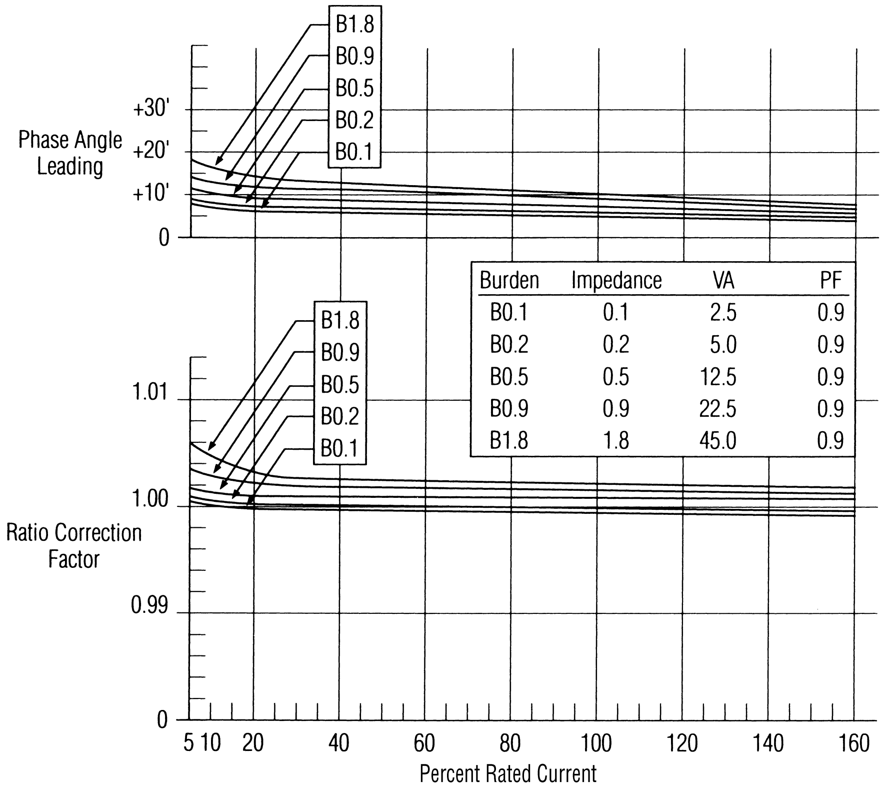


Figure 11-11. Characteristic Ratio and Phase Angle Curves for a Typical Current Transformer at 60 Hertz.

Effects of Waveform on Ratio and Phase Angle

Waveform distortion in the primary current may have slight effects on the ratio and phase angle but in general such effects are negligible. Even a large amount of third harmonic in the primary current wave is reasonably well reproduced in the secondary, thus causing little error. Higher harmonics could cause errors but these are not normally present in sufficient magnitude to be significant.

Effects of Secondary Leads on Ratio and Phase Angle

In the current transformer the secondary current I_S must be the same in all parts of the secondary circuit, including the burden, since it is a series circuit. Thus, the secondary current and, therefore, the true ratio and phase angle, will be the same whether measured at the transformer or at the meter at the end of the secondary leads. The only effect of the secondary leads is on the burden. With long secondary leads, the leads may constitute the major portion of the secondary burden. In all cases the secondary leads must be included in all tests and calculations as part of the secondary burden.

Effects of Common Secondary Leads

In a polyphase circuit where two or three current transformers are used it is a common practice to use one wire as the common secondary lead for all of the current transformers.

This fact must be taken into account when measuring or calculating the effect of the leads as part of the secondary burden. If the current transformers are connected in wye as shown in Figure 11-24, the neutral secondary lead carries no current if the primary load current is balanced. In this case the resistance of the common lead is not part of the burden on any of the current transformers. If the two current transformers are connected open delta as shown in Figure 11-12, the common secondary lead carries a current whose magnitude is the same as the other leads under conditions of balanced line currents and an open-delta burden as shown. However, the current in the common lead is not in phase with the current in either of the other two leads. Thus, the lead resistance of the common lead does not affect the burden on the two current transformers equally.

Figure 11-12 is a schematic and a phasor diagram of a two-stator polyphase meter whose current elements are connected to two current transformers. Note that if the lead resistance R_L is an appreciable part of the burden, the burden on the two current transformers is not the same because of the effect of the common lead resistance. The effective burdens differ in both magnitude and phase. The burden on one current transformer is $V_1I_1 \cos \theta_{B1}$ and the other is $V_3I_3 \cos \theta_{B3}$. The secondary currents I_1 and I_3 were assumed to be equal, but the terminal voltages V_1 and V_3 are not equal. In addition the phase angles of the two burdens θ_{B1} and θ_{B3} are not equal. Thus, the effect of the common secondary lead resistance results in unequal burdens on the two current transformers even though the two elements of the meter are identical.

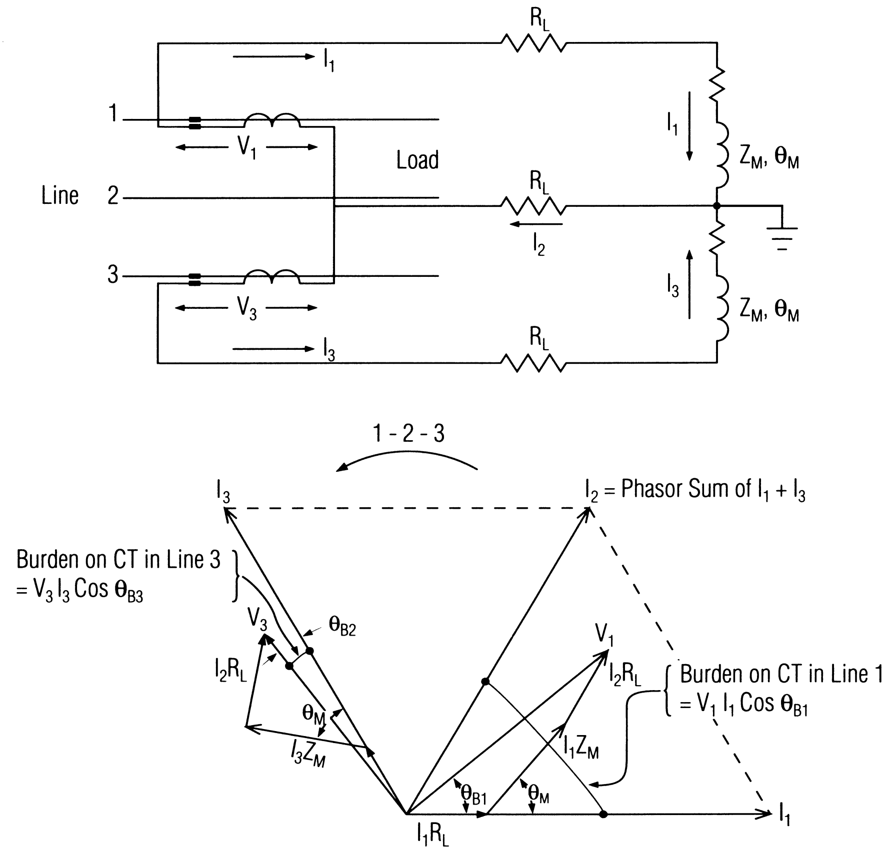
If a burden of 2.1 VA at 0.60 power factor lagging and a lead resistance of 0.1 ohm (100 feet of No. 10 wire) are assumed, the burdens on the two transformers would be 6.34 VA at 0.79 power factor lagging on the current transformer in line 1 and 5.05 VA at 0.996 power factor leading on the current transformer in line 3.

Actually these small differences in burden would have little effect on the ratio and phase angle of a modern current transformer. However, if a much longer common secondary lead with a resistance of 0.3 ohm or more is used, the effect might cause significant error unless appropriate corrections are applied.

In most installations the common lead resistance is kept low so that the resulting error is insignificant. In the most accurate work, if long secondary leads must be used and exact corrections must be applied, the current transformers can be tested under actual three-phase conditions. If the common lead is eliminated by using separate return leads for each transformer, the calculations of burden are simplified.

Difficulties with Low-Ampere-Turn Designs

With a given current transformer core, the number of ampere-turns needed to excite this core to a certain flux density is essentially a constant value. The exciting-current ampere-turns must be taken from the primary ampere-turns and the remainder supplies the secondary ampere-turns.



Z_M	=	Impedance of Meter Coil
θ_M	=	Phase Angle of Meter Impedance
R_L	=	Resistance of Each Secondary Lead
I_1	=	Secondary Current of Current Transformer in Line 1
I_3	=	Secondary Current of Current Transformer in Line 3
I_2	=	Current In Common Secondary Lead
V_1	=	Terminal Voltage of Current Transformer in Line 1
V_3	=	Terminal Voltage of Current Transformer in Line 3
θ_{B1}	=	Phase Angle of Burden on Current Transformer in Line 1
θ_{B3}	=	Phase Angle of Burden on Current Transformer in Line 3

Figure 11-12. Effect of Common Secondary Lead on Burdens of Current Transformers.

As the total ampere-turns of the primary become lower, the exciting ampere-turns become a greater percentage of the total, thus increasing the errors. When the primary ampere-turns are less than about 600, it becomes difficult to design current transformers with small errors. Only by using special core materials and compensation methods can the errors be reduced to reasonable values.

Dangers Due to an Open Secondary

The secondary circuit of a current transformer must never be opened when current is flowing in the primary. With an open secondary, the secondary impedance becomes infinite, the flux rises to saturation, and the voltage drop in the primary is increased due to the reflected secondary impedance. The primary voltage is stepped up by the ratio of the transformer and the secondary voltage rises to dangerously high values. Voltages of several thousand volts are possible under open-circuit conditions. Such voltages are dangerous to personnel and can damage the transformer.

Permanence of Accuracy

The accuracy of a current transformer does not change appreciably with age. It may be permanently changed by mechanical or electrical failure and it may be temporarily changed by magnetization.

INSTRUMENT TRANSFORMER CORRECTION FACTOR

Ratio Correction Factor and Related Terms

The marked ratio, the true ratio, and the ratio correction factor have been defined and discussed. In addition to the RCF, the terms percent ratio (or percent marked ratio), ratio error, and percent ratio error are often used when stating the errors in ratio of instrument transformers. It is unfortunate that there are four numerically different terms used to describe the same phenomenon, as they are easily confused. Table 11-1 defines these and related terms with algebraic formulas which provide the means of converting one term to another. Of the four, the RCF is most easily understood and has the least chance of misapplication, since neither percent nor + or − are involved. The RCF is the only one of the four terms defined in IEEE Standard C57.13 and it is therefore the preferred term.

Examples: If RCF is 1.0027, the percent ratio is 100.27%, the ratio error is +0.0027, and the percent ratio error is +0.27%.

If the RCF is 0.9973, the percent ratio is 99.73%, the ratio error is −0.0027, and the percent ratio error is −0.27%.

Note that the proper sign, + or −, must be used for the ratio error or the percent ratio error and the word percent or a percent sign (%) must be used with the percent ratio and the percent ratio error.

Combined Ratio Correction Factor

Where both a voltage and a current transformer are used for the measurement of watts or watthours, the combined ratio correction factor is

$$RCF_K = RCF_E \times RCF_I$$

where RCF_K is the combined ratio correction factor
RCF_E is the ratio correction factor of the voltage transformer
RCF_I is the ratio correction factor of the current transformer

The combined ratio correction factor RCF_K corrects for the ratio error of both the voltage and current transformers but does not correct for the effects of phase angles.

Table 11-1. Definitions of Instrument Transformer Ratio, Ratio Correction Factor, and Related Terms.

Term	Formula	Application
Marked (Nominal) Ratio	$\frac{\text{Marked Primary Voltage}}{\text{Marked Secondary Voltage}}$	VT
Marked (Nominal) Ratio	$\frac{\text{Marked Primary Current}}{\text{Marked Secondary Current}}$	CT
True Ratio	$\frac{\text{True Primary Voltage}}{\text{True Secondary Voltage}}$	VT
True Ratio	$\frac{\text{True Primary Current}}{\text{True Secondary Current}}$	CT
True Primary Voltage	True Secondary Voltage $\times$ Marked Ratio $\times$ RCF	VT
True Primary Current	True Secondary Current $\times$ Marked Ratio $\times$ RCF	CT
Ratio Correction Factor (RCF)	$\frac{\text{True Ratio}}{\text{Marked Ratio}}$	VT, CT
Ratio Correction Factor (RCF)	$\frac{\text{True Primary Voltage}}{\text{True Secondary Voltage} \times \text{Marked Ratio}}$	VT
Ratio Correction Factor (RCF)	$\frac{\text{True Primary Current}}{\text{True Secondary Current} \times \text{Marked Ratio}}$	CT
Percent Ratio	$100 \times \text{RCF}$	VT, CT
Ratio Error	$\frac{\text{True Ratio} - \text{Marked Ratio}}{\text{Marked Ratio}} = (\text{RCF} - 1)$	VT, CT
Percent Ratio Error	$100 \times (\text{RCF} - 1)$ $= 100 \times \frac{\text{True Ratio} - \text{Marked Ratio}}{\text{Marked Ratio}}$	VT, CT

Approximate Method of Multiplying Two Numbers Close to One by Addition

The problem of multiplication of ratio and phase angle correction factors occurs often in calculating instrument transformer corrections. Since the numerical value of these correction factors is close to one, the work may be simplified by using an approximate method involving addition and subtraction rather than multiplication. The correction factors can be represented by $(1 \pm a)$ and $(1 \pm b)$, where a and b are small decimal fractions. The multiplication can then be written:

$$(1 \pm a)(1 \pm b) = 1 \pm a \pm b \pm ab$$

This is approximately equal to $1 \pm a \pm b$ since ab is the product of two small numbers and is therefore extremely small.

Example: $(0.9987)(1.0025) = 1.00119675$ exactly

Using the approximate method:

$0.9987 = 1 - 0.0013$, hence $a = -0.0013$

$1.0025 = 1 + 0.0025$, hence $b = +0.0025$

$$1 - 0.0013 + 0.0025 = 1.0012$$

Note: ab = $-0.0013 \times 0.0025 = -0.00000325$
and $1.0012 - 0.00000325 = 1.00119675$.

However, the figures beyond the fourth decimal place are not significant so the answer given by the approximate method is as accurate as is justified by the original figures.

If the correction factors are within 1% of 1.0000 (0.9900 to 1.0100), the error in this approximation will not exceed 0.01% (0.0001).

Another way to use this approximation is to add the two values and subtract 1.

$$0.9987 + 1.0025 = 2.0012$$

$$2.0012 - 1.0000 = 1.0012$$

The multiplication of correction factors can be done by inspection using this approximation.

Phase Angle Correction Factor

Figure 11-13 shows the schematic and phasor diagrams of a meter connected to a high-voltage line using a voltage and a current transformer.

The primary power W_P is equal to the product of the primary voltage E_P, the primary current I_P, and the true power factor of the primary circuit ($\cos\theta$):

$$W_P = E_P I_P \cos\theta$$

The secondary power W_S measured by the meter is equal to the product of the secondary voltage E_S, the secondary current I_S, and the power factor of the secondary circuit ($\cos\theta_2$):

$$W_S = E_S I_S \cos\theta_2$$

The power factor of the secondary circuit ($\cos\theta_2$) is called the apparent power factor and differs from the primary power factor ($\cos\theta$) because of the effect of the phase angles beta (β) and gamma (γ) of the current and voltage transformers respectively.

If the instrument transformers had 1:1 ratios and no errors due to ratio, then the subscripts could be omitted. For this condition:

$$W_P = EI\cos\theta$$

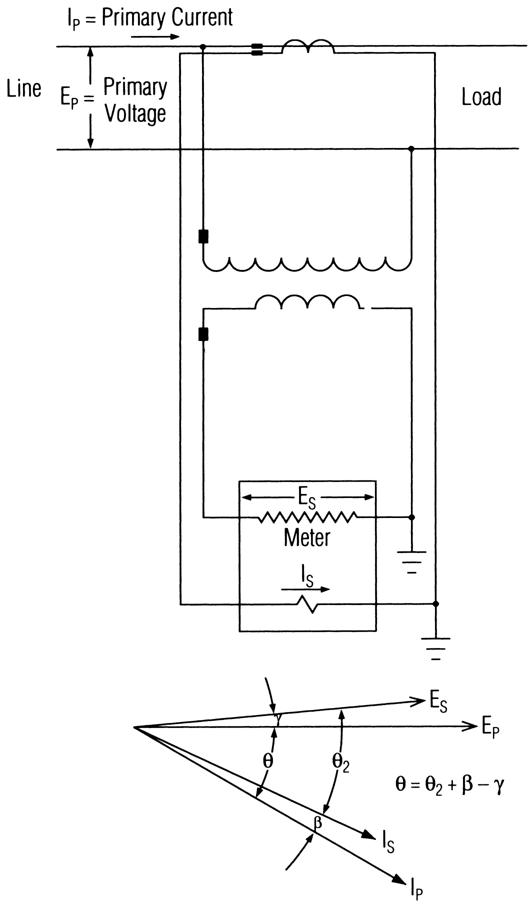
$$W_S = EI\cos\theta_2$$

In this special case, the primary power W_P would be equal to the secondary power W_S were it not for the difference between $\cos\theta$ and $\cos\theta_2$ which is due to the phase angles of the instrument transformers.

The phase angle correction factor (PACF) is defined by IEEE as the ratio of the true power factor to the measured power factor. It is a function of the phase angles of the instrument transformer and the power factor of the primary circuit being measured.

Note that the phase angle correction factor is the factor that corrects for the phase displacement of the secondary current or voltage, or both, due to the instrument transformer phase angles.

The measured watts or watthours in the secondary circuits of instrument transformers must be multiplied by the phase angle correction factor and the true ratio to obtain the true primary watts or watthours.



Current Transformer:

N_I = Marked (Nominal) Ratio
RCF_I = Ratio Correction Factor
β = Phase Angle

Load:

E_P = Primary Voltage
I_P = Primary Current
$\cos\theta$ = Primary (True) Power Factor

Meter:

E_S = Secondary Voltage
I_S = Secondary Current
$\cos\theta_2$ = Secondary (Apparent) Power Factor

Voltage Transformer:

N_E = Marked (Nominal) Ratio
RCF_E = Ratio Correction Factor
γ = Phase Angle

W_P = Primary Power (True Power Supplied to Load) = $E_P I_P \cos\theta$
W_S = Secondary Power (Power Measured by the Meter) = $E_S I_S \cos\theta_2$

$$E_P I_P \cos\theta = (E_S I_S \cos\theta_2)(N_E)(N_I)(RCF_E)(RCF_I)\left[\frac{\cos(\theta_2 + \beta - \gamma)}{\cos\theta_2}\right]$$

Figure 11-13. Relations Between Primary and Secondary Power.

The combined phase angle correction factor ($PACF_K$) is used when both current and voltage transformers are involved. When current transformers only (no voltage transformers) are involved, $PACF_I$ is used.

Therefore, for the special case of 1:1 ratio and no ratio errors:

$$W_P = W_S(PACF_K)$$

and

$$PACF_K = \frac{W_P}{W_S} = \frac{EI\cos\theta}{EI\cos\theta_2} = \frac{\cos\theta}{\cos\theta_2}$$

The $PACF_K$ is therefore equal to the ratio of the true power factor ($\cos \theta$) to the apparent power factor ($\cos \theta_2$). This equation for the phase angle correction factor is not directly usable, since, in general, $\cos \theta_2$, the apparent power factor is known, but the exact value of the true power factor, $\cos \theta$, is not.

The phasor diagram in Figure 11-13 shows that $\theta = \theta_2 + \beta - \gamma$. In this phasor diagram all the angles shown have a plus (+) sign and are positive. The secondary current and voltage phasors have been drawn so that they lead their respective primary phasors. Therefore, β and γ are both positive by definition. The angles θ and θ_2 between the voltage and current phasors are considered positive (+) when the current phasors are lagging the voltage phasors (lagging power factor). Hence, θ and θ_2 are both positive as drawn. Substituting $\theta = \theta_2 + \beta - \gamma$ into the previous equation:

$$PACF_K = \frac{\cos(\theta_2 + \beta - \gamma)}{\cos \theta_2}$$

When a current transformer is used alone, $PACF_I$ may be determined by using the formula for $PACF_K$ with the $-\gamma$ term deleted.

If $\cos \theta_2$, β, and γ are known, $PACF_K$ can now be calculated using trigonometric tables. Care must be taken to use the proper signs for θ, β, and γ, as previously noted.

Example:

Given: $\cos \theta_2 = 0.80$ lag, $\beta = -13'$, $\gamma = +10'$

Then:

$$\begin{aligned}
\theta_2 &= \cos^{-1} 0.80 = 36°52' \\
\theta &= \theta_2 + \beta - \gamma \\
\theta &= (+36°52') + (-13') - (+10') = 36°29' \\
\cos \theta &= \cos 36°29' = 0.804030 \\
PACF_K &= \frac{0.804030}{0.800000} = 1.0050
\end{aligned}$$

This method of evaluating the PACF is straight forward but too time consuming for practical work. Therefore, Tables 11-2 and 11-3 have been calculated by this method to give the PACF directly in terms of the apparent power factor ($\cos \theta_2$) and the combined value of the phase angles ($\beta - \gamma$).

Use of Tables 11-2 and 11-3 to Find the Phase Angle Correction Factor

In the example just given, $\cos \theta_2 = 0.80$ lagging and $\beta - \gamma = (-13 \text{ minutes}) - (+10 \text{ minutes}) = -23$ minutes. Hence, Table 11-3 must be used as indicated by the heading "For Lagging Current When $\beta - \gamma$ is Negative." At the intersection of the 0.80 power factor column and the 23 minute row the phase angle correction factor is 1.0050.

Two precautions are necessary when using these tables:

1. The algebraic signs of the phase angles and the minus sign in the formula must be carefully observed when calculating $\beta - \gamma$;
2. Care must be used in selecting either Table 11-2 or 11-3 according to the notes heading these tables regarding leading or lagging power factors and the resultant sign of $\beta - \gamma$.

Table 11-2. Phase Angle Correction Factors (PACFs).

For Lagging Current When ($\beta - \gamma$) is Positive
For Leading Current When ($\beta - \gamma$) is Negative

$\beta - \gamma$	Apparent Power Factor (Cos θ_2)																				$\beta - \gamma$
	.05	.10	.15	.20	.25	.30	.35	.40	.45	.50	.55	.60	.65	.70	.75	.80	.85	.90	.95	.99	
1'	.9942	.9971	.9981	.9986	.9989	.9991	.9992	.9993	.9994	.9995	.9996	.9996	.9997	.9997	.9997	.9998	.9998	.9999	.9999	1.0000	1'
2'	.9884	.9942	.9962	.9971	.9977	.9981	.9984	.9987	.9988	.9990	.9991	.9992	.9993	.9994	.9995	.9996	.9996	.9997	.9998	.9999	2'
3'	.9826	.9913	.9942	.9957	.9966	.9972	.9977	.9980	.9983	.9985	.9987	.9988	.9990	.9991	.9992	.9993	.9995	.9996	.9997	.9999	3'
4'	.9768	.9884	.9923	.9943	.9955	.9963	.9969	.9973	.9977	.9980	.9982	.9984	.9986	.9988	.9990	.9991	.9993	.9994	.9996	.9998	4'
5'	.9709	.9855	.9904	.9929	.9944	.9954	.9961	.9967	.9971	.9975	.9978	.9981	.9983	.9985	.9987	.9989	.9991	.9993	.9995	.9998	5'
6'	.9651	.9826	.9885	.9914	.9932	.9944	.9953	.9960	.9965	.9970	.9973	.9977	.9980	.9982	.9985	.9987	.9989	.9992	.9994	.9997	6'
7'	.9593	.9797	.9866	.9900	.9921	.9935	.9945	.9953	.9960	.9965	.9969	.9973	.9976	.9979	.9982	.9985	.9987	.9990	.9993	.9997	7'
8'	.9535	.9768	.9847	.9886	.9910	.9926	.9938	.9947	.9954	.9960	.9965	.9969	.9973	.9976	.9979	.9983	.9986	.9989	.9992	.9997	8'
9'	.9477	.9739	.9827	.9872	.9899	.9917	.9930	.9940	.9948	.9955	.9960	.9965	.9969	.9973	.9977	.9980	.9984	.9987	.9991	.9996	9'
10'	.9419	.9711	.9808	.9857	.9887	.9907	.9922	.9933	.9942	.9950	.9956	.9961	.9966	.9970	.9974	.9978	.9982	.9986	.9990	.9996	10'
11'	.9361	.9682	.9789	.9843	.9876	.9898	.9914	.9927	.9936	.9945	.9951	.9957	.9963	.9967	.9972	.9976	.9980	.9984	.9989	.9995	11'
12'	.9303	.9653	.9770	.9829	.9865	.9889	.9907	.9920	.9931	.9939	.9947	.9953	.9959	.9964	.9969	.9974	.9978	.9983	.9988	.9995	12'
13'	.9245	.9624	.9751	.9815	.9853	.9880	.9899	.9913	.9925	.9934	.9943	.9950	.9956	.9961	.9967	.9972	.9976	.9982	.9987	.9995	13'
14'	.9186	.9595	.9731	.9800	.9842	.9870	.9891	.9907	.9919	.9929	.9938	.9946	.9952	.9958	.9964	.9969	.9975	.9980	.9987	.9994	14'
15'	.9128	.9566	.9712	.9786	.9831	.9861	.9883	.9900	.9913	.9924	.9934	.9942	.9949	.9955	.9961	.9967	.9973	.9979	.9986	.9994	15'
16'	.9070	.9537	.9693	.9772	.9820	.9852	.9875	.9893	.9908	.9919	.9929	.9938	.9945	.9952	.9959	.9965	.9971	.9977	.9985	.9993	16'
17'	.9012	.9508	.9674	.9758	.9808	.9843	.9868	.9887	.9902	.9914	.9925	.9934	.9942	.9949	.9956	.9963	.9969	.9976	.9984	.9993	17'
18'	.8954	.9479	.9655	.9743	.9797	.9833	.9860	.9880	.9896	.9909	.9920	.9930	.9939	.9946	.9954	.9961	.9967	.9975	.9983	.9992	18'
19'	.8896	.9450	.9636	.9729	.9786	.9824	.9852	.9873	.9890	.9904	.9916	.9926	.9935	.9943	.9951	.9958	.9966	.9973	.9982	.9992	19'
20'	.8838	.9421	.9616	.9715	.9775	.9815	.9844	.9867	.9884	.9899	.9911	.9922	.9932	.9940	.9949	.9956	.9964	.9972	.9981	.9992	20'
21'	.8780	.9392	.9597	.9701	.9763	.9806	.9836	.9860	.9879	.9894	.9907	.9918	.9928	.9937	.9946	.9954	.9962	.9970	.9980	.9991	21'
22'	.8721	.9363	.9578	.9686	.9752	.9796	.9829	.9853	.9873	.9889	.9903	.9914	.9925	.9935	.9943	.9952	.9960	.9969	.9979	.9991	22'
23'	.8663	.9334	.9559	.9672	.9741	.9787	.9821	.9846	.9867	.9884	.9898	.9911	.9922	.9932	.9941	.9950	.9958	.9967	.9978	.9990	23'
24'	.8605	.9305	.9540	.9658	.9729	.9778	.9813	.9840	.9861	.9879	.9894	.9907	.9918	.9929	.9938	.9947	.9956	.9966	.9977	.9990	24'
25'	.8547	.9276	.9520	.9643	.9718	.9768	.9805	.9833	.9855	.9874	.9889	.9903	.9915	.9926	.9936	.9945	.9955	.9965	.9976	.9989	25'
26'	.8489	.9247	.9501	.9629	.9707	.9759	.9797	.9826	.9850	.9869	.9885	.9899	.9911	.9923	.9933	.9943	.9953	.9963	.9975	.9989	26'
27'	.8431	.9218	.9482	.9615	.9696	.9750	.9789	.9820	.9844	.9864	.9880	.9895	.9908	.9920	.9930	.9941	.9951	.9962	.9974	.9989	27'
28'	.8373	.9189	.9463	.9601	.9684	.9741	.9782	.9813	.9838	.9859	.9876	.9891	.9904	.9917	.9928	.9939	.9949	.9960	.9973	.9988	28'
29'	.8315	.9160	.9444	.9586	.9673	.9731	.9774	.9806	.9832	.9854	.9872	.9887	.9901	.9914	.9925	.9936	.9947	.9959	.9972	.9988	29'
30'	.8256	.9131	.9424	.9572	.9662	.9722	.9766	.9800	.9826	.9848	.9867	.9883	.9898	.9911	.9923	.9934	.9946	.9957	.9971	.9987	30'

Table 11-2 (Concluded). Phase Angle Correction Factors (PACFs).

For Lagging Current When ($\beta - \gamma$) is Positive
For Leading Current When ($\beta - \gamma$) is Negative

$\beta - \gamma$	Apparent Power Factor (Cos θ_2)																			$\beta - \gamma$
	.05	.10	.15	.20	.25	.30	.35	.40	.45	.50	.55	.60	.65	.70	.75	.80	.85	.90	.95	.99	
31'	.8198	.9102	.9405	.9558	.9650	.9713	.9758	.9793	.9821	.9843	.9863	.9879	.9894	.9908	.9920	.9932	.9944	.9956	.9970	.9987	31'
32'	.8140	.9073	.9386	.9544	.9639	.9704	.9750	.9786	.9815	.9838	.9858	.9875	.9891	.9905	.9917	.9930	.9942	.9954	.9969	.9986	32'
33'	.8082	.9044	.9367	.9529	.9628	.9694	.9743	.9780	.9809	.9833	.9854	.9872	.9887	.9902	.9915	.9928	.9940	.9953	.9968	.9986	33'
34'	.8024	.9015	.9348	.9515	.9616	.9685	.9735	.9773	.9803	.9828	.9849	.9868	.9884	.9899	.9912	.9925	.9938	.9952	.9967	.9985	34'
35'	.7966	.8986	.9328	.9501	.9605	.9676	.9727	.9766	.9797	.9823	.9845	.9864	.9880	.9896	.9910	.9923	.9936	.9950	.9966	.9985	35'
36'	.7908	.8958	.9309	.9486	.9594	.9666	.9719	.9760	.9792	.9818	.9840	.9860	.9877	.9893	.9907	.9921	.9935	.9949	.9965	.9985	36'
37'	.7850	.8929	.9290	.9472	.9583	.9657	.9711	.9753	.9786	.9813	.9836	.9856	.9874	.9890	.9905	.9919	.9933	.9947	.9964	.9984	37'
38'	.7791	.8900	.9271	.9458	.9571	.9648	.9704	.9746	.9780	.9808	.9832	.9852	.9870	.9887	.9902	.9916	.9931	.9946	.9963	.9984	38'
39'	.7733	.8871	.9252	.9444	.9560	.9639	.9696	.9739	.9774	.9803	.9827	.9848	.9867	.9884	.9899	.9914	.9929	.9944	.9962	.9983	39'
40'	.7675	.8842	.9232	.9429	.9549	.9629	.9688	.9733	.9768	.9798	.9823	.9844	.9863	.9881	.9897	.9912	.9927	.9943	.9961	.9983	40'
41'	.7617	.8813	.9213	.9415	.9537	.9620	.9680	.9726	.9763	.9793	.9818	.9840	.9860	.9878	.9894	.9910	.9925	.9942	.9960	.9982	41'
42'	.7559	.8784	.9194	.9401	.9526	.9611	.9672	.9719	.9757	.9788	.9814	.9836	.9856	.9875	.9892	.9908	.9924	.9940	.9959	.9982	42'
43'	.7501	.8755	.9175	.9386	.9515	.9601	.9664	.9713	.9751	.9783	.9809	.9832	.9853	.9872	.9889	.9905	.9922	.9939	.9958	.9981	43'
44'	.7443	.8726	.9156	.9372	.9503	.9592	.9657	.9706	.9745	.9778	.9805	.9829	.9850	.9869	.9886	.9903	.9920	.9937	.9957	.9981	44'
45'	.7384	.8697	.9136	.9358	.9492	.9583	.9649	.9699	.9739	.9772	.9800	.9825	.9846	.9866	.9884	.9901	.9918	.9936	.9956	.9980	45'
46'	.7326	.8668	.9117	.9344	.9481	.9574	.9641	.9693	.9734	.9767	.9796	.9821	.9843	.9863	.9881	.9899	.9916	.9934	.9955	.9980	46'
47'	.7268	.8639	.9098	.9329	.9470	.9564	.9633	.9686	.9728	.9762	.9791	.9817	.9839	.9860	.9878	.9897	.9914	.9933	.9954	.9980	47'
48'	.7210	.8610	.9079	.9315	.9458	.9555	.9625	.9679	.9722	.9757	.9787	.9813	.9836	.9857	.9876	.9894	.9912	.9931	.9953	.9979	48'
49'	.7152	.8581	.9060	.9301	.9447	.9546	.9618	.9672	.9716	.9752	.9783	.9809	.9832	.9854	.9873	.9892	.9911	.9930	.9952	.9979	49'
50'	.7094	.8552	.9040	.9286	.9436	.9536	.9610	.9666	.9710	.9747	.9778	.9805	.9829	.9851	.9871	.9890	.9909	.9929	.9951	.9978	50'
51'	.7036	.8523	.9021	.9272	.9424	.9527	.9602	.9659	.9705	.9742	.9774	.9801	.9825	.9848	.9868	.9888	.9907	.9927	.9950	.9978	51'
52'	.6978	.8494	.9002	.9258	.9413	.9518	.9594	.9652	.9699	.9737	.9769	.9797	.9822	.9845	.9865	.9885	.9905	.9926	.9949	.9977	52'
53'	.6919	.8465	.8983	.9244	.9402	.9509	.9586	.9646	.9693	.9732	.9765	.9793	.9819	.9842	.9863	.9883	.9903	.9924	.9948	.9977	53'
54'	.6861	.8436	.8963	.9229	.9390	.9499	.9578	.9639	.9687	.9727	.9760	.9789	.9815	.9839	.9860	.9881	.9901	.9923	.9947	.9976	54'
55'	.6803	.8407	.8944	.9215	.9379	.9490	.9571	.9632	.9681	.9722	.9756	.9785	.9812	.9836	.9858	.9879	.9900	.9921	.9946	.9976	55'
56'	.6745	.8378	.8925	.9201	.9368	.9481	.9563	.9625	.9675	.9717	.9751	.9781	.9808	.9832	.9855	.9877	.9898	.9920	.9945	.9975	56'
57'	.6687	.8349	.8906	.9186	.9356	.9471	.9555	.9619	.9670	.9711	.9747	.9778	.9805	.9829	.9852	.9874	.9896	.9918	.9944	.9975	57'
58'	.6629	.8320	.8887	.9172	.9345	.9462	.9547	.9612	.9664	.9706	.9742	.9774	.9801	.9826	.9850	.9872	.9894	.9917	.9943	.9975	58'
59'	.6571	.8291	.8867	.9158	.9334	.9453	.9539	.9605	.9658	.9701	.9738	.9770	.9798	.9823	.9847	.9870	.9892	.9915	.9942	.9974	59'
60'	.6512	.8262	.8848	.9143	.9323	.9444	.9531	.9599	.9652	.9696	.9733	.9766	.9794	.9820	.9845	.9868	.9890	.9914	.9941	.9974	60'

Table 11-3. Phase Angle Correction Factors (PACFs).

For Lagging Current When ($\beta - \gamma$) is Negative
For Leading Current When ($\beta - \gamma$) is Positive

$\beta - \gamma$	Apparent Power Factor (Cos θ_2)																				$\beta - \gamma$
	.05	.10	.15	.20	.25	.30	.35	.40	.45	.50	.55	.60	.65	.70	.75	.80	.85	.90	.95	.99	
1'	1.0058	1.0029	1.0019	1.0014	1.0011	1.0009	1.0008	1.0007	1.0006	1.0005	1.0004	1.0004	1.0003	1.0003	1.0003	1.0002	1.0002	1.0001	1.0001	1.0000	1'
2'	1.0116	1.0058	1.0038	1.0028	1.0023	1.0018	1.0016	1.0013	1.0012	1.0010	1.0009	1.0008	1.0007	1.0006	1.0005	1.0004	1.0004	1.0003	1.0002	1.0001	2'
3'	1.0174	1.0087	1.0058	1.0043	1.0034	1.0028	1.0023	1.0020	1.0017	1.0015	1.0013	1.0012	1.0010	1.0009	1.0008	1.0007	1.0005	1.0004	1.0003	1.0001	3'
4'	1.0232	1.0116	1.0077	1.0057	1.0045	1.0037	1.0031	1.0027	1.0023	1.0020	1.0018	1.0016	1.0014	1.0012	1.0010	1.0009	1.0007	1.0006	1.0004	1.0002	4'
5'	1.0291	1.0145	1.0096	1.0071	1.0056	1.0046	1.0039	1.0033	1.0029	1.0025	1.0022	1.0019	1.0017	1.0015	1.0013	1.0011	1.0009	1.0007	1.0005	1.0002	5'
6'	1.0349	1.0174	1.0115	1.0085	1.0068	1.0055	1.0047	1.0040	1.0035	1.0030	1.0026	1.0023	1.0020	1.0018	1.0015	1.0013	1.0011	1.0008	1.0006	1.0002	6'
7'	1.0407	1.0203	1.0134	1.0100	1.0079	1.0065	1.0054	1.0047	1.0040	1.0035	1.0031	1.0027	1.0024	1.0021	1.0018	1.0015	1.0013	1.0010	1.0007	1.0003	7'
8'	1.0465	1.0232	1.0153	1.0114	1.0090	1.0074	1.0062	1.0053	1.0046	1.0040	1.0035	1.0031	1.0027	1.0024	1.0020	1.0017	1.0014	1.0011	1.0008	1.0003	8'
9'	1.0523	1.0260	1.0173	1.0128	1.0101	1.0083	1.0070	1.0060	1.0052	1.0045	1.0040	1.0035	1.0031	1.0027	1.0023	1.0020	1.0016	1.0013	1.0009	1.0004	9'
10'	1.0581	1.0289	1.0192	1.0142	1.0113	1.0092	1.0078	1.0067	1.0058	1.0050	1.0044	1.0039	1.0034	1.0030	1.0026	1.0022	1.0018	1.0014	1.0010	1.0004	10'
11'	1.0639	1.0318	1.0211	1.0157	1.0124	1.0102	1.0086	1.0073	1.0063	1.0055	1.0049	1.0043	1.0037	1.0033	1.0028	1.0024	1.0020	1.0015	1.0010	1.0005	11'
12'	1.0697	1.0347	1.0230	1.0171	1.0135	1.0111	1.0093	1.0080	1.0069	1.0060	1.0053	1.0046	1.0041	1.0036	1.0031	1.0026	1.0022	1.0017	1.0011	1.0005	12'
13'	1.0755	1.0376	1.0249	1.0185	1.0146	1.0120	1.0101	1.0087	1.0075	1.0065	1.0057	1.0050	1.0044	1.0039	1.0033	1.0028	1.0023	1.0018	1.0012	1.0005	13'
14'	1.0813	1.0405	1.0268	1.0199	1.0158	1.0129	1.0109	1.0093	1.0081	1.0070	1.0062	1.0054	1.0048	1.0041	1.0036	1.0030	1.0025	1.0020	1.0013	1.0006	14'
15'	1.0871	1.0434	1.0288	1.0214	1.0169	1.0139	1.0117	1.0100	1.0086	1.0075	1.0066	1.0058	1.0051	1.0044	1.0038	1.0033	1.0027	1.0021	1.0014	1.0006	15'
16'	1.0930	1.0463	1.0307	1.0228	1.0180	1.0148	1.0124	1.0107	1.0092	1.0081	1.0071	1.0062	1.0054	1.0047	1.0041	1.0035	1.0029	1.0022	1.0015	1.0007	16'
17'	1.0988	1.0492	1.0326	1.0242	1.0191	1.0157	1.0132	1.0113	1.0098	1.0086	1.0075	1.0066	1.0058	1.0050	1.0043	1.0037	1.0031	1.0024	1.0016	1.0007	17'
18'	1.1046	1.0521	1.0345	1.0256	1.0203	1.0166	1.0140	1.0120	1.0104	1.0091	1.0079	1.0070	1.0061	1.0053	1.0046	1.0039	1.0032	1.0025	1.0017	1.0007	18'
19'	1.1104	1.0550	1.0364	1.0271	1.0214	1.0176	1.0148	1.0126	1.0110	1.0096	1.0084	1.0074	1.0064	1.0056	1.0049	1.0041	1.0034	1.0027	1.0018	1.0008	19'
20'	1.1162	1.0579	1.0383	1.0285	1.0225	1.0185	1.0156	1.0133	1.0115	1.0101	1.0088	1.0077	1.0068	1.0059	1.0051	1.0043	1.0036	1.0028	1.0019	1.0008	20'
21'	1.1220	1.0608	1.0402	1.0299	1.0236	1.0194	1.0163	1.0140	1.0121	1.0106	1.0093	1.0081	1.0071	1.0062	1.0054	1.0046	1.0038	1.0029	1.0020	1.0009	21'
22'	1.1278	1.0637	1.0422	1.0313	1.0248	1.0203	1.0171	1.0146	1.0127	1.0111	1.0097	1.0085	1.0075	1.0065	1.0056	1.0048	1.0039	1.0031	1.0021	1.0009	22'
23'	1.1336	1.0665	1.0441	1.0328	1.0259	1.0213	1.0179	1.0153	1.0133	1.0116	1.0101	1.0089	1.0078	1.0068	1.0059	1.0050	1.0041	1.0032	1.0022	1.0009	23'
24'	1.1394	1.0694	1.0460	1.0342	1.0270	1.0222	1.0187	1.0160	1.0138	1.0121	1.0106	1.0093	1.0081	1.0071	1.0061	1.0052	1.0043	1.0034	1.0023	1.0010	24'
25'	1.1452	1.0723	1.0479	1.0356	1.0281	1.0231	1.0194	1.0166	1.0144	1.0126	1.0110	1.0097	1.0085	1.0074	1.0064	1.0054	1.0045	1.0035	1.0024	1.0010	25'
26'	1.1510	1.0752	1.0498	1.0370	1.0293	1.0240	1.0202	1.0173	1.0150	1.0131	1.0115	1.0101	1.0088	1.0077	1.0066	1.0056	1.0047	1.0036	1.0025	1.0010	26'
27'	1.1569	1.0781	1.0517	1.0384	1.0304	1.0249	1.0210	1.0180	1.0156	1.0136	1.0119	1.0104	1.0092	1.0080	1.0069	1.0059	1.0048	1.0038	1.0026	1.0011	27'
28'	1.1627	1.0810	1.0537	1.0399	1.0315	1.0259	1.0218	1.0186	1.0161	1.0141	1.0123	1.0108	1.0095	1.0083	1.0071	1.0061	1.0050	1.0039	1.0026	1.0011	28'
29'	1.1685	1.0839	1.0556	1.0413	1.0326	1.0268	1.0225	1.0193	1.0167	1.0146	1.0128	1.0112	1.0098	1.0086	1.0074	1.0063	1.0052	1.0040	1.0027	1.0012	29'
30'	1.1743	1.0868	1.0575	1.0427	1.0338	1.0277	1.0233	1.0200	1.0173	1.0151	1.0132	1.0116	1.0102	1.0089	1.0077	1.0065	1.0054	1.0042	1.0028	1.0012	30'

Table 11-3 (Concluded). Phase Angle Correction Factors (PACFs).

For Lagging Current When ($\beta - \gamma$) is Negative
For Leading Current When ($\beta - \gamma$) is Positive

$\beta - \gamma$	Apparent Power Factor (Cos θ_2)																			$\beta - \gamma$
	.05	.10	.15	.20	.25	.30	.35	.40	.45	.50	.55	.60	.65	.70	.75	.80	.85	.90	.95	.99	
31'	1.1801	1.0897	1.0594	1.0441	1.0349	1.0286	1.0241	1.0206	1.0179	1.0156	1.0137	1.0120	1.0105	1.0092	1.0079	1.0067	1.0055	1.0043	1.0029	1.0012	31'
32'	1.1859	1.0926	1.0613	1.0456	1.0360	1.0296	1.0249	1.0213	1.0184	1.0161	1.0141	1.0124	1.0108	1.0095	1.0082	1.0069	1.0057	1.0045	1.0030	1.0013	32'
33'	1.1917	1.0955	1.0632	1.0470	1.0371	1.0305	1.0256	1.0219	1.0190	1.0166	1.0145	1.0128	1.0112	1.0097	1.0084	1.0072	1.0059	1.0046	1.0031	1.0013	33'
34'	1.1975	1.0984	1.0651	1.0484	1.0383	1.0314	1.0264	1.0226	1.0196	1.0171	1.0150	1.0131	1.0115	1.0100	1.0087	1.0074	1.0061	1.0047	1.0032	1.0014	34'
35'	1.2033	1.1012	1.0671	1.0498	1.0394	1.0323	1.0272	1.0233	1.0202	1.0176	1.0154	1.0135	1.0119	1.0103	1.0089	1.0076	1.0063	1.0049	1.0033	1.0014	35'
36'	1.2091	1.1041	1.0690	1.0512	1.0405	1.0332	1.0280	1.0239	1.0207	1.0181	1.0158	1.0139	1.0122	1.0106	1.0092	1.0078	1.0064	1.0050	1.0034	1.0014	36'
37'	1.2149	1.1070	1.0709	1.0527	1.0416	1.0342	1.0287	1.0246	1.0213	1.0186	1.0163	1.0143	1.0125	1.0109	1.0094	1.0080	1.0066	1.0052	1.0035	1.0015	37'
38'	1.2207	1.1099	1.0728	1.0541	1.0427	1.0351	1.0295	1.0253	1.0219	1.0191	1.0167	1.0147	1.0129	1.0112	1.0097	1.0082	1.0068	1.0053	1.0036	1.0015	38'
39'	1.2265	1.1128	1.0747	1.0555	1.0439	1.0360	1.0303	1.0259	1.0224	1.0196	1.0172	1.0151	1.0132	1.0115	1.0099	1.0084	1.0070	1.0054	1.0037	1.0016	39'
40'	1.2323	1.1157	1.0766	1.0569	1.0450	1.0369	1.0311	1.0266	1.0230	1.0201	1.0176	1.0154	1.0135	1.0118	1.0102	1.0087	1.0071	1.0056	1.0038	1.0016	40'
41'	1.2382	1.1186	1.0785	1.0584	1.0461	1.0379	1.0318	1.0273	1.0236	1.0206	1.0180	1.0158	1.0139	1.0121	1.0104	1.0089	1.0073	1.0057	1.0038	1.0016	41'
42'	1.2440	1.1215	1.0805	1.0598	1.0472	1.0388	1.0326	1.0279	1.0242	1.0211	1.0185	1.0162	1.0142	1.0124	1.0107	1.0091	1.0075	1.0058	1.0039	1.0017	42'
43'	1.2498	1.1244	1.0824	1.0612	1.0484	1.0397	1.0334	1.0286	1.0247	1.0216	1.0189	1.0166	1.0145	1.0127	1.0110	1.0093	1.0077	1.0060	1.0040	1.0017	43'
44'	1.2556	1.1273	1.0843	1.0626	1.0495	1.0406	1.0342	1.0292	1.0253	1.0221	1.0194	1.0170	1.0149	1.0130	1.0112	1.0095	1.0079	1.0061	1.0041	1.0017	44'
45'	1.2614	1.1302	1.0862	1.0640	1.0506	1.0415	1.0349	1.0299	1.0259	1.0226	1.0198	1.0174	1.0152	1.0133	1.0115	1.0097	1.0080	1.0063	1.0042	1.0018	45'
46'	1.2672	1.1330	1.0881	1.0655	1.0517	1.0425	1.0357	1.0306	1.0265	1.0231	1.0202	1.0178	1.0156	1.0136	1.0117	1.0099	1.0082	1.0064	1.0043	1.0018	46'
47'	1.2730	1.1359	1.0900	1.0669	1.0529	1.0434	1.0365	1.0312	1.0270	1.0236	1.0207	1.0181	1.0159	1.0139	1.0120	1.0102	1.0084	1.0065	1.0044	1.0019	47'
48'	1.2788	1.1388	1.0919	1.0683	1.0540	1.0443	1.0373	1.0319	1.0276	1.0241	1.0211	1.0185	1.0162	1.0141	1.0122	1.0104	1.0086	1.0067	1.0045	1.0019	48'
49'	1.2846	1.1417	1.0938	1.0697	1.0551	1.0452	1.0380	1.0326	1.0282	1.0246	1.0215	1.0189	1.0166	1.0144	1.0125	1.0106	1.0087	1.0068	1.0046	1.0019	49'
50'	1.2904	1.1446	1.0958	1.0711	1.0562	1.0461	1.0388	1.0332	1.0288	1.0251	1.0220	1.0193	1.0169	1.0147	1.0127	1.0108	1.0089	1.0069	1.0047	1.0020	50'
51'	1.2962	1.1475	1.0977	1.0726	1.0573	1.0471	1.0396	1.0339	1.0293	1.0256	1.0224	1.0197	1.0172	1.0150	1.0130	1.0110	1.0091	1.0071	1.0048	1.0020	51'
52'	1.3020	1.1504	1.0996	1.0740	1.0585	1.0480	1.0404	1.0345	1.0299	1.0261	1.0229	1.0201	1.0176	1.0153	1.0132	1.0112	1.0093	1.0072	1.0049	1.0020	52'
53'	1.3078	1.1533	1.1015	1.0754	1.0596	1.0489	1.0411	1.0352	1.0305	1.0266	1.0233	1.0204	1.0179	1.0156	1.0135	1.0114	1.0094	1.0073	1.0049	1.0021	53'
54'	1.3136	1.1562	1.1034	1.0768	1.0607	1.0498	1.0419	1.0359	1.0310	1.0271	1.0237	1.0208	1.0182	1.0159	1.0137	1.0117	1.0096	1.0075	1.0050	1.0021	54'
55'	1.3194	1.1591	1.1053	1.0782	1.0618	1.0507	1.0427	1.0365	1.0316	1.0276	1.0242	1.0212	1.0186	1.0162	1.0140	1.0119	1.0098	1.0076	1.0051	1.0022	55'
56'	1.3252	1.1619	1.1072	1.0797	1.0630	1.0517	1.0435	1.0372	1.0322	1.0281	1.0246	1.0216	1.0189	1.0165	1.0142	1.0121	1.0100	1.0078	1.0052	1.0022	56'
57'	1.3310	1.1648	1.1091	1.0811	1.0641	1.0526	1.0442	1.0379	1.0328	1.0286	1.0250	1.0220	1.0192	1.0168	1.0145	1.0123	1.0101	1.0079	1.0053	1.0022	57'
58'	1.3368	1.1677	1.1111	1.0825	1.0652	1.0535	1.0450	1.0385	1.0333	1.0291	1.0255	1.0224	1.0196	1.0171	1.0147	1.0125	1.0103	1.0080	1.0054	1.0023	58'
59'	1.3427	1.1706	1.1130	1.0839	1.0663	1.0544	1.0458	1.0392	1.0339	1.0296	1.0259	1.0227	1.0199	1.0174	1.0150	1.0127	1.0105	1.0082	1.0055	1.0023	59'
60'	1.3485	1.1735	1.1149	1.0853	1.0674	1.0553	1.0466	1.0398	1.0345	1.0301	1.0263	1.0231	1.0203	1.0177	1.0152	1.0129	1.0107	1.0083	1.0056	1.0023	60'

For an installation where a current transformer is used, but no voltage transformer is used:

$$PACF_{\mathrm{I}} = \frac{\cos(\theta_2 + \beta)}{\cos\theta_2}$$

Tables 11-2 and 11-3 can still be used to find the phase angle correction factor using the value of β itself for $\beta - \gamma$, since γ is not involved.

The $\mathrm{PACF_K}$ depends upon the phase angles of the instrument transformers (β and γ) and on the apparent power factor of the load ($\cos\theta_2$). Thus the phase angle correction factor varies with the apparent power factor of the load. In actual practice the difference between the apparent power factor ($\cos\theta_2$) and the true power factor ($\cos\theta$) is so small that for ordinary values of phase angle either power factor can be used with Tables 11-2 and 11-3 to find the phase angle correction factor. The value of $\beta - \gamma$ must be accurately known. Note in Tables 11-2 and 11-3 that the $\mathrm{PACF_K}$ increases rapidly at low power factors.

Tables 11-2 and 11-3 cover values of $\beta - \gamma$ from zero to one degree by minutes and from 0.05 to 1.00 power factor in steps of 0.05. Interpolation between values may be done but will rarely be required with these tables. Values of $\beta - \gamma$ greater than 60 minutes are rarely encountered with modern instrument transformers.

Transformer Correction Factor

The correction factor for the combined effect of ratio error and phase angle of an instrument transformer is called the transformer correction factor (TCF). It is the factor by which the reading of a wattmeter or the registration of a watthour meter must be multiplied to correct for the effect of ratio error and phase angle.

$$TCF = RCF \times PACF$$

then

$$TCF_{\mathrm{I}} = RCF_{\mathrm{I}} \times \frac{\cos(\theta_2 + \beta)}{\cos\theta_2} = RCF_{\mathrm{I}} \times PACF_{\mathrm{I}}$$

$$TCF_{\mathrm{I}} = RCF_{\mathrm{I}} \times PACF_{\mathrm{I}}$$

and

$$TCF_{\mathrm{E}} = RCF_{\mathrm{E}} \times \frac{\cos(\theta_2 + \gamma)}{\cos\theta_2}$$

$$TCF_{\mathrm{E}} = RCF_{\mathrm{E}} \times PACF_{\mathrm{E}}$$

When both current and voltage transformers are used, the PACF should be determined for the combination in one step as previously shown and not calculated separately and combined. The product of the two separate phase angle correction factors is not exactly equal to the true value of the overall phase angle correction factor.

Final Correction Factor

The correction factor for the combined effects of ratio error and phase angle, where both current and voltage transformers are used, is called the final correction factor (FCF) and is also referred to as the instrument transformer correction factor. It is the factor by which the reading of a wattmeter, or the registration of a watthour meter, operated from the secondaries of both a current and voltage transformer must be multiplied to correct for the effect of ratio errors and phase displacement of the current and voltage caused by the instrument transformers.

$$FCF = RCF_K \times PACF_K$$

The Nominal Instrument Transformer Ratio

If the marked or nominal ratio of the voltage transformer is N_E and the marked or nominal ratio of the current transformer is N_I, the product of these two marked ratios is the nominal instrument transformer ratio, N_K.

$$N_K = N_E \times N_I$$

Summary of Basic Instrument Transformer Relationships

Table 11-4 is a summary of the relation of primary and secondary values in a single-phase metering installation using instrument transformers. This table can be used as a reference that ties together most of the factors which have been covered in detail in the preceding pages. Table 11-4 is in terms of the primary and secondary power in watts. If both sides of all of these equations are multiplied by time in hours they would then apply equally well in terms of energy in watthours. All of the equations in this table apply to the metering installation whose schematic and phasor diagrams are shown in Figure 11-13.

Compensating Errors

The equation for the transformer correction factor (TCF = RCF × PACF) shows that for some values of RCF and PACF, their product would be closer to one than either separately. For example, (1.0032)(0.9970) = 1.0002. Thus, under some conditions the overall effect of the error in ratio may be offset by an opposite effect due to the phase angle.

This fact is used as a basis for the tolerance limits of the standard accuracy classifications of IEEE Std. C57.13, where the specified tolerances of ratio and phase angle are interdependent. These classifications are set up on the basis of a maximum overall tolerance in terms of TCF for power factors from unity to 0.6 lagging. This is covered later under the subheading IEEE Standard Accuracy Classes for Metering.

When a current and a voltage transformer are used, the combined ratio correction factor can be improved by matching transformers with opposite ratio errors since $RCF_K = RCF_E \times RCF_I$.

To reduce the effect of phase angle errors, which are dependent upon $\beta - \gamma$, current and voltage transformers can be selected having phase angles of the same sign (i.e., both positive or both negative) thus reducing the overall phase angle error.

Current and voltage transformers are not usually matched to balance errors in this manner but occasionally these methods may be useful.

Table 11-4. Summary of Fundamental Relations for Single-Phase Metering Installations Involving Instrument Transformers.

Primary Power = *Primary Volts* × *Primary Amperes* × *Primary Power Factors*

$$W_P = E_P \times I_P \times \cos\theta$$

$$W_P = E_S N_E (RCF_E) \times I_S N_I (RCF_I) \times \cos(\theta_2 + \beta - \gamma)$$

These terms can be rearranged to give:

$$W_P = E_S I_S \times N_E N_I \times (RCF_E)(RCF_I) \times \cos(\theta_2 + \beta - \gamma)$$

Multiplying the first term by $\cos\theta_2$ and dividing the last term by $\cos\theta_2$ is the same as multiplying by $\frac{\cos\,\theta_2}{\cos\,\theta_2} = 1$, which does not change the product, which gives:

$$W_P = E_S I_S \cos\theta_2 \times N_E N_I \times (RCF_E)(RCF_I) \times \frac{\cos\,\theta_2 + \beta - \gamma}{\cos\,\theta_2}$$

$$W_P = W_S \times N_K \times RCF_K \times PACF_K$$

$$W_P = W_S \times N_K \times FCF$$

Primary Power = *Secondary Power* × *Nominal Instrument Transformer Ratio* × *Final Correction Factor*

W_P = Primary power (watts)
E_P = Primary voltage
I_P = Primary current
$\cos\theta$ = Primary power factor
θ = Angle between E_P and I_P
N_E = Marked (Nominal) ratio of voltage transformer
N_I = Marked (Nominal) ratio of current transformer
β = Phase angle of current transformer
γ = Phase angle of voltage transformer
W_S = Secondary power (watts)
E_S = Secondary voltage
I_S = Secondary current
$\cos\theta_2$ = Secondary (apparent) power factor
θ_2 = Angle between E_S and I_S
RCF_E = Ratio Correction Factor of voltage transformer
RCF_I = Ratio Correction Factor of current transformer
RCF_K = Combined Ratio Correction Factor, voltage transformer and current transformer
$PACF_K$ = Phase Angle Correction Factor, voltage transformer and current transformer
FCF = Final Correction Factor

See Figure 11-13 for the corresponding schematic and phasor diagrams.

APPLICATION OF CORRECTION FACTORS

When Correction Factors Should Be Applied

In most metering installations using instrument transformers, no corrections need be applied if instrument transformers meeting IEEE Std. C57.13 accuracy specifications are used within the burden and power factor limits of these specifications and the secondary leads are short enough so they cause no appreciable error. Under such conditions, the error contributed by any single instrument transformer should not exceed the IEEE standard accuracy class. Where both a current and a voltage transformer are used, their combined error could theoretically reach the sum of the maximum errors represented by the standard accuracy classes of the two transformers, but will in most cases be much less. In polyphase metering, the total error is the weighted average of the combined errors of the current and voltage transformer on each phase and can never be greater than the maximum errors on the worst phase. For 0.3% Standard Accuracy Class transformers the maximum errors, under the IEEE-specified conditions, is summarized in Table 11-5.

These maximum errors would occur rarely in an actual combination of instrument transformers. There is a good probability that the errors would be less than 0.3 to 0.5%, which would be acceptable for most metering applications.

Special cases may arise that make the application of instrument transformer corrections necessary or desirable. Such cases could be due to the use of older types of instrument transformers that do not meet IEEE Std. C57.13 accuracy specifications, the necessity of using heavier burdens than specified by IEEE, the use of long secondary leads, power factor of the load below 0.6 lagging, power factor of the load leading, and requirements for higher than normal accuracy for special installations, such as large wholesale installations, interchange metering between power companies, or measurement of total generator output during efficiency tests of power station generators and turbines.

The decision as to when instrument transformer corrections should be applied is a matter of policy that must be decided by each utility company on the basis of both technical and economic considerations. In general, most utilities do not apply instrument transformer corrections for routine work and may or may not apply corrections in special cases.

If the meter is to be adjusted to compensate for the errors of the instrument transformers, great care must be taken to make this adjustment in the proper direction. An error in the sign of the correction applied results in doubling the overall error instead of eliminating it. The best precaution against this type of mistake is the use of prepared forms which are set up to show each step in the process.

With a well prepared form, correction factors can be applied easily. The actual field work may involve nothing more than adding the percent error caused by the transformers to the percent error of the meter. Several methods of applying corrections will be shown.

Table 11-5. Maximum Percent Errors for Combinations of 0.3% IEEE Accuracy Class Instrument Transformers under IEEE-Specified Conditions of Burden, and Load Power Factors between 1.00 and 0.6 Lag.

	Percent Error at 100% Load	Percent Error at 10% Load
Current Transformers	0.3	0.6
Voltage Transformers	0.3	0.3
Maximum Percent Error	0.6	0.9

Determining the Meter Adjustment in Percent Registration to Correct for Instrument Transformer Errors—Calculations Based on Tables 11-2 and 11-3

It has been shown in Table 11-4 that:

Primary Power = Secondary Power × Nominal Instrument Transformer Ratio × Final Correction Factor

Multiplying both sides by hours gives:

True Primary Watthours = True Secondary Watthours × N_K × FCF

But the indicated primary watthours are:

Indicated Primary Watthours = Indicated Secondary Watthours × N_K

The overall percent registration of the installation, or primary percent registration, is:

$$\text{Primary Percent Registration} = \frac{\text{(Indicated Primary Watthours) (100)}}{\text{True Primary Watthours}}$$

Substituting equivalent secondary values gives:

$$\text{Primary Percent Registration} = \frac{\text{(Indicated Secondary Watthours) }(N_K)\text{ (100)}}{\text{(True Secondary Watthours) }(N_K)\text{ (FCF)}}$$

$$\text{Primary Percent Registration} = \frac{\text{(Indicated Secondary Watthours) (100)}}{\text{(True Secondary Watthours) (FCF)}}$$

$$\text{Primary Percent Registration} = \frac{\text{(Secondary Percent Registration)}}{\text{(FCF)}}$$

$$\text{Primary Percent Registration} = \frac{\text{Percent Registration Meter Only}}{\text{(FCF)}}$$

Thus, the overall percent registration may be obtained by dividing the percent registration of the meter by the final correction factor.

Example:

Given: Percent Registration of Meter Alone = 99.75% and FCF = 1.0037

Then: Primary (or overall) Percent Registration $= \frac{99.75}{1.0037} = 99.38\%$

To divide using the approximate method for numbers close to 1, add one to the numerator and subtract the denominator: 0.9975 divided by 1.0037, is approximately equivalent to 1.9975 minus 1.0037 = 0.9938, and 0.9938 × 100 = 99.38%.

The primary (overall) percent registration can be made 100.00% if the percent registration of the meter is adjusted to 100 times the final correction factor.

If the meter in the preceding example were adjusted to 100.37% registration, then

$$\text{Primary (overall) Percent Registration} = \frac{100.37}{1.0037} = 100.00\%$$

Table 11-6 shows a standard form that can be used to determine the required meter adjustment by this method. This method is particularly useful when meter tests are made with a fixed routine, such as light-load, full-load, and inductive-load, made respectively with 10 and 100% rated current at 1.0 power factor and with 100% rated current at 0.5 power factor lagging.

This method is applicable to installations with current and voltage transformers, or to either, and the calculations are simplified by using addition and subtraction for the multiplication of quantities near unity, as previously explained. Ratio correction factors and phase angles are used directly and the result is the accuracy performance to which the meter should be adjusted to compensate for instrument transformer errors.

The ratio correction factors and phase angles are taken from test data on the instrument transformers or from the manufacturers' certificates. These values must be the values that apply at the terminals of the meter and be based on the actual burdens. If long secondary leads are used from the voltage transformer to the meter, the effect of the lead drop on the ratio and phase angle as seen at the meter must be included. This can be determined by test or calculation as previously explained. If the available instrument transformer data are not based on the actual burden, the desired value may be determined by interpolation or calculation by methods to be explained later.

Table 11-6. Calculation of Meter Accuracy Settings.

Item	Symbol	Load		
		Light	Heavy	Inductive
		Power Factor 1.0		P.F. 0.5 Lag
		10% Cur.	100% Current	
Phase Angle, Minutes				
Current Transformer	β	+10	− 2	− 2
Voltage Transformer	γ	+ 8	+ 8	+ 8
Combined	$\beta - \gamma$	+ 2	-10	-10
Ratios				
Current Transformer	RCF_I	1.0043	0.9992	0.9992
Voltage Transformer	RCF_E	0.9976	0.9976	0.9976
Effect of Combined Phase Angle	$PACF_K$	1.0000	1.0000	1.0000
By Addition		3.0019	2.9968	3.0018
Subtract (No. of Terms Added Minus 1)		2.	2.	2.
Final Correction Factor	FCF	1.0019	0.9968	1.0018
Meter Accuracy Setting Required to Compensate = (100)(FCF)	Percent Registration	100.19%	99.68%	100.18%
% Error Caused by Inst. Trans. ≈ (1-FCF)(100)	% E	0.19%−	0.32%+	0.18%−
% Meter Adjustment Required to Compensate	% E	0.19%+	0.32%−	0.18%+

The appropriate ratio correction factors and phase angles are then entered in Table 11-6 as shown. The phase angle correction factor at unity power factor is 1.0000, within 0.02% or less, for all values of ($\beta - \gamma$) up to 60 minutes. At 0.50 power factor lagging, the phase angle correction factor is read from Table 11-3 as 1.0050 for a value of ($\beta - \gamma$) of -10 minutes. The operations indicated in Table 11-6 are performed and the meter accuracy settings in percent registration are determined as shown. The bottom two lines show the percent errors caused by the instrument transformers and the percent errors to which the meter should be set to compensate. This method is discussed in the next section. The meter is then adjusted to the desired tolerance of these settings and the compensation has been accomplished.

The calculations in this table have been carried to 0.01%, as it is normal practice to use one more place in calculations of this kind than is used in the final result. If the final overall accuracy of the installation were to be reported, it would normally be rounded to the nearest 0.1%.

The same setup may be used when only a current transformer or a voltage transformer is used. It is only necessary to enter zero under phase angle and 1.0000 under ratio correction factor in the places where no transformer is used and make the additions and subtractions indicated. For polyphase installations, when correction factors and phase angles are not widely divergent, the ratio correction factors and phase angles for the current transformers for all phases may be respectively averaged and the average values of ratio correction factor and phase angle of the current and voltage transformers used for the calculations.

Alternatively, calculations may be made on each stator using the ratio correction factors and phase angles for the transformers connected to that stator. For precise work, where either voltage or current transformer phase angles materially differ, this method is preferred.

Overall Percent Error Caused by the Instrument Transformers Alone

The percent error due to the instrument transformers may be derived as follows:

True Primary Watthours = True Secondary Watthours $\times$ N_K $\times$ FCF

Indicated Primary Watthours = Indicated Secondary Watthours $\times$ N_K

$$\text{Overall Percent Error} = \frac{\text{Indicated} - \text{True}}{\text{True}} \times 100 =$$

$$\frac{(\text{Indicated Secondary Watthours})(N_K) - (\text{True Secondary Watthours})(N_K)(\text{FCF})}{(\text{True Secondary Watthours})\ (N_K)(\text{FCF})} \times 100$$

Overall Percent Error =

$$\frac{(\text{Indicated Secondary Watthours}) - (\text{True Secondary Watthours})\ (\text{FCF})}{(\text{True Secondary Watthours})(\text{FCF})} \times 100$$

This is the overall percent error of the installation including both meter and transformer errors. To find the errors due to the transformers alone, assume that the meter is correct. Then, Indicated Secondary Watthours = True Secondary Watthours, and substituting in the preceding equation:

Percent Error Caused by Instrument Transformer =

$$\frac{(\text{True Secondary Watthours}) - (\text{True Secondary Watthours})(\text{FCF})}{(\text{True Secondary Watthours})\ (\text{FCF})} \times 100$$

Percent Error Caused by Instrument Transformer =

$$\frac{1 - \text{FCF}}{\text{FCF}}(100) \approx (1 - \text{FCF}) \times 100$$

Where $\approx$ means "is approximately equal to."

The second or approximate form is the most convenient to use and will not be in error by more than 0.01% for values of FCF between 0.9900 and 1.0100 or more than 0.02% for values of FCF between 0.9800 and 1.0200.

Example:

Given FCF = 0.9853

Percent Error Caused by Instrument Transformer =

$$\frac{1 - 0.9853}{0.9853} \times 100 = \frac{(0.0147)(100)}{0.9853} = 1.49\% \text{ using the exact method.}$$

Percent Error Caused by Instrument Transformer $\approx (1 - 0.9853)100 = 0.0147 \times 100 = 1.47\%$ using the approximate method.

Note that the sign of the error will be minus for values of FCF greater than 1.

A form such as Table 11-6 can be used to determine the final correction factor from which the percent error caused by the instrument transformers is determined. This is shown on the next to bottom line of Table 11-6.

Determining the Overall Percent Error by Adding the Percent Errors Caused by Instrument Transformers and the Meter

It can be shown that: Overall Percent Error $\approx$ Percent Error Caused by the Instrument Transformer + Percent Error of the Meter.

This expression is an approximation that is good only when the percent errors are small. When adding percent errors up to $\pm 1.0\%$, the error in this approximation will not exceed 0.01%. When adding percent errors up to $\pm 2.0\%$, the error in this approximation will not exceed 0.04%. This expression is convenient to use and may be used for errors up to two or three percent without significant error.

Example:

Meter Error		Instrument Transformer Error		Overall Error
+ 0.32%	+	−0.15%	=	+ 0.17%

The required compensation can be made by adjusting the percent error of the meter to the same magnitude as the percent error caused by the instrument transformers, but with the opposite sign. This is shown in the last line of Table 11-6.

A Graphical Method of Determining the Percent Error Caused by the Instrument Transformers and the Required Compensation

The percent error caused by the instrument transformers and the required meter adjustment to compensate may be determined by using the chart shown in Figure 11-14.

A straight edge is placed on the chart so that one end intercepts the ratio correction factor scale on the left at the desired value of RCF and the other end intercepts the phase angle scale on the right at the desired value of $(\beta - \gamma)$. The percent error, or percent meter adjustment, is read from the center scale that represents the desired power factor. The proper half of the phase angle scale to be used depends upon the load power factor and the sign of ($\beta - \gamma$) and this is indicated in the headings for this scale. The sign of the error caused by the instrument transformers and the sign of the percent error of the required compensating meter adjustment is indicated in the blocks between the 100 and 95% power factor scales. The chart is designed to give percent errors for a current and voltage transformer combined, by using the RCF_K and the combined phase angle ($\beta - \gamma$).

To use the chart for an installation involving a current transformer only, use RCF_I on the RCF scale and β in place of ($\beta - \gamma$). For polyphase values, the percent errors may be determined separately for each phase, or average values of RCF_K

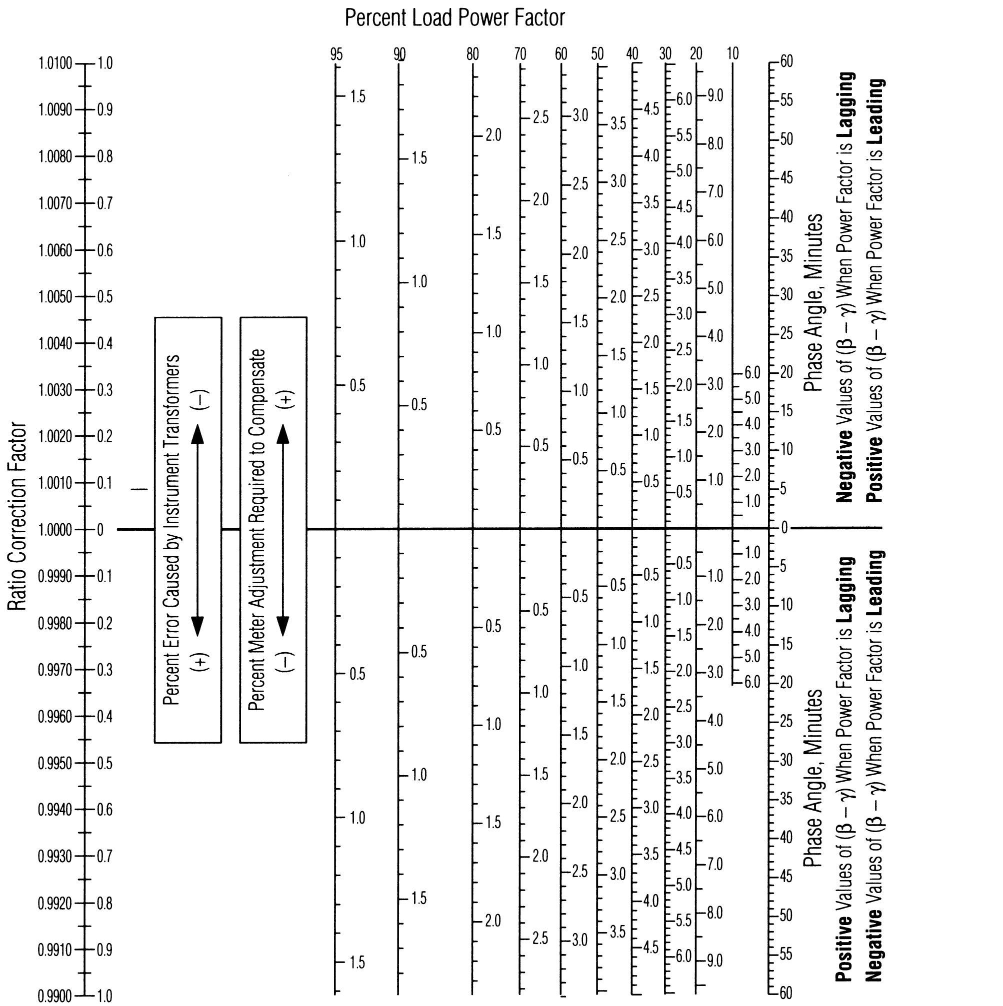


Figure 11-14. Percent Error Calculation Chart for Effects of Instrument Transformer Ratio and Phase Angle.

and ($\beta - \gamma$) may be used to obtain the total percent error in one step. The chart is based on the approximate formula for the percent error caused by the instrument transformer previously discussed. Thus, the results read from the chart may differ by a few hundredths of a percent from the values computed from Tables 11-2 and 11-3.

Example:

For a load power factor 70%, lagging:

Current Transformer:	RCF_I	=	1.0043	β	=	+12
Voltage Transformer:	RCF_E	=	1.0012	γ	=	+7
Combined Values:	RCF_K	=	1.0055	$\beta - \gamma$	=	+5

One end of the straight edge is placed on the RCF scale at 1.0055 and the other end on the lower half of the phase angle scale at 5. The straight edge then intercepts the 70% power factor scale at 0.40% in the upper half of the chart. Therefore, the error caused by the instrument transformers is −0.40% and the meter must be adjusted to +0.40% (fast) to compensate.

Application of Instrument Transformer and Watthour Standard Corrections in One Step to a Three-Phase, Three-Stator, Four-Wire, Wye Metering Installation

Most special installations justifying the application of corrections for the instrument transformers will be three phase. If the load is reasonably balanced, the work may be greatly simplified by averaging the corrections. In addition, the corrections for the calibration errors of the watthour standards may also be included. The required total percent error caused by all of the instrument transformers and all of the watthour standards can be calculated for any load and power factor. These calculations may be made and checked before going into the field to test the meter. The actual work in the field then simply requires the addition of these percent errors to the apparent percent error of the meter as determined by test.

To use this method, forms such as Tables 11-7, 11-8, and 11-9 are prepared and completed as needed. For a three-phase, three-stator, four-wire, wye installation the procedure is described in the following paragraphs.

The procedure is shown for a test method using three watthour standards and a special three-phase phantom load, such that the meter is tested under actual three-phase conditions. It is also suitable for a three-phase customer's load test using three watthour standards, one in series with each meter stator respectively. This second method is limited to the system load and power factor of the installations at the time of test, but is occasionally useful for installations having a relatively constant load. This procedure can also be used to apply corrections when using the usual standard test methods requiring only one watthour standard to make single-phase series tests on the three-phase meter. The method is therefore adaptable to any test procedure desired.

The RCFs and phase angles of the three current transformers at various values of secondary current are entered in the proper spaces in Table 11-7 as shown. These values would be available from certificates or test data. The averages of all these values are computed and entered.

Table 11-7. Average Ratio and Phase Angle Calculation Sheet for Polyphase Installations.

Location: APPLEGATE SUB. **Circuit:** SEA VIEW LINE - NO. 1
C. T. Ratio: 400:5 **V. T. Ratio:** 16,500:110 **V. T. Sec. Voltage:** 120
Date: 12-17-91 **Calculated By:** C. E. P. **Checked By:** G. T.

Ratio		Secondary Amperes					
C.T. Serial Nos.	Symbol	0.5	1	2	3	4	5
675 932	RCF_I	1.0037	1.0013	1.0007	1.0002	0.9997	0.9990
675 933	RCF_I	1.0035	1.0010	1.0006	1.0001	0.9996	0.9998
675 934	RCF_I	1.0030	1.0007	1.0003	0.9998	0.9992	0.9981
Average	RCF_I	1.0034	1.0010	1.0005	1.0000	0.9995	0.9987

V.T. Serial Nos.	Symbol						
183 276	RCF_E	1.0021					
183 283	RCF_E	1.0017					
183 341	RCF_E	1.0025	Enter Average RCF_E In All Spaces Below				
Average	RCF_E	1.0021	1.0021	1.0021	1.0021	1.0021	1.0021
Combined Average $(RCF_I)(RCF_E) = RCF_K$		1.0055	1.0031	1.0026	1.0021	1.0016	1.0008

Phase Angle, Minutes		Secondary Amperes					
C.T. Serial Nos.	Symbol	0.5	1	2	3	4	5
675 932	β	− 10	− 4	+ 2	+ 4	+ 6	+ 7
675 933	β	− 13	− 5	+ 1	+ 3	+ 5	+ 6
675 934	β	− 8	− 2	+ 3	+ 6	+ 8	+ 9
Average	β	− 10	− 4	+ 2	+ 4	+ 6	+ 7

V.T. Serial Nos.	Symbol						
183 276	γ	+ 11					
183 283	γ	+ 12					
183 341	γ	+ 7	Enter Average γ In All Spaces Below				
Average	γ	+ 10	+ 10	+ 10	+ 10	+ 10	+ 10
Combined Average β − γ		− 20	− 14	− 8	− 6	− 4	− 3

The RCFs and phase angles of the voltage transformers are entered and averaged. The average values of these are recopied into the additional spaces as shown, so that they may be combined with the current transformer values.

The RCF_K and average phase angle (β and γ) are computed and entered as shown.

These combined values will apply to this installation indefinitely unless the instrument transformers or burdens are changed. A form similar to Table 11-8 is now filled out. First the desired three-phase power factors and test voltages are entered in the spaces to the left. In the example shown, power factors of 1.00, 0.87 lag and 0.50 lag at 120 V are shown. Other values can be used as required.

Table 11-8. Watthour Meter Test, Combined Error Calculation Sheet for Three-Stator, Three-Phase Meters Tested Three-Phase Using Three Watthour Standards or Single-Phase Series Using One Watthour Standard.

Location: APPLEGATE SUB. **Circuit:** SEA VIEW LINE - NO. 1

Date: 12-17-91 **Calculated By:** C. E. P. **Checked By:** G. T.

	Secondary Amperes	Calibrated Percent Errors of Standards No. 367	No. 368	No. 369	(A) Combined Average Percent Error of Standards	Combined Average Ratio Correction Factor (RCF_K)	× Combined Average Phase Angle Cor. Fact. ($PACF_K$)	= Combined Average Final Correction Factor (FCF)	(B) % Error Caused by Instrument Trans. (1-FCF)(100)	Combined % Error Inst. Trans. Plus Standards (A) + (B)
P.F. 1.00	**0.5***	.08–	.06–	.08–	.07–	1.0055	1.0000	1.0055	.55–	.62–
Volts 120	**1***	.12–	.02–	.10–	.08–	1.0031	1.0000	1.0031	.31–	.39–
	2	.07–	.05–	.10–	.07–	1.0026	1.0000	1.0026	.26–	.33–
	3	.03–	.02–	.03–	.03–	1.0021	1.0000	1.0021	.21–	.24–
	4	.05–	.08+	.02–	0	1.0016	1.0000	1.0016	.16–	.16–
	5	.02–	.03+	.02–	0	1.0008	1.0000	1.0008	.08–	.08–

	Secondary Amperes	No. 367	No. 368	No. 369	(A)	RCF_K	$PACF_K$	FCF	(B)	(A) + (B)
P.F. .87 Lag.	**0.5***	.12–	.10–	.15–	12–	1.0055	1.0033	1.0088	.88–	1.00–
Volts 120	**1***	.17–	.08–	.17–	.14–	1.0031	1.0023	1.0054	.54–	.68–
	2	.09+	.13+	.13–	.03+	1.0026	1.0013	1.0039	.39–	.36–
	3	.05+	.03+	.07–	.0	1.0021	1.0009	1.0030	.30–	.30–
	4	.02–	.02+	0	0	1.0016	1.0007	1.0023	.23–	.23–
	5	.17–	.02+	.01+	.05–	1.0008	1.0005	1.0013	.13–	.18–

	Secondary Amperes	No. 367	No. 368	No. 369	(A)	RCF_K	$PACF_K$	FCF	(B)	(A) + (B)
P.F. .50 Lag.	**0.5***	.15–	.20–	.20–	.18–	1.0055	1.0101	1.0156	1.56–	1.74–
Volts 120	**1***	.25–	.14–	.20–	.20–	1.0031	1.0070	1.0101	1.01–	1.21–
	2	.14+	.21+	.20+	.18+	1.0026	1.0040	1.0066	.66–	.48–
	3	.10+	.07+	.10+	.09+	1.0021	1.0030	1.0051	.51–	.42–
	4	.02–	.02+	.02+	.01+	1.0016	1.0020	1.0036	.36–	.35–
	5	.23–	.10+	.03+	.03–	1.0008	1.0015	1.0023	.23–	.26–

*** On 1 ampere coil of watthour standard. All other points on 5 ampere coil.**

The percent errors of the three watthour standards to be used for the test are then entered in the spaces provided. These values are determined by tests of the watthour standards at the current, voltage, and power factors to be used. Since, on a balanced load all three stators operate at a single-phase power factor equal to the three-phase load power factor, the three watthour standards will be running at the same speed and power factor. The errors can therefore be averaged and entered in Column A. Where only one watthour standard is used for a single-phase series test of a polyphase meter, the errors of the watthour standard should be entered directly in Column A, as no average is involved. In this case the preceding three columns are not needed.

The combined average ratio correction factors from Table 11-7 are now entered in the proper column of Table 11-8. These are the same at all power factors.

The $PACF_K$ is determined from Tables 11-2 or 11-3 for the desired values of load power factor as shown in Table 11-8 and the average values of $(\beta - \gamma)$ previously determined in Table 11-7. The product of the average RCF_K and the average $PACF_K$ gives the average final correction factor. The percent error caused by the instrument transformers is equal to $(1 - FCF) \times 100$. This is entered in Column B. The values in Columns A and B are added algebraically and entered in the final column to give the combined percent error caused by the instrument transformers and the watthour standards.

If correction for the watthour standards is not desired, this can be omitted, in which case the values in Column A would be zero.

The values in Column B could also be obtained directly from Table 11-7 and the chart shown in Figure 11-14. This is a simpler but slightly less accurate method.

Table 11-9 is a watthour meter test form suitable for this method. The revolutions of the three watthour standards for each test run are entered and added as shown. (Where only one watthour standard is used for a single-phase series test of a polyphase meter, its revolutions should be entered directly in the column for the total revolutions. In this case the preceding three columns are not needed.) The indicated percent error is computed from the total revolutions and entered as shown. The percent error caused by the instrument transformers and watthour standards from the last column of Table 11-8 is entered as shown in Table 11-9. This value, plus the percent error indicated, is equal to the overall percent error. Only the values at 0.87 power factor have been shown on Table 11-9. Values at other power factors would be obtained in the same manner. Meter adjustments are made as required to reduce the overall percent error to the desired tolerances. Table 11-9 has been filled in to show an "as left" curve at 0.87 power factor lagging, taken after all adjustments had been made. The "as found" tests and adjustments would be on previous sheets and are not shown in Table 11-9.

This method is simple and fast in actual use as the corrections are precalculated before starting the meter tests. The forms reduce the whole operation to simple bookkeeping and allow the calculations to be checked at any time. If only standard single-phase series tests are made on polyphase meters, the forms shown in Tables 11-8 and 11-9 may be simplified to one column for the watthour standard data.

Application of Instrument Transformer and Watthour Standard Corrections in One Step to a Three-Phase, Two-Stator, Three-Wire, Delta Metering Installation

It can be shown mathematically that the following statement is true: In a three-phase, three-wire metering circuit having balanced voltages, currents, and burdens, using two voltage transformers having equal ratio and phase angle errors and two current transformers having equal ratio and phase angle errors, the true primary power may be determined by applying the instrument transformer corrections separately to the single-phase power in each meter stator at the single-phase power factor of each stator, or the instrument transformer corrections may be applied in one step to the total three-phase secondary power at the three-phase power factor of the circuit.

Table 11-9. Watthour Meter Test.

Location: APPLEGATE SUB. **Circuit:** SEA VIEW LINE - NO. 1

Meter Nameplate Data

Meter Code No. P014-7581 **Mfg.** G.E. **Type** DS-20 **Volts** 120 **Amps** 2.5 **ϕ** 3 **EL.** 3 **W.** 4

Meter Ser. No. 15321762 **Kh** .09 **Dial K** 1 **Rr** 111 1/9 **Mult. By** 12,000

C. T. Ratio 400:5 **V. T. Ratio** 16,500:110 **Demand : Time** — **Rev.** — **Chart Div.** —

As Found: **Pri. K.W. Load** — **Sec. A** — **P. F.** — **Reg. Read** 4321.2 **Time** 9:10 AM

As Left: **Pri. K.W. Load** — **Sec. A** — **P. F.** — **Reg. Read** 4321.2 **Time** 2:30 PM

Test Volts 120 **Creep** No **Remarks** No lead on line at time of test.

As Found Seal T - 32 - 90 Test made with 3 phase phantom load.

As Left Seal T - 32 - 91

Test Data

Sec. Amps.	Cur. Coil of Standard	P. F.	Rev. Whm / Standard	Adj.	Standard No. 3.67 Rev.	Standard No. 3.68 Rev.	Standard No. 3.69 Rev.	Total Rev. of Standards	% E Indicated	% Error Caused by Inst. Trans. and Standards	% Error Over-All
.05	1	.87 Lag	2/15		4.95	4.96	4.99	14.90	.67+	1.00–	.30–
					4.95	4.95	4.99	14.89	.74+		
1	1	.87 Lag	2/15	"As left" Curve	4.97	4.99	4.97	14.93	.47+	.68–	.15–
					4.96	4.98	4.97	14.91	.60+		
2	5	.87 Lag	20/30		9.97	9.95	9.96	29.88	.40+	.36–	.04+
					9.97	9.95	9.96	29.88	.40+		
3	5	.87 Lag	20/30		9.98	9.95	9.96	29.89	.37+	.30–	.05+
					9.98	9.96	9.96	29.90	.33+		
4	5	.87 Lag	20/30		9.99	9.96	9.97	29.92	.27+	.23–	.04+
					9.99	9.96	9.97	29.92	.27+		
5	5	.87 Lag	20/30		10.02	9.94	9.98	29.94	.20+	.18–	.02+
					10.02	9.94	9.98	29.94	.20+		

Tested By: G. T. **Witness:** John Doe **Page** 3 **of** 3 **Pages**

For the three-phase, two-stator, three-wire delta installations, if the errors of the instrument transformers on both phases are reasonably similar, the instrument transformer RCFs and phase angles may be averaged and the total error of the instrument transformers at the three-phase power factor determined in exactly the same manner as for the three-stator meter using Tables 11-7 and 11-8. This method does not involve appreciable error if the errors of the instrument transformers on both phases are reasonably similar. The only difference is that only two current and two voltage transformers will now be shown on Table 11-7.

However, the watthour standard corrections must be weighted before averaging as the two watthour standards are running at different speeds. Also, the corrections entered for the watthour standards must be at the single-phase power factor of each stator.

This is easily done using a prepared form such as Table 11-10. If the three-phase power factor is cos θ, then the two-stator power factors, for balanced loads, are cos ($\theta + 30°$) and cos ($\theta - 30°$).

Since the speed of each watthour standard is proportional to the single-phase power factor at which it is running, their percent errors must be weighted before averaging by the factors

$$\frac{PF_1}{PF_1 + PF_2} \text{ and } \frac{PF_2}{PF_1 + PF_2}$$

where PF_1 and PF_2 are the two single-phase power factors of the stators involved. This is illustrated clearly in the column headings and in the example shown in Table 11-10. The remaining columns of Table 11-10 would be filled in similar to Table 11-8 using the three-phase power factor to determine the $PACF_K$.

The same form (Table 11-9) may be used for the watthour meter test as was used for the three-stator meter. In this case only two columns for the revolutions of the two watthour standards will be used. Otherwise the procedure is identical to the procedure for the three-stator meter.

This method is quite satisfactory for the three-phase phantom load test using two watthour standards, since balanced loads are applied. It can be used for a customer's load test using two watthour standards if the load on the circuit is reasonably balanced. For customers' load tests with badly imbalanced loads this method cannot be used. In such cases the corrections must be applied to each stator and watthour standard separately.

When only one watthour standard is used for a single-phase series test of a two-stator polyphase meter, both stators operate during the test at the same single-phase power factor and it is not necessary to use Table 11-10 at all. Table 11-8 is used and the watthour standard error entered directly in Column A.

Summary of Basic Formulas for Applying Instrument Transformer Corrections

Table 11-11 summarizes the basic formulas for applying instrument transformer corrections in a form for convenient reference.

Individual Stator Calculations

In the preceding discussion the voltage transformers and the current transformers were assumed to be reasonably matched, i.e., have nearly similar ratio and phase angle errors. If each of the current transformers is of the same make, model, and type, it is usually found that they will have similar accuracy characteristics. This is also true of voltage transformers. In these cases the procedures previously described for applying corrections will lead to no significant errors.

At times it is necessary to use instrument transformers with widely dissimilar correction factors. When a high degree of accuracy is required, calculation of the effect of instrument transformer errors on each individual meter stator should be made. Correction factors may be calculated by referring to the basic meter formula and comparing meter registration to true power.

For a three-phase, three-wire delta circuit,

$$\text{True Power} = \sqrt{3}\ EI \cos \theta$$

Meter Registration, for a balanced symmetrical load, =

$$EI \times \text{Ratio Correction Factor}_A \times \cos (\theta_2 - 30° + \beta_A - \gamma_A)$$
$$+ EI \times \text{RCF}_B \times \cos (\theta_2 + 30° + \beta_B - \gamma_B).$$

Table 11-10. Watthour Meter Test, Combined Error Calculation Sheet for Two-Stator, Three-Phase Meters Tested Three Phase Using Two Watthour Standards.

Location: APPLEGATE SUB. **Circuit:** SEA VIEW LINE - NO. 2
Date: 12-17-91 **Calculated By:** C. E. P. **Checked By:** G. T.

	Secondary Amperes	% Error Tot. Std. No. 367 in A Phase, Operating at .87 P.F. Lag	Ⓐ $(\%E)\left(\frac{PF_1}{PF_1+PF_2}\right)$	% Error Tot. Std. No. 367 in C Phase, Operating at .87 P.F. Lead	Ⓑ $(\%E)\left(\frac{PF_2}{PF_1+PF_2}\right)$	Ⓒ Combined Weighted Average Percent Error of Standards Ⓐ + Ⓑ	Combined Average Ratio Correction Factor (RCF_K) (RCF_K) ×	Combined Average Phase Angle Cor. Fact. ($PACF_K$) ($PACF_K$) =	Combined Average Final Correction Factor (FCF) (FCF)	Ⓓ % Error Caused by Instrument Trans. (1-FCF)(100) (1-FCF)(100)	Combined % Error Inst. Trans. Plus Rot. Stds. Ⓒ + Ⓓ
3 PH. P.F. 1.00	0.5*	.12–	.06–	.13+	.06+	0					
Volts 120	1*	.17–	.08–	.20+	.10+	.02+					
	2	.09+	.04+	.15–	.07–	.03–					
	3	.05+	.02+	.30–	.15–	.13–					
	4	.02–	.01–	.25–	.12–	.13–					
	5	.17–	.08–	.10+	.05+	.03–					
Stator P.F.s →		.50 Lag	→	1.00		**					
3 PH. P.F. .87 Lag	0.5*	.15–	.05–**	.08–	.05–**	.10–					
Volts 120	1*	.25–	.08–	.10–	.07–	.15–					
	2	.14+	.05+	.10–	.07–	.02–					
	3	.10+	.03+	.03–	.02–	.01+					
	4	.02–	.01–	.02–	.02–	.03–					
	5	.23–	.08–	.02–	.02–	.10–					
Stator P.F.s →		0	→	.87 Lag							
3 PH. P.F. .50 Lag	0.5*	—	0	.15–	.15–	.15–					
Volts 120	1*	—	0	.17–	.17–	.17–					
	2	—	0	.13–	.13–	.13–					
	3	—	0	.07–	.07–	.07–					
	4	—	0	0	0	0					
	5	—	0	.01+	.01+	.01+					

*** On 1 ampere coil of watthour standard. All other points on 5 ampere coil.**

**** Examples of Weighting Calculation**

$$(\%E)\left(\frac{PF_1}{PF_1 + PF_2}\right) = (.15–)\left(\frac{.50}{.50 + 1.00}\right) = (.15–)\ (1/3) = .05–$$

$$(\%E)\left(\frac{PF_2}{PF_1 + PF_2}\right) = (.08–)\left(\frac{1.00}{.50 + 1.00}\right) = (.08–)\ (2/3) = .05–$$

Table 11-11. Summary of Basic Formulas for Applying Instrument Transformer Corrections.

Overall (Primary) Percent Registration	$\frac{\text{Percent Registration of Meter Only}}{FCF}$
Required Percent Registration of Meter Only to Compensate for Instrument Transformer Errors	$FCF \times 100$
Percent Error Caused by Instrument Transformers Only	$\approx (1 - FCF) \times 100$
Required Percent Error Adjustment of Meter Only to Compensate for Instrument Transformer Errors	$\approx (FCF - 1) \times 100$
Overall (Primary) Percent Error	≈ Percent Error Caused by Instrument Transformers Only + Percent Error of Meter Only

It has been shown that the phase angle error depends on the apparent power factor of the load. Because of the phase voltage and the line current displacement as seen by each stator, the power factor under which stator A operates differs from that of stator B. Hence, when either the current or voltage transformer phase angle errors differ widely, calculation of correction factors for individual stators is advisable. Differences in signs may lead to unsuspected errors.

In the following example, although values of β and γ would average to zero, signs have been applied to give maximum error.

Given the following conditions:

Three-phase power factor = 0.866 (30° lagging), balanced load
Combined RCF, stator A = 0.997
Combined RCF, stator B = 1.001
β, stator A = −12 minutes
β, stator B = + 12 minutes
γ, stator A = + 12 minutes
γ, stator B = −12 minutes
Secondary Meter Registration =

$$EI \times RCF_A \times \cos(\theta_2 - 30° + \beta_A - \theta_A) + EI \times RCF_B \times \cos(\theta_2 + 30° + \beta_B - \gamma_B)$$

With the transformer errors listed above, at 5 amperes, 120V secondary:

$$\begin{aligned}\text{Secondary Meter Registration} &= 120 \times 5 \times 0.997 \times \cos[30° - 30° + (-12') - (+12')] \\ &\quad + 120 \times 5 \times 1.001 \times \cos[30° + 30° + 12' - (-12')] \\ &= 598.2 \cos 24' + 600.6 \cos 60° \, 24' \\ &= 598.2 + 296.6 \\ &= 894.8 \\ \text{True Power} &= \sqrt{3} \times 120 \times 5 \times \cos 30° = 900 \\ \text{FCF} &= \frac{900}{894.8} = 1.0058\end{aligned}$$

Cosines have been used in this calculation to make clear the phase angle errors possible. Similar results may be obtained by use of PACF, Tables 11-2 and 11-3.

BURDEN CALCULATIONS

Voltage Transformer Burdens

The secondary burdens of voltage transformers are connected in parallel across the secondary of the transformer. The voltampere burden is equal to $\frac{E^2}{Z}$ where Z is the impedance.

Usually voltage transformer burdens are expressed as voltamperes at a given power factor. To calculate the total burden on the secondary of a voltage transformer, the burden of each device should be divided into in-phase and quadrature-phase components and added. (Voltamperes cannot be added directly unless they are all at the same power factor.)

The in-phase component is:

$$\text{Watts} = (\text{Voltamperes})(\text{Cos } \theta) = \text{VA} \times \text{PF}$$

The quadrature-phase component is:

$$\text{VARs} = (\text{Voltamperes})(\text{Sin } \theta) = \sqrt{(1 - \text{PF})^2}$$

$$\text{Total Voltamperes} = \sqrt{(\text{Total Watts})^2 + (\text{Total VARs})^2}$$

$$\text{Power Factor of Combined Burden} = \text{Cos } \theta = \frac{\text{Total Watts}}{\text{Total Voltamperes}}$$

Current Transformer Burdens

When more than two instruments or meters with the required wiring are connected in series with the secondary of a current transformer the total burden impedance is:

$$\text{Total Burden Impedance (Z)} = \sqrt{(\text{Sum of resistances})^2 + (\text{Sum of reactances})^2}$$

The voltampere burden on a current transformer is equal to I^2Z. Burdens are usually computed at 5 amperes rated secondary current. It may be necessary to convert burdens stated in meter manuals at 2.5 amperes to 5.0 amperes.

When the burdens are expressed in voltamperes at a given power factor, the burden of each device and the secondary conductors should be divided into in-phase and quadrature-phase components, and added.

The in-phase component is:

$$\text{Watts} = (\text{Voltamperes})(\cos \theta) = \text{VA} \times \text{PF} = I^2R$$

The quadrature-phase component is:

$$\text{VARs} = (\text{Voltamperes})(\sin \theta) = \text{VA}\sqrt{(1 - \text{PF})^2} = I^2X$$

Where X is the inductive reactance, $X = 2\pi fL$, L is the inductance in henries, and f is the frequency in hertz.

$$\text{Total Voltamperes} = \sqrt{(\text{Total Watts})^2 + (\text{Total VARs})^2}$$

$$\text{Power Factor of Combined Burden} = \text{Cos } \theta = \frac{\text{Total Watts}}{\text{Total Voltamperes}} = \frac{R}{Z}$$

It should be particularly noted that the secondary lead resistance must be included in the burden calculations for current transformers.

The basic formulas for burden calculations are summarized in convenient form in Table 11-12 for both current and voltage transformers.

Polyphase Burdens

When the secondary burdens of instrument transformers are interconnected, as is often the case in polyphase metering, no simple method of computing the burdens on each transformer is applicable to all cases. Such combinations of burden must be computed phasorially on the basis of the actual circuit.

For wye-connected burdens on wye-connected instrument transformers, each transformer is affected by the burden directly across its terminals from the polarity to the neutral secondary leads. Thus, each transformer "sees" only the burden on its own phase and burdens are easily calculated. The same situation is true for an open-delta burden on transformers connected open delta. These are the normal arrangements for metering burdens.

Unusual cases, such as wye-connected burdens on open-delta-connected instrument transformers, delta-connected burdens, on wye-connected instrument transformers, and complex combinations of single-phase and three-phase burdens must be analyzed individually. Since such analysis is complex, this type of burden should be avoided in metering applications when possible.

The Circle, or Farber Method for Determination of Voltage Transformer Accuracy

The accuracy of a voltage transformer is primarily affected by the burden connected to the secondary of the transformer. This burden is usually expressed in terms of voltamperes and percent power factor.

The circle, or Farber Method, copyrighted 1960 by Westinghouse Electric Corporation, provides an easy method for determining the accuracy of a voltage transformer at any desired burden by using only the phase angle and RCF of the transformer at zero burden and one other known burden. Normally the manufacturer furnishes this information with the transformer.

Table 11-12. Methods of Expressing Burdens of Instrument Transformers.

	Conversion to Watts and VAR	
Voltage Transformers		
Burden Expression	*Watts at 120 V*	*VARs at 120 V, 60 Hz*
VA = Voltamperes at 120 V, 60 Hz PF = Burden power factor	$VA \times \mathrm{PF}$	$VA \times \sqrt{(1 - PF)^2}$
Current Transformers		
Burden Expression	*Watts at 5 A*	*VARs at 5 A, 60 Hz*
R = Resistance in ohms L = Inductance in millihenries	$25 \times R$	$9.43 \times L$
Z = Inductance in ohms, 60 Hz PF = Burden power factor	$25 \times Z \times PF$	$25 \times Z \times \sqrt{(1 - PF)^2}$
VA = Voltamperes at 5 A, 60 Hz PF = Burden power factor	$VA \times PF$	$VA \times \sqrt{(1 - PF)^2}$

The circle, or Farber Method is a graphical method in which voltamperes are represented by arcs, and the percent power factor by the straight lines which are plotted on a special graph paper that has the RCF as the vertical axis and the phase angle as the horizontal axis.

Graph paper is scaled so that a given distance represents 0.0010 units on the RCF axis and 3.438 minutes on the phase angle. A sample is shown in Figure 11-15a.

An example of the use of the circle method is shown in Figure 11-15b. The following data are test results at 120 secondary volts for a 2400:120 volt voltage transformer: At 0 voltampere burden, RCF = 0.9979 and phase angle = +2.0 minutes; At 50 voltamperes, 85% power factor burden, RCF = 1.0040 and phase angle = +1.0 minute. Performance at other voltampere and power factor burdens can be plotted by making radii proportional to voltamperes and angles equal to burden power factor angles.

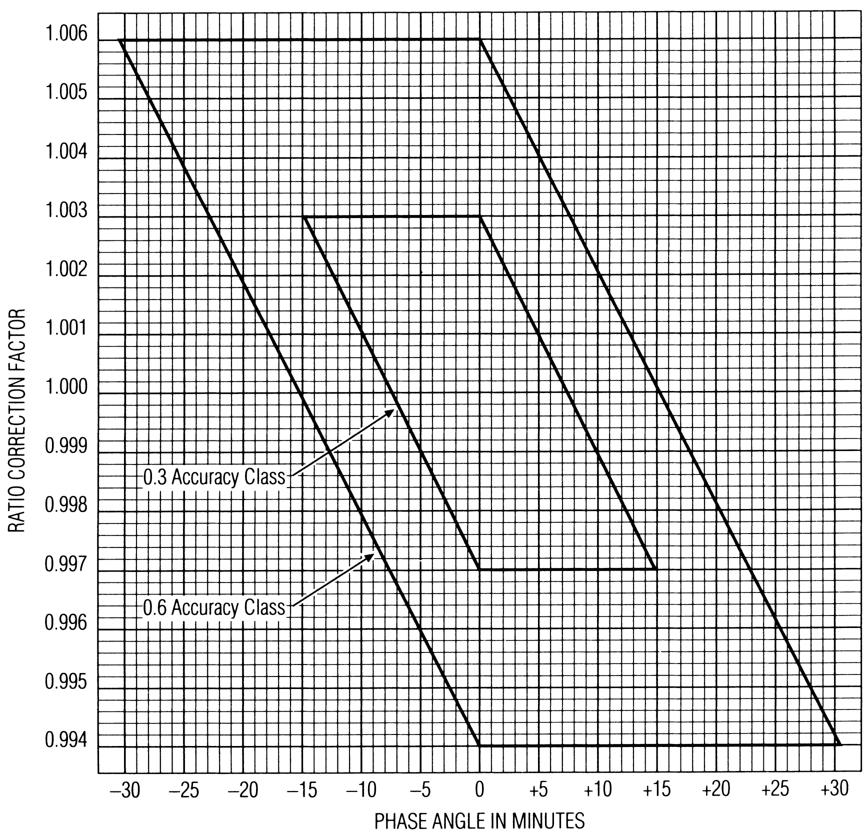
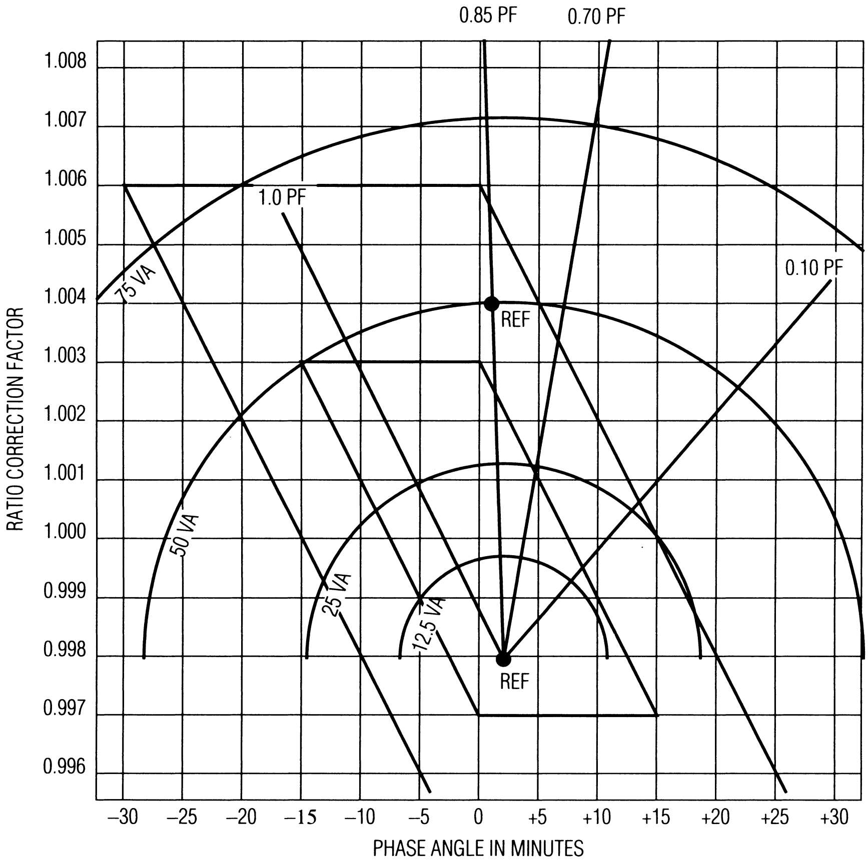


Figure 11-15a. Sample of Graph Paper Specifically Scaled for Voltage Transformer Circle Diagram.

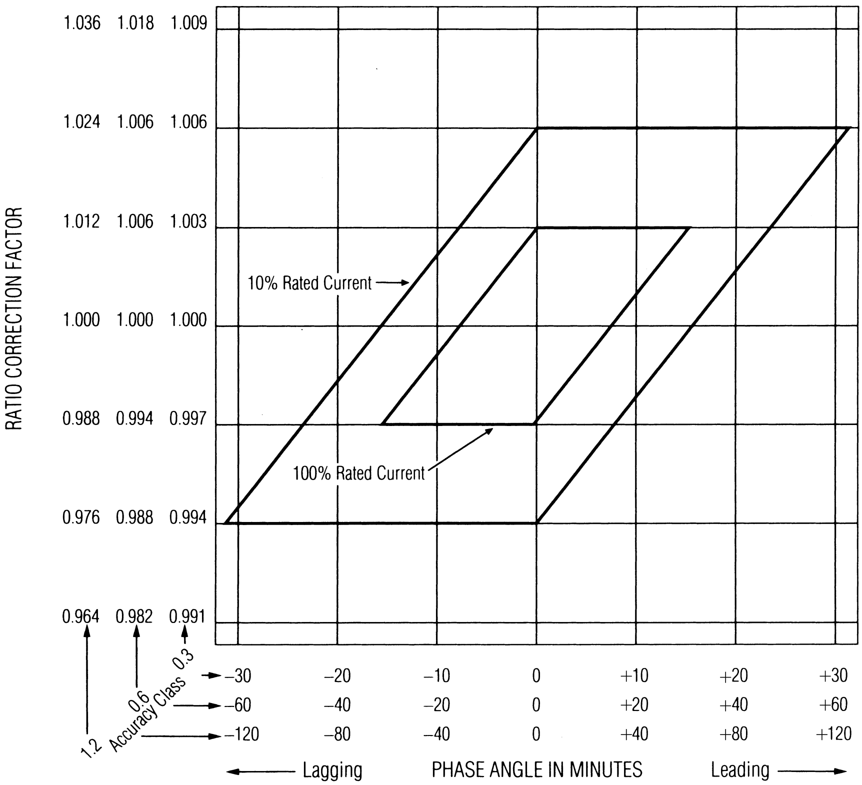


Note: Points representing two sets of performance data are plotted as REF on the grid. Points along the line which connects two given burdens represent performance at various burdens with the same power factor.

Figure 11-15b. Circle Method for Determination of Voltage Transformer Accuracy.

IEEE STANDARD ACCURACY CLASSES FOR METERING

The standard accuracy classifications of instrument transformers for metering are based on the requirement that the transformer correction factor (TCF) shall be within the stated limits over a specified range of power factor of the metered load and with specified secondary burdens. Note that the requirement is in terms of the TCF, rather than in either of its components, the RCF or phase angle correction factor (PACF). Since at 1.0 power factor the PACF is insignificant, the TCF is equal to RCF. The PACF is limited to values and direction (+ or −) such that its effect on the TCF does not cause the latter to exceed the limits of its stated class at power factors other than unity. Transformer standard accuracy classes can best be shown by parallelograms as is done in Figure 11-16a for current transformers and

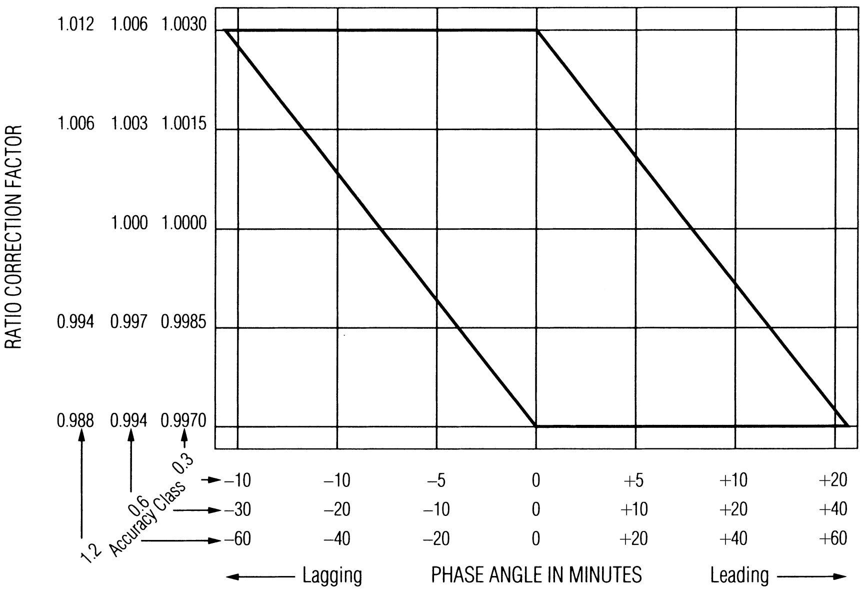


Note: The accuracy requirements for 100 percent rated current also apply at the continuous-thermal-current rating of the transformer.

Figure 11-16a. Parallelograms Showing Graphical Equivalent of IEEE Accuracy Classes 0.3, 0.6, and 1.2 for Current Transformers for Metering.

Figure 11-16b for voltage transformers. Note that the inclination of the accuracy class parallelogram for voltage transformers is opposite that of current transformers. The current transformer allowable TCF at 10% current is double that at 100% current.

It has been shown that a TCF is not a constant but depends on the secondary burden. Hence, the standard accuracy class is designated by the limiting percent error caused by the transformer followed by the standard burden designation at which the transformer accuracy is determined. For a current transformer the accuracy class may be written: 0.3 B-0.5, 0.6 B-1.8. This means that at burden B-0.5 the transformer would not affect the meter accuracy more than ± 0.3% at 100% rated current or ± 0.6% at 10% rated current, and at burden B-1.8 the transformer would not affect the meter accuracy more than ± 0.6% at 100% rated current or ± 1.2% at 10% rated current, when the power factor of the metered load is between 0.6 and 1.0 lagging.



Note: The transformer characteristics shall lie within the limits of the parallelogram for all voltages between 90 and 110 percent of rated voltage.

Figure 11-16b. Parallelograms Showing Graphical Equivalent of IEEE Accuracy Classes 0.3, 0.6, and 1.2 for Voltage Transformers for Metering.

Likewise the accuracy of a voltage transformer could be given as 0.3 X, 0.3 Y, 1.2 Z, with similar meanings. Accuracy classes of voltage and current transformers are shown in Tables 11-13 and 11-15.

The standard burdens for both voltage and current transformers are precisely defined by IEEE Std. C57.13. Standard burdens and characteristics are given in Tables 11-14 and 11-16.

The use of the IEEE standard accuracy classifications permits the installation of instrument transformers with reasonable assurance that errors will be held within known limits provided that burden limitations are strictly followed and secondary connections introduce no additional error.

Table 11-13. IEEE Accuracy Classes for Voltage Transformers.

Accuracy Class	Limits of Ratio Correction Factor and Transformer Correction Factor	Limits of Power Factor (Lagging) of Metered Power Load
1.2	1.012-0.998	0.6-1.0
0.6	1.006-0.994	0.6-1.0
0.3	1.003-0.997	0.6-1.0

Table 11-14. IEEE Standard Burdens for Voltage Transformers.

Burden	Voltamperes	Burden Power Factor
W	12.5	0.10
X	25.	0.70
M	35.	0.20
Y	75.	0.85
Z	200.	0.85
ZZ	400.	0.85

Table 11-15. IEEE Accuracy Classes for Metering Current Transformers.

Accuracy Class	Limits of Ratio Correction Factor and Transformer Correction Factor: 100% Rated Current, Minimum	100% Rated Current, Maximum	10% Rated Current, Minimum	10% Rated Current, Maximum	Limits of Power Factor (Lagging) of Metered Power Load
1.2	0.988	1.012	0.976	1.024	0.6-1.0
0.6	0.994	1.006	0.988	1.012	0.6-1.0
0.3	0.997	1.003	0.994	1.006	0.6-1.0

Table 11-16. IEEE Standard Burdens for Current Transformers with 5 Ampere* Secondaries.

Burden Designation**	Resistance (Ohms)	Inductance (mH)	Impedance (Ohms)	Voltamperes (at 5 A)	Power Factor
		Metering Burdens			
B-0.1	0.09	0.116	0.1	2.5	0.9
B-0.2	0.18	0.232	0.2	5.0	0.9
B-0.5	0.45	0.580	0.5	12.5	0.9
B-0.9	0.81	1.04	0.9	22.5	0.9
B-1.8	1.62	2.08	1.8	45.0	0.9

* If a current transformer is rated at other than 5 amperes, ohmic burdens for specification and rating may be derived by multiplying the resistance and inductance in the table by $[5/(\text{ampere rating})]^2$, the VA at rated current and the power factor remaining the same.

** These standard burden designations have no significance at frequencies other than 60 Hz.

HIGH-ACCURACY INSTRUMENT TRANSFORMERS

High-accuracy instrument transformers have been available from most manufacturers for specific applications for 40 or more years (primarily for high-current, low-burden applications). Interest in greater accuracy increased in the 1980s with the introduction of the solid-state, low-impedance meters.

The 0.15 % designation is based upon the same principles as the IEEE 0.3 accuracy class in accordance with IEEE Std. C57.13. Therefore, the maximum ratio correction factors and phase angle correction factors of the 0.15 parallelograms are one half those of the IEEE 0.3 parallelograms. Referring to Figure 11-16a and 11-16b, the 0.15 parallelograms could be determined by extrapolation. The 0.15 parallelograms are not yet available in any approved IEEE standard; however, 0.15 parallelograms may be available from manufacturers of high accuracy instrument transformers.

Based upon the principles of the IEEE Std. C57.13 accuracy classes, the "proposed guideline" for high accuracy (0.15%) instrument transformers would require the following:

- Current transformers to have a maximum error of 0.15% or less at 100% of rated current and 0.3% or less at 5% of rated current. Proposed burdens for electronic metering applications are ±0.2 at unity power factor (UPF) and ±0.04 at UPF (a maximum impedance of 0.2 ohms and 0.04 ohms, respectively). Note: The leads will typically provide the major portion of the meter circuit burden.
- Voltage transformers are to have a maximum error of 0.15% between zero burden and the maximum IEEE rated burden, typically, Y burden (75 VA) for medium and high voltage transformers.

If accuracies greater than the above are required, the meter engineer must specify the 0.15% accuracy for specific burden and current ranges. For example, in specifying the current transformers for the bi-directional metering of a large generating plant, the engineer may desire 0.15% accuracy for IEEE standard burdens through B0.9 from 5% (or less) to 150% of rated current. These kinds of accuracies may be available with high accuracy (0.15%) instrument transformers, but they need to be specified and discussed with the manufacturer especially if loads below 10% of rated current are important.

There may be no problem meeting the above requirements with high current rated transformers. Design criteria to meet fault current requirements in lower current rated transformers sometimes limits accuracy of performance. Using lower burden type electronic meters and lower burden leads may enable higher accuracy of performance at lower system current loads. It may be necessary and desirable to reduce the meter circuit burden by locating the meter closer to the current transformers or increasing the secondary lead size (reducing resistance), or both.

TYPES OF INSTRUMENT TRANSFORMERS

General Types

Indoor

An indoor transformer is constructed for installations where it is not exposed to the weather. This construction is generally limited to circuits of 15,000 volts (110 kV BIL) or less.

Outdoor

An outdoor instrument transformer is constructed for installations exposed to the weather.

Indoor-Outdoor

For circuits rated at 24 kV or above, common designs of instrument transformers are suitable for either indoor or outdoor use. At lower voltages, units for outdoor use are provided with additional protection, particularly against moisture. Spacings between high-voltage terminals and between these terminals and ground are generally increased for outdoor types.

Types of Insulation

Both liquid filled and dry type construction is used for transformers rated 69 kV (350 kV BIL) and lower. Above 69 kV liquid filled and gas filled, construction is used.

Dry Type

The core and coils are embedded in a body of material which serves as the insulation, case, and the bushings. This construction is usually employed for individual current or voltage transformers.

The materials used to insulate and furnish mechanical construction are generally rubbers, epoxies, and thermoplastic elastomers (TPE or EPDM). Other plastics may be used, but the use is not widespread. These materials are adaptable to molding the transformer.

The core and the coils may be wrapped in layers of insulating paper or material and then impregnated.

Compound Filled

In the compound filled construction the core and coils are wrapped and impregnated in the same manner as for the dry type construction. The element is then mounted in the case and the case filled with a compound which has a high dielectric strength. These units are designed for voltages not exceeding 15 kV.

Liquid Filled

In the liquid filled construction the core and coils are insulated and then mounted in a tank which is filled with the insulating liquid.

The higher voltage transformers often have two windings, a secondary and a tertiary on a common core. Sometimes one or both windings have a tap providing other phase angle voltage sources. The maximum (VA) burden capability may depend mostly on the core and therefore is the maximum of both windings. Sometimes the burden capability and accuracy are different or they may provide an even proportion of the total VA capability.

Gas Filled

Sulfur hexafluoride gas SF_6 is used to insulate the core and coils of instrument transformers in the voltage ranges above 69 kV. Insulating gas is used instead of liquid insulation and requires special coil insulation and other precautions.

Voltage Transformers

Voltage transformers are made with various methods of winding. They are usually wound for single ratio at lower voltages and two ratios at the higher voltages, particularly for substation applications.

For special purposes, taps may be taken off at various points on the secondary winding. While these taps are usually marked, great care should be used in connecting such a transformer to be sure that the proper tap is used.

Coupling Capacitive Voltage Transformer

A coupling capacitive voltage transformer (CCVT) is a voltage transformer made up of a capacitor divider and an electromagnetic unit designed such that the secondary voltage of the electromagnetic unit is proportional to, and in phase with, the primary voltage applied to the capacitor divider. Because of stability problems (a change in the ratio over time), CCVTs have, historically, been considered to be unacceptable for watthour metering application.

In recent years, CCVTs have gained some acceptance for high voltage metering applications. However, they may warrant a more rigorous or more frequent testing schedule than would be required for conventional wound-type voltage transformers.

Autotransformers

An autotransformer is one having only one coil with taps brought out at the proper points in the coil to give the voltages desired. Any portion of the coil may be used as the line-voltage connection and any other portion as the load connection. The ratio of such a transformer is approximately:

$$\frac{\text{Line voltage}}{\text{Load voltage}} = \frac{\text{Number of turns used for line winding}}{\text{Number of turns used for load winding}}$$

Autotransformers may be used for special purposes as in the phase-shifting transformers used with VARhour meters. The widespread use of solid-state meters with VAR measurement capability has significantly reduced the need for phase-shifting transformers.

Current Transformers

Wound (Wound Primary) Type

This type of current transformer (CT) has the primary and secondary windings completely insulated and permanently assembled on the core. The primary is usually a multi-turn winding.

Three-Wire Transformers

The primary winding is in two equal sections, each of which is insulated from the other and to ground so that the transformer can be used for measuring total power in the conventional three-wire, single-phase power service. Three-wire transformers are used on low voltage only since it is difficult to provide the necessary insulation between the two primary windings. Two two-wire CTs are commonly used for three-wire metering.

Window Type

This type is similar in construction to the wound type except that the primary winding is omitted and an opening is provided through the core through which a bus or primary conductor may be passed to serve as the primary winding. Complete insulation for such a primary is not always provided by the transformer.

By looping the primary conductor through the core, a number of different ratios may be obtained. For instance, if a transformer had a ratio of 1,200:5 or 240:1 with a single turn, it would have a ratio of 120:1 with two turns, 80:1 with three turns, etc. In other words, the ratio with any number of turns would be:

$$\text{Ratio} = \frac{\text{Original Ratio}}{\text{Turns}}$$

The number of turns in the primary is the number of times the conductor passes through the hole in the core and not the number of times the cable passes some point on the outside.

Bar Type

The bar type is similar to the window type but has an insulated primary provided. The bar in bar type may be removable or fixed.

Window Type as a Three Wire

This is done by passing one wire of a three-wire, single-phase service through the window in one direction and the other line in the opposite direction. The ratio of the CT would be one-half the marked ratio.

Dual Ratio

The series/parallel type has the primary divided into two sections and may be used as a dual ratio transformer. A 200 × 400:5 CT has a ratio of 200:5 when the primary coils are connected in series and 400:5 when connected in parallel.

The tapped secondary type, designated 200/400:5 for example, provides the advantage of changing ratio without interrupting service.

Split-Core Type

This type has a secondary winding completely insulated and permanently assembled on the core but has no primary winding. It may or may not have insulation for a primary winding. Part of the core is separable or hinged to permit its encircling a primary conductor or an uninsulated conductor operating at a voltage within the voltage rating of the transformer.

The exciting current of this type of CT may be relatively large and the losses and the ratio error and phase angle may also be relatively large.

Multi-Core

When it is necessary or desirable to operate two or more separate burdens from a single CT, a complete secondary winding and magnetic circuit must be supplied for each burden and the individual magnetic circuits linked by a common primary winding. A double-secondary CT is designated 200:5//5 for example.

Each secondary function is entirely independent of the other.

Miniature Transformers

These transformers are exceptionally small, not larger than a four inch cube, and for use in metering low-voltage circuits. The typical continuous current rating factors are one, two, three, and four times the nominal rating. Each type and ratio of CT may have a different rating factor.

With rated current in the primary, the open secondary voltage is low and may be considered non-hazardous. Current transformers should never be open-circuited, even though miniature CTs may not develop enough voltage before they saturate and damage themselves. An open circuit can cause the CT to be magnetized, and in larger units can cause a failure as well as voltages in excess of 2,500 volts.

Bushing Type

This type has a secondary winding completely insulated and permanently assembled on a ring-type core but has no primary winding or insulation for a primary winding. The circuit breaker or power transformer bushing with its conductor or stud becomes the completely insulated single-turn primary winding of the bushing type CT.

For metering application, considerable improvement in accuracy over the range of primary current is obtained by using special core materials and compensated secondary windings. Bushing type CTs, at ratings above 100 amperes, may have accuracies within acceptable revenue metering limits. The burden capability of these CTs is directly related to core cross-section and inversely related to ratio.

SELECTION AND APPLICATION OF INSTRUMENT TRANSFORMERS

Before specifying instrument transformers for any installation, the characteristics of the transformers must be taken into account to make sure that the units proposed meet all requirements. Certain types of installations present no unusual features and standard units may be specified; others require careful study before a final decision is made. For detailed specifications, see IEEE Std. C57.13.

Voltage Transformers

Basic Impulse Insulation Level

The basic impulse insulation level (BIL) rating of a voltage transformer indicates the factory dielectric test that the transformer insulation is capable of withstanding. The dielectric test values, minimum creepage distances associated with each BIL, the appropriate BIL level for each primary voltage rating, and conditions for transformer application are given in IEEE Std. C57.13. In a wye system, with voltage transformers connected line to grounded neutral, the transformer may be subjected to 1.73 times normal voltage during a ground fault. Hence the distinction among the various groups must be maintained to avoid over-stressing transformer insulation under such conditions.

Insulation must be de-rated when transformers are installed at altitudes greater than 3,300 feet (1,000 meters) above sea level. See IEEE C57.13.

The BIL of voltage transformers should be coordinated with associated equipment. In a substation with a BIL level of 200 kV, it is considered poor practice to use voltage transformers of 150 kV BIL. When deciding on the insulation level to be used, questions such as whether the power circuits are overhead or underground and adequacy of lightning arrester protection should be considered.

Thermal Rating

The thermal rating of a voltage transformer is the voltamperes that the transformer will carry continuously at rated voltage and frequency without causing the specified temperature limits to be exceeded. It has little, if anything, to do with the burdens at which accuracies are established. It must be remembered that whether the transformer remains within its accuracy class depends upon the burden (load) on the secondary.

See earlier discussions on standard burdens and burden calculations.

Current Transformers

Basic Impulse Insulation Level

The Basic Impulse Insulation Level is a useful guide in selecting current transformers for installation in critical locations. Current transformers should not be rated at a lower level than the other station or service equipment.

Continuous Thermal Current Rating Factor

Current transformers may carry a thermal rating factor of 1.0, 1.33, 1.5, 2.0, 3.0, or 4.0. This means that the nameplate current rating may be multiplied by the rating factor applicable to give the maximum current the transformers can carry continuously in an ambient temperature not exceeding 30°C. High-voltage current transformers typically have a rating factor of 1.5. For altitudes above 3,300 feet or 24 hour temperatures appreciably different from 30°C, refer to IEEE Std. C57.13.

The IEEE accuracy classifications for current transformers apply throughout the current range defined by the continuous thermal current rating factor.

Short-Time Thermal Limit or Rating

The short-time thermal current limit of a current transformer is the rms, symmetrical primary current that may be carried with the secondary winding short-circuited for a stated period, usually 1 second, without exceeding a maximum specified temperature in any winding. When this current limit is expressed as a rating, it is a number which represents: “how many times normal primary current”.

Short-Time Mechanical Limit or Rating

This limit indicates the maximum current value (or as a rating: how many times normal primary current), for one second, that the current transformer can stand without mechnical failure. The possible mechanical failure is the distortion of the primary winding. Hence the bar-type or through-type has a practically unlimited mechanical rating.

When indoor current transformers are in locations critical to public safety it is sometimes necessary to use a higher rated transformer than the circuit requires to obtain the necessary mechanical and thermal short-time ratings. Both of these short-time ratings should be matched to possible fault currents in the circuit.

Relay Applications

For relaying (system protection) applications, current transformers must meet requirements that differ greatly from those of metering. Since relays operate under abnormal conditions, high-current characteristics are important.

Current transformers for relaying service are given standard accuracy class ratings by letters and numbers, such as T200 or C200, which describe their capabilities up to 20 times normal current rating. The standard relay accuracy indicates the RCF will not exceed the 10% accuracy limits at loads from one to 20 times nominal, and at the rated burden. The letters T and C indicate whether performance is based on tests (T) or calculated (C).

Transformer Installation Procedures

Usually each utility develops its own standard for metering installations based on local requirements and the type of test facilities desired. These local standards are published and made available for installation guidance. This *Handbook* is not intended to describe the many practices followed for physically mounting and locating instrument transformers.

Current Transformer Secondaries

The secondaries of CTs should be kept shorted during storage and installation until the secondary leads and burden have been connected. This is to avoid the dangers of high voltage that could occur on an open secondary if the primary were energized. Some utilities make the shorting of secondaries a rule for all CTs. Some utilities have relaxed this rule for the miniature CTs as these will saturate before the secondary voltage reaches a dangerous value. See discussion under a subsequent subheading, "Wire Tracing with Instruments."

Precautions in Routing Secondary Leads

The secondary leads for a set of current or voltage transformers comprising one metering installation should be routed to avoid the pick-up of induced voltages from other conductors. Such induced voltages could cause errors in the metering.

The effects of induced voltages can be reduced by running the secondary leads in a group as a cable or together in a single conduit. In addition, the leads should be kept well away from other conductors carrying heavy current and should not be run in the same conduit with such conductors. Cabling will reduce the effects of stray fields by a partial cancellation of the induced voltages. Steel conduit will provide some magnetic shielding against stray fields. Shielded cable, in conjuction with proper bonding and grounding methods, will also provide excellent protection. The polarity and neutral secondary wires from a given instrument transformer should never be run in different conduits or by different routes. This could produce a loop that would be sensitive to induced voltages.

INSTRUMENT TRANSFORMER CONNECTIONS

Voltage Transformers

Single-Phase Circuits

Figure 11-17 shows the connection for one voltage transformer supplying single-phase voltage to the potential element of a meter. Note the standard polarity designations H_1 and H_2 for the primary and X_1 and X_2 for the secondary. The non-polarity secondary lead X_2 is grounded and at one point only. The numbers at the meter terminals show the secondary voltage corresponding to the original line voltage 1-2.

Three-Phase, Three-Wire Delta with Three-Wire Secondary

Figure 11-18 shows the connection which is most commonly used for three-wire delta polyphase metering. Note that both the primary and secondary of the transformer across lines 2 and 3 have been reversed. This is the usual practice as it avoids a physical crossover of the high-voltage jumper between the transformers. The adjacent high-voltage bushings of the two transformers are tied together and to line 2. The secondaries are likewise tied together and grounded at one point only.

The number 2 secondary lead is common to both transformers and carries the phasor sum of the currents drawn by coils 1-2 and 3-2. This leads to some difficulty in very precise metering, particularly if long secondary leads are used, as it is difficult to calculate the exact effect of this common lead resistance. See previous subsections of this chapter for the effect of lead resistance. Generally, the common lead will not produce any significant error for watthour metering and saves one wire.

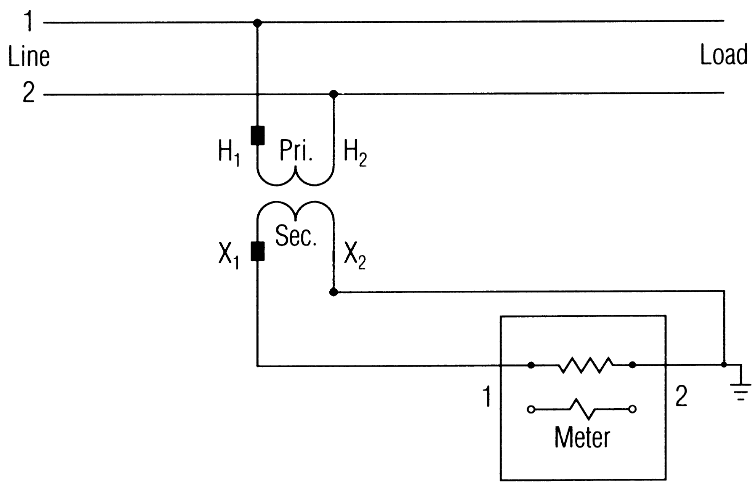


Figure 11-17. Single Phase.

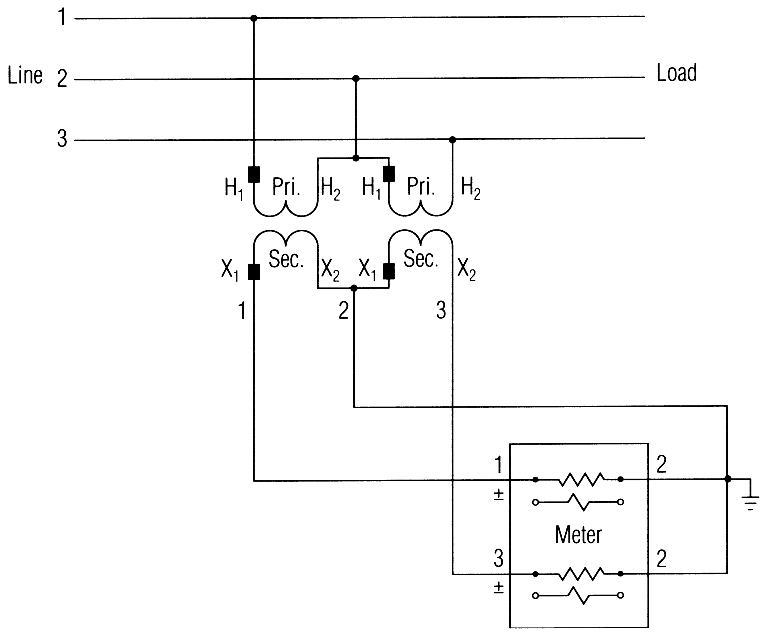


Figure 11-18. Three-Phase, Three-Wire Open-Delta, Three-Wire Secondary.

Three-Phase, Three-Wire Delta with Four-Wire Secondary

Where long secondary leads are used and where correction factors are to be applied, the four-wire secondary shown in Figure 11-19 is preferred.

Three-Phase, Wye-Wye, Four-Wire Secondary

Figure 11-20 shows this connection which is the usual one for a four-wire primary system. Here the neutral secondary wire again carries the phasor sum of the burden currents, but for a balanced voltage and burden this sum is zero. Hence, single-phase tests may be made using the lead resistance of a single lead.

Grounding—Primary

The primary of a voltage transformer is not normally grounded independent of the system.

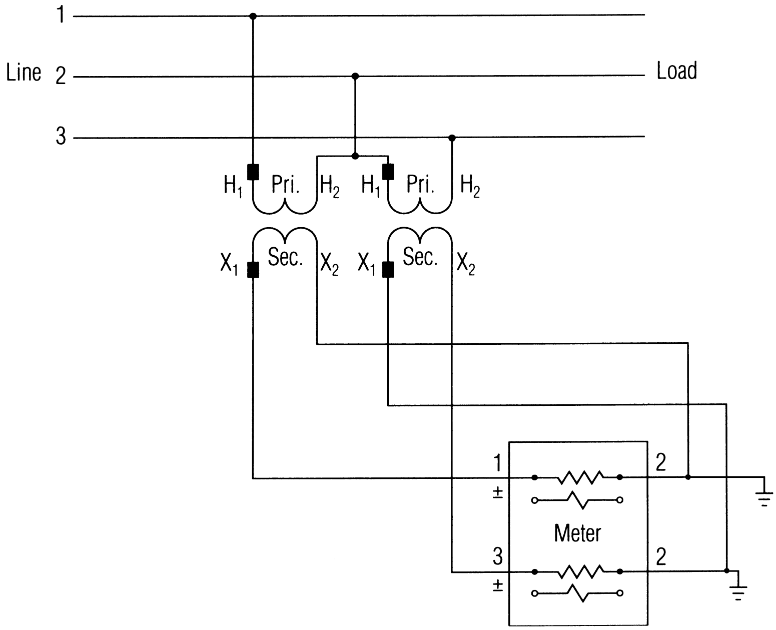


Figure 11-19. Three-Phase, Three-Wire Open-Delta, Four-Wire Secondary.

Grounding—Secondary

It is standard practice to ground the common or neutral secondary wire or wires of the voltage transformer. Secondary grounding is necessary for safety to prevent a high static potential in secondary leads and as a safeguard in case of insulation failure which could cause high voltage to appear on the secondary leads. The ground connection should be made at one point only. In order to "provide the maximum protection to personnel and connected equipment," IEEE Std. C57.13.3 recommends that this point of grounding be at the switchboard (or meter cabinet). Standard C57.13.3 is a "Guide for the Grounding of Instrument Transformer Secondary Circuits and Cases." Additional grounds should be avoided due to the indeterminate resistance and voltage gradients in the parallel ground path.

Grounding—Cases

Transformer cases normally are grounded for safety from static potential or insulation failure. In overhead construction grounding may be prohibited by local regulations to keep overhead fault potentials away from sidewalks or streets. For safety, any standard for grounding voltage transformer cases must be strictly followed as the operators depend on the fact that these cases are either grounded or isolated without exception.

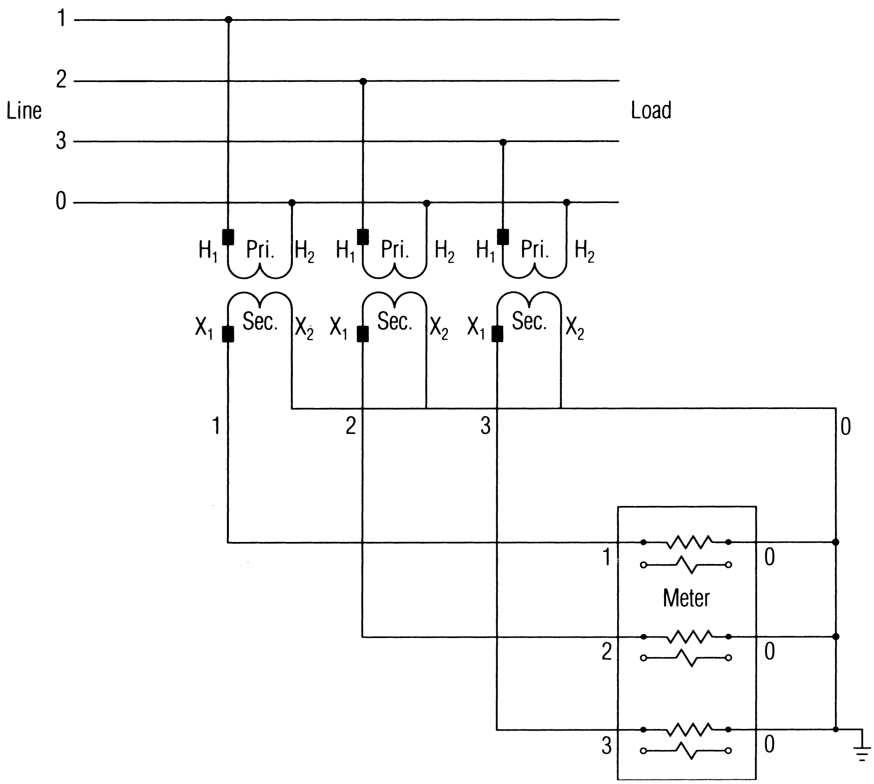


Figure 11-20. Three-Phase, Four-Wire, Wye-Wye, Four-Wire Secondary.

Primary Fuses

The use of primary fuses on a voltage transformer is a highly controversial subject. The primary fuse could protect the transformer from damage due to high-voltage surges and the system from an outage due to failure of the transformer. To accomplish this purpose the fuse must have a very small current rating as the normal primary current of a voltage transformer is exceedingly small. A suitable primary fuse for this application has appreciable resistance which may cause errors in the overall ratio and phase angle measurements. In addition such a small fuse may be mechanically weak and may fail due to aging without any transformer failure.

If a primary fuse opens for any reason, the load will be incorrectly metered or not metered until the fuse(s) is(are) replaced. Such incident causes error or lack of meter data for billing and settlement purposes

In many cases, circuit protective equipment is relied upon without the additional fusing of the voltage transformer primaries.

Secondary Fuses

The secondary leads of a voltage transformer are often fused, especially in high-voltage applications. The secondary fuses protect the transformers from short circuits in the secondary wiring. Fuses and fuse clips may introduce sufficient resistance in the circuit to cause metering errors. When corrosion is present this effect may become serious. A voltage transformer is not normally subject to overload as its metering burden is fixed at a value far below the thermal capacity of the transformer. Hence, the only value of the fuses is short-circuit protection. The most likely chance of a short circuit is during test procedures and normally the transformer can stand a momentary short without damage. When voltage transformers are used for both metering and relay service, an accidental short will operate the relays and cause an interruption. In such cases the metering circuit can be fused after separation for relaying and metering have been made. The individual utility's standard practices will usually dictate what situations require voltage transformer fusing.

Effect of Secondary Lead Resistance, Length, and Size of Leads

The effect of secondary lead resistance in a voltage transformer circuit is to cause a voltage drop in the leads so that the voltage at the meter is less than the voltage at the terminals of the transformer. See discussion of "Effects of Secondary Lead Resistance on the Ratio and Phase Angle as Seen by the Meter."

When the lead resistance exceeds a few tenths of an ohm, this voltage drop can cause errors equal to or greater than the errors due to ratio and phase angle of the transformer.

Meters can be adjusted to compensate for these errors but most companies object to upsetting meter calibrations to take care of secondary lead errors. They avoid this problem by limiting secondary lead lengths to, for example, a limit of not over 100 feet of No. 10 wire. When greater distances are involved, they use either larger secondary conductors or meters adjacent to the transformers with contact devices to transmit the intelligence to the station.

With normal watthour meter burdens the error due to the leads will usually be within acceptable limits if the total lead resistance does not exceed 0.3 ohms. If the lead resistance is larger, or if heavy burdens are used, calculations should be made to determine if corrections are necessary.

Current Transformers

Two-Wire, Single-Phase

Figure 11-21 shows the connections for one CT supplying single-phase current to the current coil of a meter. Again, the grounding of the non-polarity secondary lead is at one point only.

Three-Wire, Three-Phase

This connection is shown in Figure 11-22. The grounding of the common connection is at one point only. The common lead carries the phasor sum of the secondary currents in each transformer. To avoid the problem of applying corrections for the common lead resistance, the connection shown in Figure 11-23, using four secondary leads, is occasionally employed.

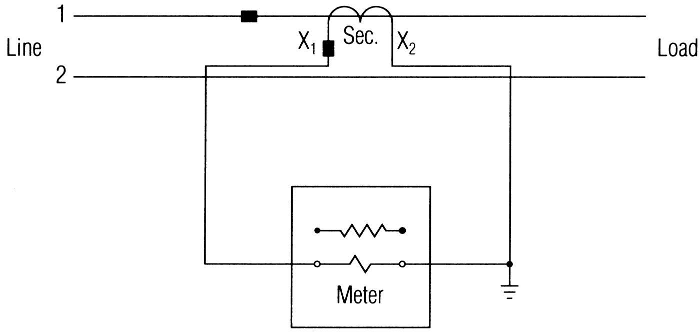


Figure 11-21. Two-Wire, Single-Phase.

Four-Wire, Three-Phase with Wye-Connected Secondaries

This connection is shown in Figure 11-24. The grounding of the common lead is at one point only. On a balanced load the common lead carries no current.

Four-Wire, Three-Phase with Delta-Connected Secondaries

Figure 11-25 shows this connection which is sometimes used to provide three-wire metering from a four-wire system. It is often used for indicating and graphic meters and relays and sometimes for watthour metering. The metering is theoretically correct only at balanced voltages, but on modern power systems the voltage is normally balanced well enough to give acceptable accuracy for watthour metering. With delta-connected current transformers, the secondary currents to the

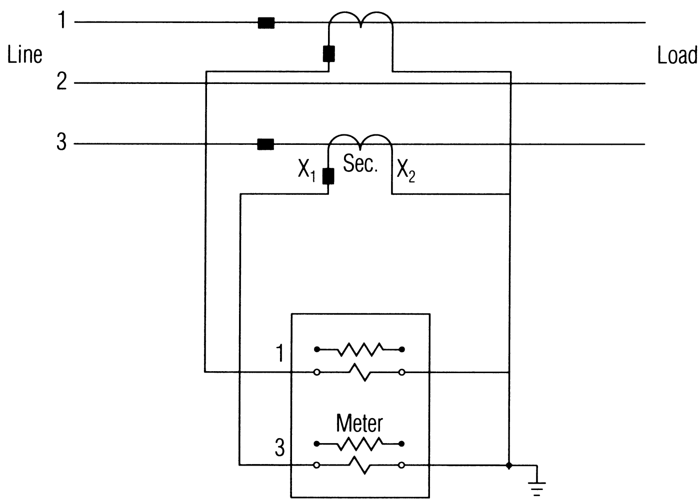


Figure 11-22. Three-Wire, Three-Phase, Three-Wire Secondary.

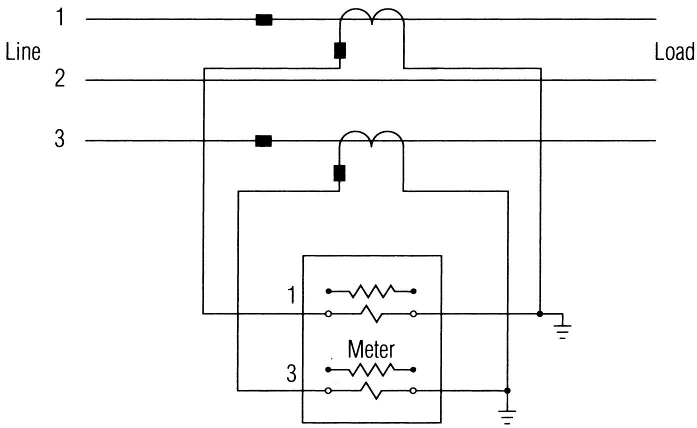


Figure 11-23. Three-Wire, Three-Phase, Four-Wire Secondary.

meter are displaced 30° from the primary line currents and also increased by the square root of three ($\sqrt{3}$) in magnitude due to the phasor addition. This circuit is equivalent to the 2 1/2-stator meter used by some companies. It permits the use of a standard two-stator meter with none of the test complications that the 2 1/2-stator meter involves.

For connections of meters with instrument transformers, see Chapter 12, "Meter Wiring Diagrams."

Parallel Secondaries for Totalized Metering

The paralleling of CT secondaries for totalized metering is covered in Chapter 10, "Special Metering", under the "Totalization" section. That section outlines the details and precautions involved in this method.

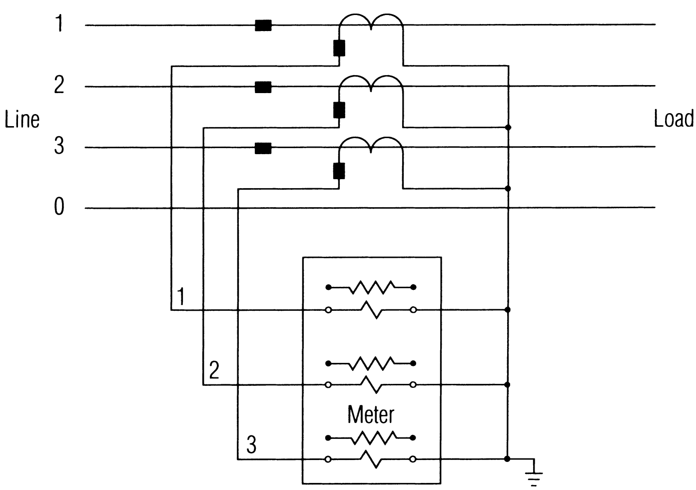


Figure 11-24. Four-Wire, Three-Phase, Four-Wire Secondary.

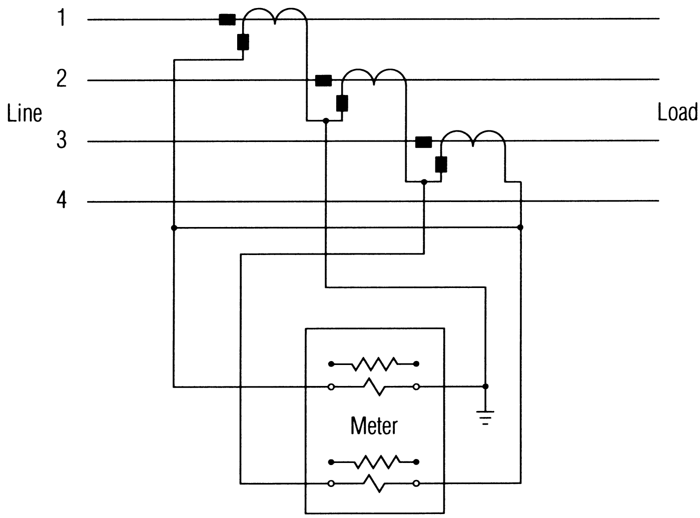


Figure 11-25. Four-Wire, Three-Phase with Delta-Connected Secondaries.

With the proper precautions, acceptable metering accuracy may be obtained. Without proper consideration of all the factors involved, the errors may be excessive, particularly at low current values.

Grounding

It is standard practice to ground the non-polarity secondary lead of a CT. Grounding is a necessary safety precaution for protection against static voltages and insulation failure. Normally, all metal cases of instrument transformers should be grounded. (Local regulations may prohibit such grounding in overhead construction.) If grounded, the CT secondary circuit must be grounded in one place ONLY. In order to "provide the maximum protection to personnel and connected equipment," IEEE Std. C57.13.3 recommends that this point of grounding be at the switchboard (or meter cabinet). Standard C57.13.3 is a "Guide for the Grounding of Instrument Transformer Secondary Circuits and Cases." When CT secondaries are connected in parallel and grounded, there must be only one ground for the set of CTs and this should be at the point where the secondary leads are paralleled at the meter. Additional grounds must be avoided due to the indeterminate resistance and voltage gradients in the parallel ground path and the resultant metering errors. On circuits of 250 volts or less, grounding of the CT secondary is not necessarily required, but is a good practice for protection of personnel and equipment.

Number of Secondary Wires

The use of common secondary wires has been discussed under the various connections. The resistance of a CT secondary lead adds to the burden, but unless this added resistance causes the total burden to exceed the burden rating of the transformer, it has a relatively small effect on the transformer accuracy. For most installations the common lead is used to save wire. For very precise metering, separate return leads might be justified if the lead resistance is large.

Common Lead for Both Current and Voltage Transformers

Generally, the CT secondary common lead and voltage transformer secondary common lead are kept separate to maintain the integrity of the individual current loops especially for secondary common lead grounding at the meter end (meter cabinet).

In some situations, the same secondary common lead for both current and voltage transformers may be used as discussed below.

When the load is not balanced and the same common secondary lead (neutral secondary wire) is used on four-wire star metering installations for both current and voltage transformers, there will be a small amount of neutral current flowing in this common lead from the neutral connection (neutral point) of both current and voltage transformers to where the neutral wire is grounded (ground point). This neutral current will result in a voltage drop between the neutral and ground points, and will shift the phasor neutral point of voltage away from its zero (absolute) origin. This minor phasor neutral shift in the voltage causes some measurement error in the meter. Such error has been found to be insignificant as compared to the errors in current and voltage transformers themselves. For example, for a situation with 20% load imbalance and a common lead of #10 Cu 165 feet long resulting in 0.2 ohms of resistance, the error is approximately 0.0042%. Such an error is relatively insignificant.

This error can be further reduced by minimizing the load imbalance condition, using a larger conductor size for the secondary common lead, and/or reducing the distance between the neutral and grounding points of the common lead.

For these reasons, a common lead may be used for both current and voltage transformer secondary neutrals especially when the distance between the neutral and grounding point is relatively short. If this distance becomes significantly longer, over 300 feet, and achieving 100% accurate measurement is important, the use of two separate common leads for current and voltage transformers is preferred.

Other connection systems are possible for special problems. Such connections must be analyzed in detail to be sure they provide correct metering without significant error.

VERIFICATION OF INSTRUMENT TRANSFORMER CONNECTIONS

When a metering installation using instrument transformers has been completed, it is necessary to verify the connections to insure correct metering. Wrong connections can cause large errors and may go undiscovered during a normal secondary or phantom-load test.

There is no single method of verifying instrument transformer connections that can be used with complete certainty for all possible installations. The best method will depend upon the nature of the particular installation, the facilities and instrumentation available, and the knowledge and ability of the tester. A combination of several methods may often be necessary or desirable. The following methods may be used to verify the instrument transformer connections.

Visual Wire Tracing and Inspection

A reasonably conclusive method of verification of instrument transformer connections is to actually trace each secondary wire from the instrument transformers to the meter. The terminal connections of each lead are checked to see that they conform to an approved meter connection diagram applicable to the installation. The use of color-coded secondary wire greatly facilitates this type of checking.

The primary connections to the instrument transformers must also be checked for conformity with the approved connection diagram. Particular attention must be paid to the relative polarity of the primary and secondary of all instrument transformers. Often some of the instrument transformers in an installation are connected with primary polarity opposite to the standard practice in order to facilitate a symmetrical primary construction and to avoid unnecessary cross-overs of the primary leads. These must be carefully noted to see that a corresponding reversal has been made at the secondary. If H_2 is used as the primary polarity terminal, then X_2 becomes the secondary polarity terminal.

All modern instrument transformers should have permanent and visible polarity markings. If the polarity is not clearly marked, the visual tracing method will be inconclusive and other methods required.

The nominal ratio of all instrument transformers should be noted from the nameplate and checked against the ratio specified for the installation.

All meter test switches and devices should be checked for proper connection and operation. The installation should also be checked to see that proper secondary grounds have been installed.

If the wiring is sufficiently accessible to permit a complete visual check, this method is generally reliable although it is subject to human error. If some of the wiring is concealed, this method can only be used if there is some means of identifying both ends of each concealed wire. The use of color-coded secondary wire makes such identification reasonably certain provided that the colors have not become unrecognizable through fading and that no concealed splices have been made. Where tags or wire markers are used, the reliability of the visual check depends upon the markings being correct.

Wire Tracing with Instruments

When the secondary wiring cannot be traced visually it may be traced electrically. Generally, the secondary windings of the current transformers may be shorted at the transformer terminals so that the secondary leads may be safely removed for test. The utmost precautions must be taken to assure that the secondary winding of a current transformer is never opened while the primary is energized, as dangerously high voltages can be induced in the secondary winding. This voltage is a lethal hazard to personnel and may also damage the current transformer.

The open-circuit voltage of a current transformer has a peaked wave form which can break down insulation in the current transformer or connected equipment. In addition, when the secondary is opened, the magnetic flux in the core rises to an abnormally high value which can cause a permanent change in the magnetic condition of the iron. This change can increase the ratio and phase angle errors of the current transformer. Demagnetization may not completely restore the transformer to its original condition. If the open circuit continues for some length of time, the insulation may be damaged by excessive heating resulting from the greatly increased iron losses.

If the shorting of the secondary windings of the current transformers cannot be done with complete safety, then the primary circuits must be de-energized and made safe for work. All standard safety practices and company safety rules covering high-voltage work must be rigorously followed to insure the safety of personnel.

Once the secondary windings have been shorted at the CT terminals, secondary leads may then be disconnected one at a time from the instrument transformers and the meter and checked out with an ohmmeter or other test device. Each lead is checked for continuity and to verify that it is electrically clear of all other leads and ground. The normal secondary grounds must be lifted for this test. When the leads are reconnected care must be used to be sure all connections are properly made and securely tightened. When the grounds are replaced they should be tested to be sure they properly ground the circuit. Only one lead at a time should be removed to avoid the possibility of a wrong reconnection.

If a good portable resistance bridge is available, the resistance of the secondary leads may be measured. This would check the possibility of poor connections or abnormally high resistance due to any cause, as well as confirm lead resistance.

Particular attention should be paid to all current transformer shorting devices to see that they work properly. If shorting clips in meter sockets are present, they should be tested to be sure that they open when the meter is installed. This type of verification is most conveniently done on a new installation before the service is energized.

When the service is already energized, this wire tracing method requiring the removal of wires from terminals may be impractical and unsafe.

Interchanging Voltage Leads

This method can be used for a two-stator meter on a three-wire polyphase circuit. With normal connections, the meter is observed to see that it has forward rotation. The non-common or polarity voltage leads to each stator are removed and reconnected to the opposite stators. If the rotation ceases or reverses, the original connections may be assumed correct and should be restored. This method gives fairly reliable results if the load on the circuit is reasonably balanced. On imbalanced loads this method is not reliable. Several incorrect connections can cause rotation to cease on this test under special conditions.

Phasor Analysis of Voltages and Currents from Secondary Measurements

With an ammeter, voltmeter, and phase rotation and phase angle meter, data may be quickly obtained from which the complete phasor diagram of the secondary currents and voltages may be constructed graphically to scale. First, the phase rotation of the secondary voltages is determined with the phase rotation meter and the magnitude of the voltages measured with the voltmeter. The voltage and current terminals of the meter or test switch are suitably numbered on a connection diagram for identification. One voltage is selected as the zero reference and the magnitude and phase angle of all currents relative to this voltage are measured and plotted to scale on the phasor diagram. Then the phase angles of the other voltages are measured relative to one of the currents and also plotted on the phasor diagram. The phasor voltage and current in each meter stator are now known.

The phasor diagram so constructed is compared with the standard phasor diagram for the type of metering involved and from this comparison it is usually possible to determine whether the installation has been correctly connected. To make this comparison a positive check on the connections, some knowledge of the load power factor is needed. Usually an estimate of the load power factor can be made on the basis of the type of load connected. On badly imbalanced loads of completely unknown power factor this method is not positive. It also may be indeterminate if the secondary currents are too low to give accurate readings on the meters used.

The reliability of this method depends upon the care taken to assure correct identification of each secondary current and voltage measured and upon the tester's ability to correctly analyze the results.

Various other methods have been used to obtain data from secondary measurements from which the phasor diagram may be constructed.

In the classic Woodson check method, three single-phase wattmeters, an ammeter, a voltmeter, a phase rotation indicator, and a special switching arrangement are used to obtain data from which the phasor diagram may be plotted. This method requires two measurements of watts, one measurement of current, and a graphical phasor construction to determine the direction and magnitude of each current phasor. The sum of the wattmeter readings is compared with the watts load on the watthour meter as determined by timing the disk. This gives an additional check.

The Woodson method has been in use by some utilities for over 60 years and is very reliable. On badly balanced loads of completely unknown power factor it is not positive, having the same limitations in the interpretation of the phasor diagram as the method using the phase angle meter. The method is primarily designed for checking three-phase, three-wire installations but may, with modifications, be used for other types.

Circuit analyzers are available that can analyze any standard metering configuration and produce a phasor diagram. With the circuit analyzer, one piece of equipment will do what once required several pieces of equipment. Additionally, power system analyzers are offered that will provide waveform displays, CT ratio and burden checks, and meter accuracy testing along with the circuit analyzer functions mentioned above. Analyzers are very reliable. However, great care must be taken to make connections to the circuit to be analyzed in accordance with the manufacturer's instructions.

Also available today are solid-state meters with built-in circuit analysis and site diagnostics. Therefore, the meter itself can assist in the determination that the current and voltage secondaries are wired correctly.

INSTRUMENT TRANSFORMER TEST METHODS

Safety Precautions in Testing Instrument Transformers

All instrument transformer testing involves the hazard of high voltage. Voltage transformers, by their very nature, are high-voltage devices and CTs can develop dangerously high voltages if the secondary is accidentally opened under load. No one should be allowed to make tests on instrument transformers until thoroughly instructed on the hazards involved and the proper safety precautions.

Many safety devices, such as safety tape, warning lights, interlocked foot switches, test enclosures with interlocked gates, and double switches requiring both hands to energize the equipment, may be used to reduce the hazards. These devices can never be made absolutely foolproof. Ultimately, the responsibility for safety rests with the individual doing the tests.

In testing current transformers it is particularly important to make all secondary connections mechanically secure so that even a strong pull on the test leads cannot open the circuit. For this reason spring test clips should not be used on current transformer secondary test leads. Only a solidly screwed or bolted connection can prevent an accidental opening of the secondary circuit with the consequent high-voltage hazard.

The metal cases of voltage transformers and one of the secondary test leads should be solidly grounded to protect the tester from high static voltages and against the danger of a high-voltage breakdown between primary and secondary. All metal-clad test equipment should also be grounded.

Insulation Tests

The insulation of instrument transformers must be adequate to protect the meters and control apparatus as well as the operators and testers, from high-voltage circuits and to insure continuity of service. The insulation tests should normally precede all other tests for reasons of safety.

When it is essential to determine the accuracy of instrument transformers removed from service in order to confirm corrections of billing, it may be advisable to make accuracy tests with extreme caution before any insulation test.

It is recognized that dielectric tests impose a severe stress on insulation and if applied frequently will hasten breakdown. It is recommended that insulation tests made by the user should not exceed 75% of the IEEE standard factory test voltage. When dielectric field tests are made on a periodic basis, it is recommended that the test voltage be limited to 65% of factory test values.

AC Applied Potential (Hi-Pot) Tests, 60 Hertz

The alternating-current test at 60 hertz should be made on each instrument transformer by the manufacturer in accordance with IEEE standards. Similar tests may be made by the user. All insulation tests for liquid-insulated transformers should be made with the transformer cases properly filled.

Hi-pot test sets with fault-current capacities below “Let Go” or “Threshold of Feeling” are a desirable safety precaution. When properly constructed such equipment does not represent a fatal hazard to the operator. Many small sets of this type are available commercially. These small test sets may not supply the charging current necessary for over-potential tests on high-voltage current and voltage transformers.

When high-potential testing equipment with larger fault-current capacity is used it must be handled with all the safety precautions necessary for any other high-voltage power equipment. Such equipment represents a fatal hazard to the operator. Some degree of protection from the hazards of such equipment may be provided by the use of an enclosed test area protected by electrical interlocks that automatically de-energize the equipment when the gate is opened.

The fundamental responsibility for safety lies with the operator who must use the utmost care to de-energize the equipment before approaching the high-voltage terminals.The operator must never fall into the bad habit of depending upon the interlocks as these could fail.

To protect the transformers being tested, some means should be provided in large-capacity hi-pot equipment to prevent destructive surges and limit the current in case of breakdown. Impedance in the form of choke coils is often used for this purpose.

When the hi-pot test voltage is very high, a spark gap may be used to prevent the accidental application of voltage above the desired value. Resistors are used in series with the spark gap to limit the current at breakdown and to damp high-frequency oscillation. The gap is set to a breakdown value slightly higher than the desired test value before the transformer to be tested is connected. The transformer under test is then connected across the gap and its resistors. Should the test voltage be exceeded, the gap flashes over and prevents the voltage from rising further.

Polarity Tests

The marking of the leads should be carefully checked by a polarity test. Most methods, as well as the instrumentation used in checking transformers for ratio and phase angle, automatically check polarity at the same time. When such facilities are not available, the circuits shown in Figures 11-26 through 11-29 may be used to determine polarity.

Polarity Tests for Voltage Transformers

Figure 11-26, Polarity Test, Voltage Transformer, voltage H_2 to X_2 is less than voltage H_1 to H_2 if polarity is correct. The reliability of this method is diminished at high ratios.

For Figure 11-27, Polarity Test, Voltage Transformer, the standard voltage transformer must have the same nominal ratio as the unknown voltage transformer. The voltmeter reads zero if polarity is correct and twice the normal secondary voltage if incorrect.

Polarity Tests for Current Transformers

Figure 11-28, Polarity Test, Current Transformer, polarity is correct if the ammeter reads less when X_2 secondary lead is connected to the line side of the ammeter than when the X_2 lead is connected to X_1 (shorted secondary circuit). CAUTION: Do not apply primary current with the secondary open. The reliability of this method is diminished at high ratios.

Figure 11-29, Polarity Test, Current Transformer, the standard current transformer must have the same nominal ratio as the unknown current transformer. The ammeter reads zero if the polarity is correct and twice the normal secondary current if incorrect. CAUTION: Do not open the CTs' secondary circuits with primary current applied.

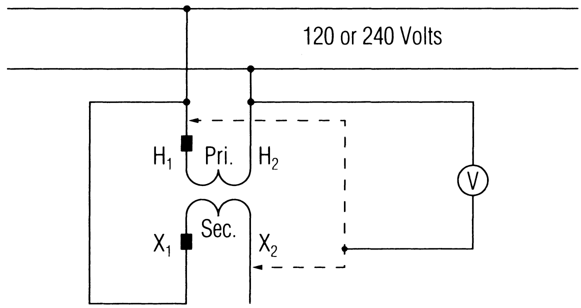


Figure 11-26. Polarity Test, Voltage Transformer.

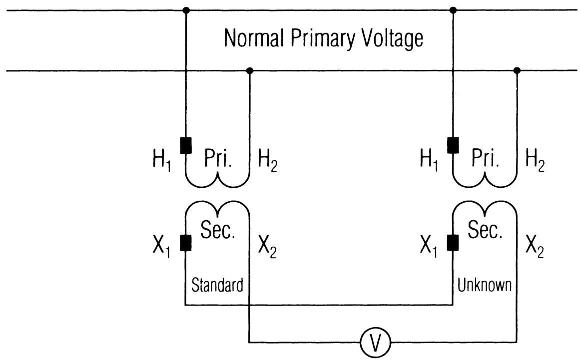


Figure 11-27. Polarity Test, Voltage Transformer.

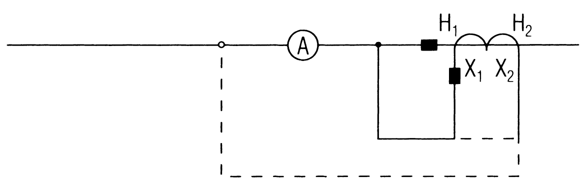


Figure 11-28. Polarity Test, Current Transformer.

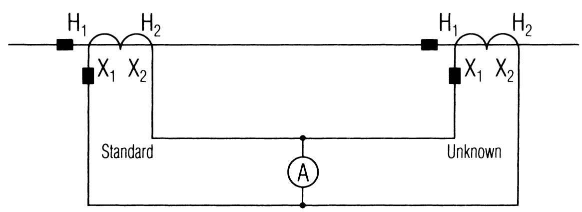


Figure 11-29. Polarity Test, Current Transformer.

Tests to Verify the Marked Ratio

Voltage Transformers

The marked ratio of a voltage transformer may be verified at the time of the polarity check with either of the circuits shown in Figures 11-26 or 11-27. In Figure 11-26, the voltage measured across H_2 to X_2 should be less than the voltage across H_1 to H_2 by an amount equal to the H_1 to H_2 applied voltage divided by the marked ratio. For example, if 120 V is applied to the primary H_1 to H_2 of a 2,400 to 120 V (20:1) transformer, then the H_2 to X_2 reading should be $(120 - \frac{120}{20})$, or 114 V. This method may be improved by using two voltmeters so that the two voltages are read simultaneously.

In the circuit shown in Figure 11-27, the voltage will not be zero unless the unknown transformer has the same ratio as the standard and this automatically verifies its ratio.

A third method that may be used is shown in Figure 11-30. The secondary voltages will be the same if the ratios of the standard and the unknown are the same. If not, the ratio of the unknown is equal to the ratio of the standard times the secondary voltage of the standard divided by the secondary voltage of the unknown. Care must be used not to apply a primary voltage in excess of the rating of either transformer.

The marked ratio of a voltage transformer may also be checked with a turn-ratio test set such as the Biddle Model TTR.

Current Transformers

The marked ratio of a CT may be checked by measuring the primary and secondary currents directly with ammeters. For large primary values a standard current transformer must be used and the secondary current of the standard is compared with the secondary current of the unknown CT when their primaries are connected in series as shown in Figure 11-31. CAUTION: Do not open the CTs' secondary circuits with primary current applied.

Today, there are power system analyzers offered that will provide a reasonably accurate ratio check for in-service CTs.

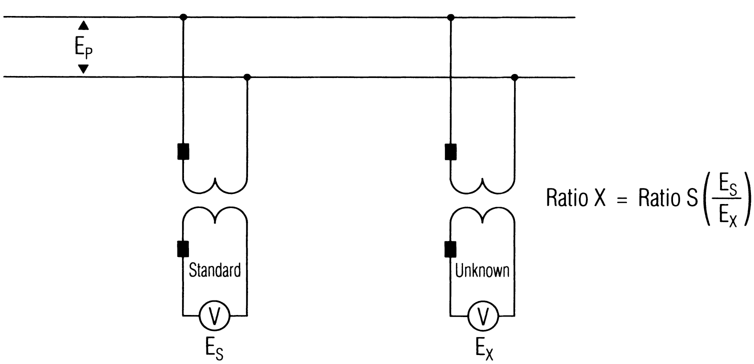


Figure 11-30. Test to Verify Marked Ratio of Voltage Transformer.

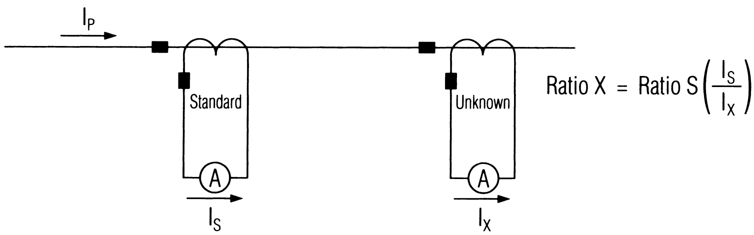


Figure 11-31. Test to Verify Marked Ratio of Current Transformer.

Testing Current Transformers for Shorted Turns with a Heavy Burden

A field method that may be used to detect shorted turns in a current transformer consists of inserting an ammeter and a resistor in series with the secondary circuit. A shorting switch is connected across the resistor. Ammeter readings are taken first with the resistor shorted out and then with the shorting switch open which adds the burden of the resistor to the circuit. If shorted turns are present, there will be a larger drop in current on the second reading than is normal for a good transformer.

Several precautions are necessary if this method is to provide reliable information on the condition of the transformer. Current transformers vary over a wide range in their abilities to maintain ratio under heavy burdens. A burden that has little effect on one type may cause a large drop in secondary current on a different type even though there are no shorted turns. Values ranging from two to 60 ohms have been used for this test but no single value is ideal for all transformers.

To be conclusive, it is necessary to know the effect of the burden used on a good transformer of the same make, model, and current rating. This effect must be known at the same value of secondary current to be used in the test. This can be done by preparing graphs or tables showing the normal effect on all makes, models, and current ratings used.

A simpler method is based on the fact that usually all of the current transformers on a given three-phase installation are of the same make, model, and current rating and the reasonable assumption that all do not have shorted turns. Thus, if the two or three transformers on the installation are tested by this method, any transformer showing a much larger drop in current with the addition of the heavy burden than the others probably has shorted turns.

Test sets with two burdens, a multi-range ammeter, and suitable switching are commercially available. With these sets the tests just described may be done quickly and safely.

In addition to shorted turns in the current transformer, the burden test will show shorts in the secondary wiring and grounds in the normally ungrounded wire.

Tests to Determine Ratio and Phase Angle

Instrument transformers may be tested for ratio and phase angle by direct or comparative methods. Direct methods involve the use of indicating instruments and standard resistors, inductors, and capacitors while comparative methods will require a standard instrument transformer of the same nominal ratio whose exact ratio and phase angle have been previously determined.

Direct Methods

Direct methods are necessary for the determination of the ratio and phase angle of instrument transformers in terms of the basic electrical standards. Such methods are used by the National Institute of Standards and Technology (NIST) to calibrate their own standard instrument transformers which in turn are used to test instrument transformer standards sent to the NIST for certification.

Direct methods are simple in theory but involve so many practical difficulties that they are not suitable for non-laboratory use.

Comparative Methods

When calibrated standard instrument transformers are available, the problems of testing instrument transformers are greatly simplified since only a comparison of nearly equal secondary values is involved.

Deflection Methods

Methods involving the use of indicating instruments connected to the secondary of the standard and unknown transformers suffer from the accuracy limitations of the instruments used. Thus the two-voltmeter or two-ammeter methods, Figures 11-30 and 11-31, are useful only as a rough check of ratio. If two wattmeters are used, a rough check on phase angle may also be made, although this involves considerable calculation after tests at 1.00 and 0.50 power factors. Accuracy may be somewhat improved by interchanging and averaging the readings of the two instruments but reading errors still limit the accuracy for ratio to about 0.2%.

A modification of the two-wattmeter method makes use of two-watthour meters in the form of two-watthour standards. This method is capable of good accuracy but requires excessive time to make the test and compute the results. In addition, it imposes the small burden of a watthour standard on the transformer under test which may not be desirable. Although this method requires extensive calculations to determine ratio and phase angle correction factors to the degree of accuracy generally required, it provides a rapid and convenient test method to determine whether transformers meet established accuracy limits. In this case, readings are compared to tables of go and no-go limits without extensive calculations. Some utility companies have adopted this method for testing the commonly used 600 V class of transformers that are not involved in metering large blocks of power. Also, this test confirms polarity and nominal ratio. See Figures 11-32 and 11-33.

Null Methods

Most modern methods of testing instrument transformers are null methods wherein the secondary voltages or currents from the standard and the unknown (X) transformer are compared and their differences balanced with suitable circuits to produce a zero or null reading on a detector. After balancing, the ratio and phase angle difference between the X-transformer and the standard transformer may be read directly from the calibrated dials of the balancing equipment. With suitable equipment of this type, tests for ratio and phase angle may be made rapidly and with a high degree of accuracy. Equipment of this type is available commercially.

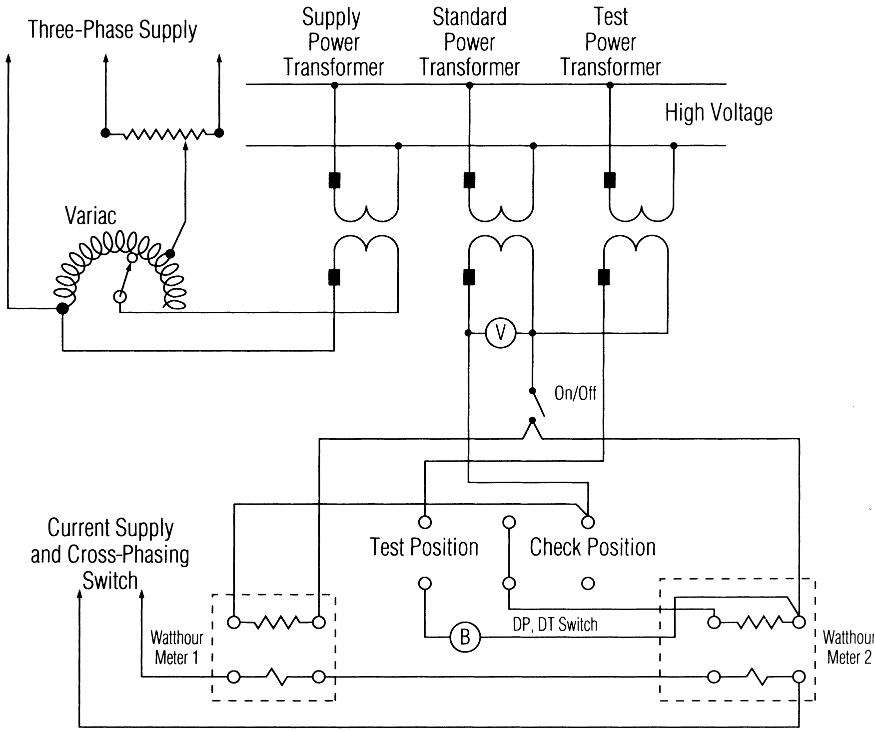


Figure 11-32. Voltage Transformer Test Circuit, Two-Watthour-Meter Method.

The Leeds & Northrup Voltage Transformer Test Set

Figure 11-34 is a simplified schematic diagram of the Leeds & Northrup voltage transformer test set. This set has two adjustable dials, one for ratio and one for phase angle. The phase-angle dial moves three sliders which are mechanically coupled. Two of these sliders change the position of a fixed mica capacitor in relation to the resistors to effect a balance for phase angle, while the third slider and rheostat compensates for the change that the first two would also make in the ratio adjustment. The ratio and phase-angle dials are independent so that the adjustment of one does not affect the other.

The balance point is determined by means of a dynamometer-type galvanometer whose field coil is supplied from a phase shifter. This is necessary as the galvanometer would read zero for zero current (the desired balance point) or for zero power factor. The zero current balance is independent of the phase relation of the field, while the zero power factor balance is not. To distinguish the two balance points, the field is supplied with a voltage of one phase angle and then with a voltage of a different phase angle. If the galvanometer remains balanced for both conditions, then the proper balance has been achieved. For convenience the galvanometer field flux is set for the in-phase and quadrature-phase condition, to make the adjustment of the two dials independent. When balance is achieved, the ratio and phase angle of the X-transformer in terms of the standard may be read directly from the dials.

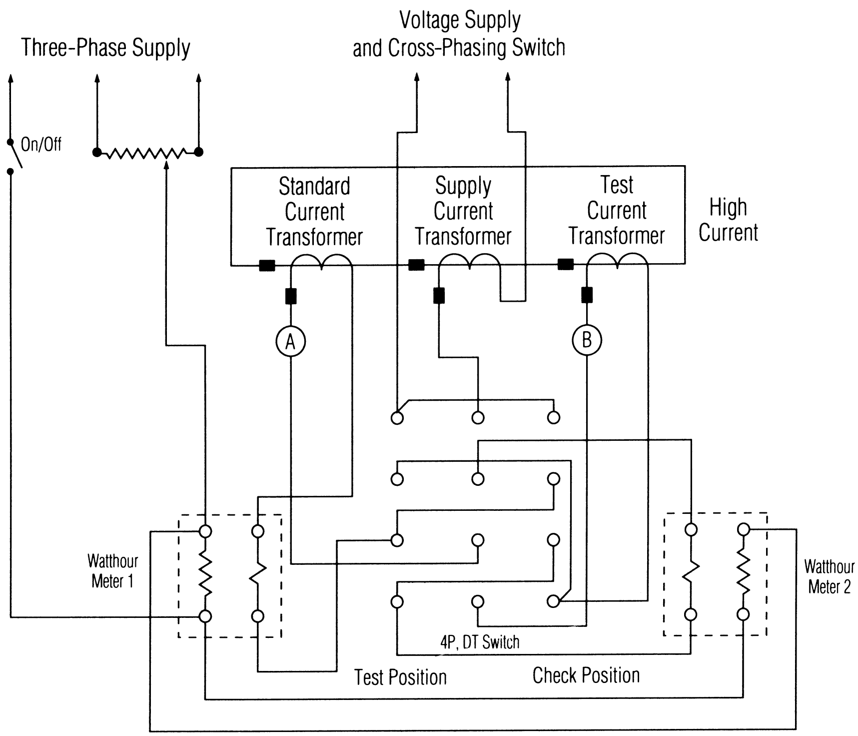


Figure 11-33. Current Transformer Test Circuit, Two-Watthour-Meter Method.

The ratio dial is calibrated from 95 to 105% ratio in divisions of 0.1% and the phase-angle dial from –120 minutes to +120 minutes in divisions of 5 minutes. With care the dials can be read to one-tenth of a division or 0.01% on ratio and 0.5 minutes on phase angle. Accuracy is stated as ±0.1% on ratio and ±5 minutes on phase angle. This set can be certified by the NIST who will give corrections to 0.01% and 1 minute phase angle and certify them to 0.05% and 2 minutes phase angle.

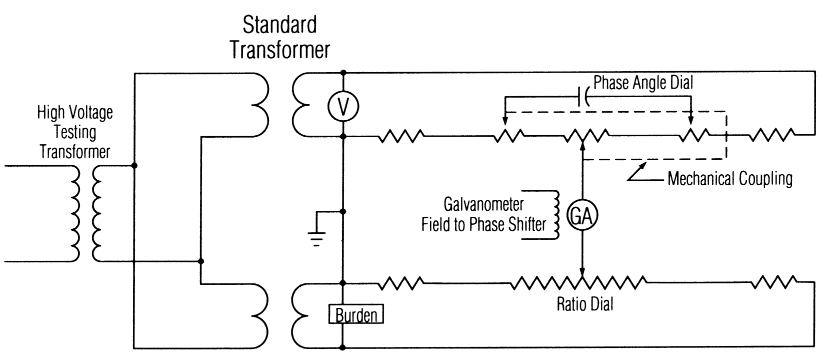


Figure 11-34. Simplified Schematic Diagram of Leeds & Northrup Silsbee Portable Voltage Transformer Test Set.

The burden of the standard circuit of the test set on the standard voltage transformer is approximately 3.10 VA at 0.995 power factor leading at 110 volts. The burden of the X-circuit on the X-transformer is approximately 1.18 VA at 1.00 power factor, 110 volts. In most cases this burden is negligible in regard to the X-transformer and the standard circuit burden may be compensated by the calibration of the standard transformer. The standard transformer burden also includes the burden of the voltmeter used in addition to the burden of the set itself.

The phase shifter used to supply the galvanometer field may have either a single-phase or three-phase primary winding. The three-phase primary winding gives somewhat better voltage regulation.

The high-voltage testing transformer is usually a voltage transformer of the same ratio as the standard and X-transformers and is used to step up 120 volts to the primary voltage required.

The Leeds & Northrup Silsbee Current Transformer Test Set

Figure 11-35 is a simplified schematic diagram of the Leeds & Northrup Silsbee current transformer test set. In this set the ratio adjustment is made by a dial that is coupled mechanically to two variable resistors, and the phase angle adjustment by a dial that varies the inductance of the air-core mutual inductor. The galvanometer and phase shifter are similar to the ones used for the voltage transformer test set. The same phase shifter may be used for both sets. At balance, the ratio and phase angle of the X-transformer, relative to the standard transformer, may be read directly from the dials.

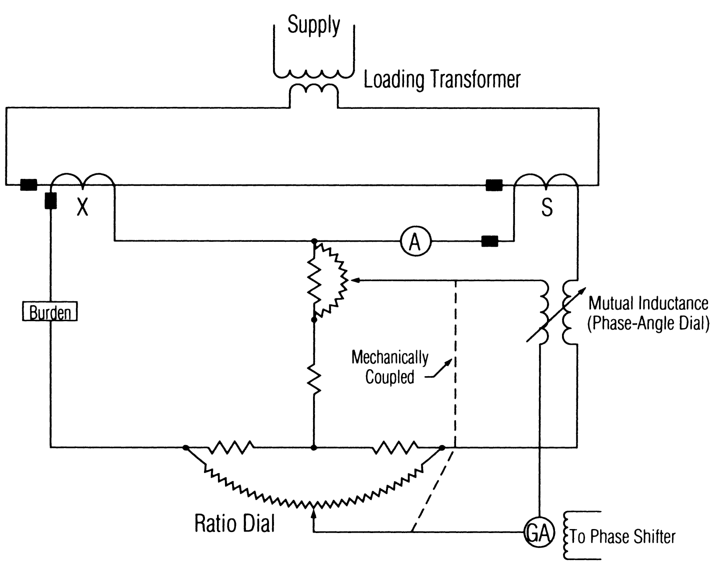


Figure 11-35. Simplified Schematic Diagram of Leeds & Northrup Silsbee Portable Current Transformer Test Set.

The ratio dial is calibrated from 95 to 105% ratio in divisions of 0.1% and the phase angle dial from −180 to +180 minutes in divisions of 5 minutes. With care, the dials can be read to one-tenth of a division or 0.01% on ratio and 0.5 minutes on phase angle. Accuracy is stated as ±0.1% on ratio and ±5 minutes on phase angle. This set can be certified by the NIST who will give corrections to 0.01% and 1 minute phase angle and certify them to 0.05% and 4 minutes phase angle.

The burden of the standard circuit is approximately 0.8 mH and 0.29 ohms. The burden of the X-circuit varies with the setting and is in the order of 0.01 to 0.02 ohms. In most cases this burden is negligible and the standard burden may be compensated for in the calibration of the standard transformer. The standard transformer burden also includes the burden of the ammeter used in addition to the burden of the set itself.

A test set of this type with reduced ranges is available on special order. This would give better readability in the range of greatest use.

The loading transformer is a stepdown transformer designed to produce the necessary primary test currents at a low voltage.

The air-core mutual inductor used in this set is very sensitive to stray fields and the proximity of magnetic materials. It must be kept several feet from conductors carrying heavy current and well away from any iron or steel. A steel bench top will cause considerable error.

At secondary currents of 0.5 amperes the galvanometer has only one-tenth the sensitivity that it has with secondary currents of 5 amperes. This makes the exact balance at this point difficult to determine. Another problem is that of inductive action in the galvanometer circuit that may occur when testing miniature current transformers. To overcome these problems a cathode ray oscilloscope may be used as a detector. This requires shielding of the internal leads in the detector circuit of the Silsbee set and the use of a shielded matching transformer of about 1¾-ohm input to 157,000-ohm output to couple the detector circuit to the oscilloscope. Care must be used in the grounding of the shield and secondary circuits to prevent false indications. Grounding at the No. 2 standard terminal of the set has proven satisfactory provided that this is the only ground on the secondary of either the standard or the X-transformer and all shield grounds are tied to this point. When the oscilloscope is used the phase shifter is not needed and adjustments may be made on the ratio and phase-angle dials simultaneously to reduce the scope pattern to a minimum peak-to-peak value. This method is rapid and very sensitive. Some transformers will show more third harmonic content than others at the balance point but this may be ignored as the balance desired is for the 60 hertz fundamental only. To avoid erroneous balances, several cycles should be displayed along the x-axis of the oscilloscope and all peaks adjusted for the same height and minimum value.

Testing Current Transformers for Abnormal Admittance

The condition of a CT can be tested by monitoring its admittance. (Admittance is the reciprocal of impedance.)

The admittance of a CT secondary loop can be measured with or without service current flowing in the secondary. The tester shown in Figure 11-36 measures admittance by injecting an audio signal into the secondary of an in-service transformer, then measuring the admittance seen by that signal. While any frequency between one and two Khz could be used, this tester uses 1580 Hz to reduce false readings caused by harmonics of 60 Hz in the secondary.

Metering current transformers have very small errors typically less than 0.3% when operated within their specified current and burden ratings. Therefore, the circuit admittance of a current transformer is nearly constant throughout its normal operating range unless a fault develops. If an admittance measurement shows deviation from normal while in service, it is likely the current transformer has: (1) an internal short such as short-circuited turns; (2) an abnormal internal or external resistance such as a high resistance joint; (3) the current transformer is being operated under abnormal conditions perhaps with a DC component in the primary; or (4) the current transformer has become magnetized (see discussion later on Demagnetizing). Most faults are immediately obvious because they produce a high admittance reading, typically greater than 1.5 times a normal reading. Transformers with a wrong ratio, such as those hooked to the wrong tap, will also have readings substantially different from normal readings.

The best way to establish a normal admittance reading is to develop a history of measurements. Admittance readings can be taken before installation, during initial field tests, and during subsequent checks. Admittance values depend on fixed features such as core design, burden rating, and the turns ratio. Changes to admittance which are caused by non-fault conditions are small when compared with changes caused by fault conditions.

In-service CTs can be tested in groups and a high admittance reading by one transformer in the group suggests a fault condition in that transformer. If all readings in the group are high the cause could be a capacitive load on both sides of the current transformer, high system noise including harmonics close to the test frequency, or the presence of DC in the primary.

Testing Current Transformers for Abnormal Burden

The condition of a CT can be evaluated by measuring the burden of the transformer.

Current transformers are designed to supply a known current as dictated by the turns ratio into a known burden, and to maintain a stated accuracy. The principle of a burden tester is to challenge the capability of the CT to deliver a current into a known burden.

The total burden of the CT secondary loop includes the burden of the watthour meter current coils, the mounting device, the test switch, connection resistances, and the loop wiring. When burden is added which exceeds the design capacity of the CT, the transformer can not supply the same level of current to the increased burden which results in a drop in the current transformer of loop current. The tester shown in Figure 11-36 measures the burden of a current transformer by adding a known ohmic resistance in series with the current transformer secondary loop, and comparing the total burden including the known resistance, with the burden when the resistance is not in the loop.

The magnitude of the current change depends on several factors and is not absolutely definable. The operating level of current in the CT secondary loop can be a significant factor. Current transformers operating at low currents are able to support several times the burden rating because at low currents the flux density of the core is low, leaving ample head room for additional flux before saturation.

Therefore, to obtain accurate readings, these burden tests are performed at full rated secondary current. At the high end of the current range, additional burden quickly pushes the current transformer out of its operating range resulting in significant drops in operating current.

Form factor affects the burden capability of a current transformer. Transformers with high form factors can support a burden greater than the nameplate specifications. For high form factor transformers, it is important to take measurements at full rated secondary current.

Other procedures for testing the burden of CTs are included in the IEEE C57.13 specification Requirements for Instrument Transformers.

Figure 11-36. Instrument for Measuring Current Transformer Secondary Admittance and Burden.

THE KNOPP INSTRUMENT TRANSFORMER COMPARATORS

Description

Knopp transformer comparators provide a direct means of measuring phase angle and ratio errors of instrument transformers. These comparators use a refined null method. The procedure is a four-step process: interconnection, precheck, null, and test results.

During precheck, the test connections, transformer integrity, dial zeroing, secondary output, and power source level are verified simultaneously. Then an appropriate multiplier is selected and the null established with two calibrated dials. The results, phase angle and ratio error, are read directly from these dials.

Null Method

The current and voltage comparators measure a transformer's ratio and phase errors with respect to a standard transformer. The following discussion of the current comparator illustrates the principles applying to the voltage comparator as well. The quantities being measured by the current comparator are best described by use of the vector diagram in Figure 11-37. I_S represents the secondary current in the standard transformer, I_X represents the secondary current in the transformer under test, and I_E is the resulting error current. If the transformer under test were identical to the standard, I_E would be zero. If the vector I_E can be resolved into its in-phase and quadrature (90°) components, the desired quantities (ratio error and phase angle) are produced. For errors which are encountered in most instrument transformers, I_Q is essentially identical to the arc represented by β (phase angle) and I_R is equal to R (ratio error). The purpose of the comparator is to resolve this vector error into its in-phase and quadrature components.

The simplified circuit diagram of the current transformer comparator is shown in Figure 11-38. The transformer secondaries are connected in series to provide current flow as illustrated.

A portion of the error current I_E is allowed to flow through the in-phase and quadrature networks and the null detector. The two networks allow two other currents to flow in this same path. One is in phase with I_S and the other is in quadrature with I_S. The magnitudes of these currents are varied by potentiometers R and Q until the portion of I_E originally injected is cancelled. This cancellation is indicated by a null on the null detector meter. The resulting positions of the potentiometers are translated into ratio error and phase angle by reading the calibrated dials attached to the potentiometer shafts.

Although the circuit details for the voltage comparator differ, the approach is fundamentally the same. That is, the vector error is resolved into its in-phase and quadrature components.

Knopp comparators can be supplied with an accessory unit that presents a digital display of phase angle and ratio error (in percent or ratio correction factor) selectable with a front panel switch.

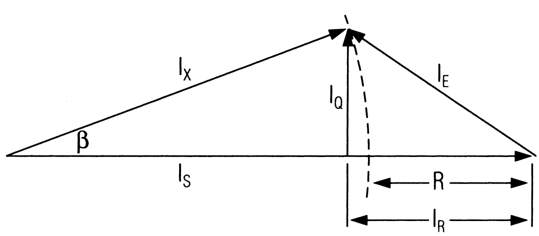


Figure 11-37. Quantities Measured by Current Comparator.

Use of Compensated Standard Method to Calibrate a Current Transformer Test Set

This method may be used to check the calibration of the Silsbee current transformer test set or the Knopp current transformer comparator or other direct-reading test sets. To do this, a window-type standard current transformer having a 5:5 or 1:1 ratio is set up with the line to the standard circuits of the test set and the secondary to the secondary circuits of the test set (Figure 11-39). With no tertiary current the set should read the error of the standard current transformer on the 5:5 range with the burden used. By applying in-phase and quadrature-phase tertiary ampere-turns the standard current transformer may be compensated to have any apparent ratio and phase angle desired. These values may be calculated from the original one-to-one test and the formulas in Figure 11-38. The readings of the test set at balance are then compared with the calculated values.

This method provides a useful check on the accuracy of the test sets. The formulas are approximations based on the assumption of small angles and can introduce slight errors when the phase angle exceeds 60 to 120 minutes.

Precautions in Testing Instrument Transformers

Stray Fields

In instrument transformer testing, precautions must be taken to prevent stray fields from inducing unwanted voltages in the test circuits. Secondary leads are usually twisted into pairs to prevent this. When test equipment is not shielded it must be kept well away from conductors carrying heavy current.

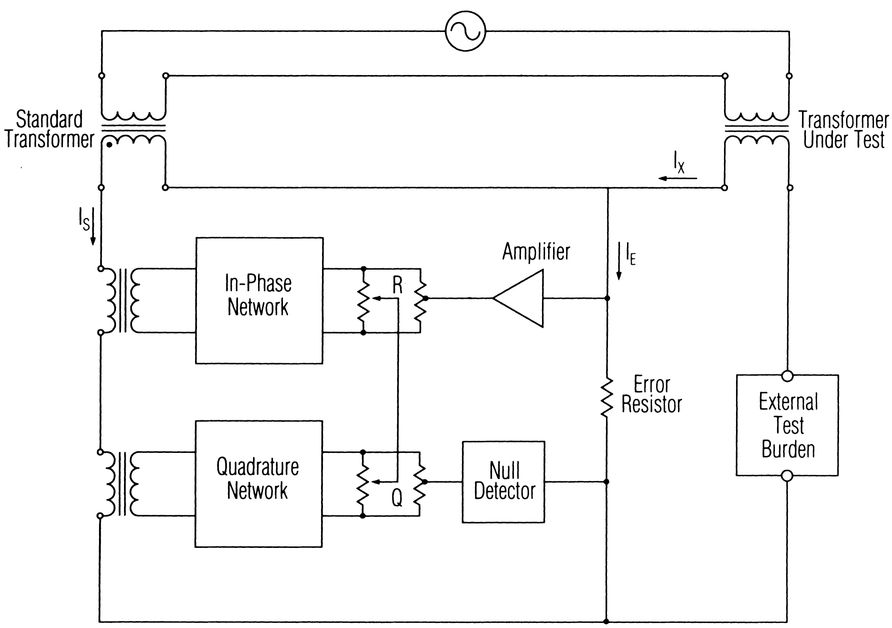
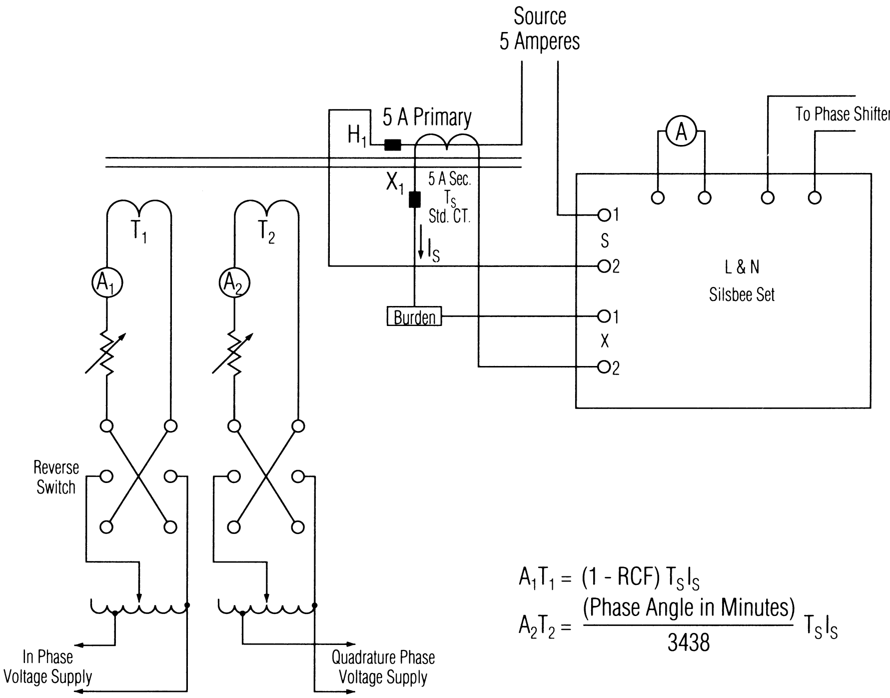


Figure 11-38. Simplified Circuit Diagram of Knopp Current Transformer Comparator.



$$A_1T_1 = (1 - RCF)\, T_S I_S$$

$$A_2T_2 = \frac{(\text{Phase Angle in Minutes})}{3438}\, T_S I_S$$

Figure 11-39. Use of Compensated 1:1 Standard to Calibrate Silsbee Set.

Effect of Return Conductor

The location of the return conductor in a heavy-current primary loop can affect the ratio and phase angle of a CT. Normally the return conductor should be kept two or three feet away from the CT under test. This effect is most pronounced where the primary current is large.

In winding down a window-type current transformer for test, tight loops may give a different result than open loops due to the return-conductor effect. Since normal operation is on a straight bus bar, the results obtained with the open loops will be more comparable to the field conditions.

Demagnetizing

Current transformers should be demagnetized before testing to ensure accurate results. Demagnetization may be accomplished by bringing the secondary current up to the rated value of 5 amperes by applying primary current and then gradually inserting a resistance of about 50 ohms into the secondary circuit. This resistance is then gradually reduced to zero and the current is reduced to zero. CAUTION: Avoid opening the secondary circuit at any time during this procedure. A reactor in place of the resistor reduces the possibility of re-magnetizing by accidentally open-circuiting during the procedure.

Today, equipment is available, such as the Transformer Analyzer shown in Figure 11-36, that not only performs current transformer admittance and burden tests, but also provides a safe and easy way to demagnetize.

A current transformer can be magnetized by passing direct current through the windings, by surges due to opening the primary under heavy load, or by accidental opening of the secondary with load on the primary. Test circuits should provide for a gradual increase and decrease of primary current to avoid surges.

Modern high-accuracy current transformers show relatively little change in accuracy due to magnetization.

Ground Loops and Stray Ground Capacitance

In all instrument transformer testing care must be taken to avoid ground loops and stray ground capacitance that might cause errors. Usually only one primary and one secondary ground are used. The location of these grounds must be carefully determined to avoid errors.

Effect of Inductive Action of Silsbee Galvanometer in Testing Small Current Transformers

In the Silsbee current transformer test set the galvanometer field coil and the galvanometer moving coil form, in effect, a small transformer. When the field coil is energized a small voltage is induced in the moving coil. The moving coil is connected in the differential circuit between the secondaries of the standard and unknown transformer and therefore the effect of this induced voltage is to cause a small current to flow in these circuits.

The effect of this current in the galvanometer moving coil is to cause a deflection that is not due to the differential current. This deflection is compensated by means of the electrical zero adjustment which consists of a movable piece of iron which distorts the field flux. In effect the electrical zero adjustment produces a false zero which eliminates the unwanted deflection of the galvanometer.

When this electrical zero adjustment has been made according to the instructions for the Silsbee set, it normally makes no difference in the results if the polarity of the leads from the phase shifter to the galvanometer field of the Silsbee set is reversed. In testing miniature current transformers it has been found that a difference as high as 0.1% at 10% current may be found when the galvanometer field is reversed. It appears that this is due to a large difference in impedance between the secondaries of the standard and unknown current transformers. The current set up by the induced voltage in the galvanometer does not divide equally and this effect is not entirely eliminated by the electrical zero adjustment.

It has been found that the average of the readings with direct and reversed galvanometer fields agrees with the results obtained when using a cathode-ray oscilloscope and matching transformer as a detector.

Accuracy

Accurate testing of instrument transformers requires adequate equipment and careful attention to detail. Readability to 0.01% and 0.5 minute phase angle is easily possible with modern equipment, but accuracy to this limit is much more difficult. For the greatest accuracy, the test equipment and standard instrument transformers should be certified by the NIST or by a laboratory whose standard accuracies are traceable to the NIST. With the greatest care, absolute accuracies in the order of 0.04% and 1 to 3 minutes phase angle may be achieved.

OPTICAL SENSOR SYSTEMS

INTRODUCTION TO OPTICAL SENSORS

Measurements of voltage and current are fundamental to revenue metering and control of the electric power system. Since the latter half of the 19th century, this function has been addressed primarily by using wound iron-core transformers. The accuracy, stability, and reliability of these devices are excellent and one should expect that they would continue to be used in the future.

Nonconventional optical methods for making voltage and current measurements have been reported in the literature for many years. While sensor concept demonstrations date back to the early 1960s, the challenge has remained to transition optical sensors from the laboratory into hardened commercial devices that meet stringent utility standards outlined by IEEE/ANSI or IEC standards documents. Today, optical current and voltage sensor products are commercially available with metering class accuracy. This section compares the similarities and contrasts the differences between conventional wound iron-core transformers and optical voltage and current sensor systems, to enable the use of nonconventional sensors in metering installations.

There are five key reasons for considering optical sensors in metering applications:

1. Oil-free insulation in the high voltage equipment;
2. The ability to measure currents with high accuracy over a wide dynamic range;
3. Complete galvanic isolation between the high voltage conductor and electronic equipment;
4. The ability to accurately measure over a wide frequency bandwidth to monitor the harmonic content of power line waveforms;
5. A small, lightweight form factor that enables greater flexibility in locating and mounting a sensor within an existing or new substation.

Each of these points is discussed in more detail below.

Oil-Free Equipment

Optical sensors typically use gas insulation or slender solid-core insulators. By removing insulating oil from the design, the utility avoids oil maintenance regimens, possible oil spills, and potentially catastrophic damage to substation equipment in the event of violent disassembly that is often associated with oil-insulated equipment.

Dynamic Range

There are many metering locations that require high accuracy over a wide range of currents. For example, the tie between a generation plant and a transmission line must be metered accurately at full load currents (e.g., 2,400 amps) when the generator is running at capacity. However, when the plant is idle or shut down, often a few amperes flow from the transmission line to keep the lights on in the plant. A single optical current sensor is able to measure these currents with metering accuracy.

Both optical voltage and current sensors provide sufficient dynamic range to support protection applications as well. For example, the metering class current sensor described above can also measure fault currents in excess of 50 kA and meet all of the protection accuracy requirements. This creates the opportunity to share the output of a single sensing system between metering and protection equipment, lowering total substation costs.

Galvanic Isolation

As shown in Figure 11-40, an optical sensor typically has a sensing structure located at or near the high voltage line. Optical fibers carry information about the measured voltage or current to ground potential, through conduit, and into an interface electronics chassis usually located in a control house. There is no electrical connection between the high voltage equipment and the interface electronics, resulting in complete galvanic isolation between the high voltage line and the control room electronics. This factor becomes increasingly important as measurement and control equipment for the power system becomes more electronic in nature. For these systems, the ability of optical sensors to “disconnect” the control room electronics from the hazards presented by the power system in the form of voltage transients is a major factor in increasing reliability. A related benefit of galvanic isolation is the lack of interaction between the sensor and the measured parameter. Issues such as ferro-resonant conditions, caused by the interaction of iron core devices and capacitance, are non-existent with optical designs.

Wide Frequency Bandwidth

As power quality monitoring becomes increasingly important, the ability to accurately monitor harmonic content up to the 100th harmonic is becoming more desirable. Available optical sensors with signal bandwidths in excess of 5 kHz fulfill this requirement.

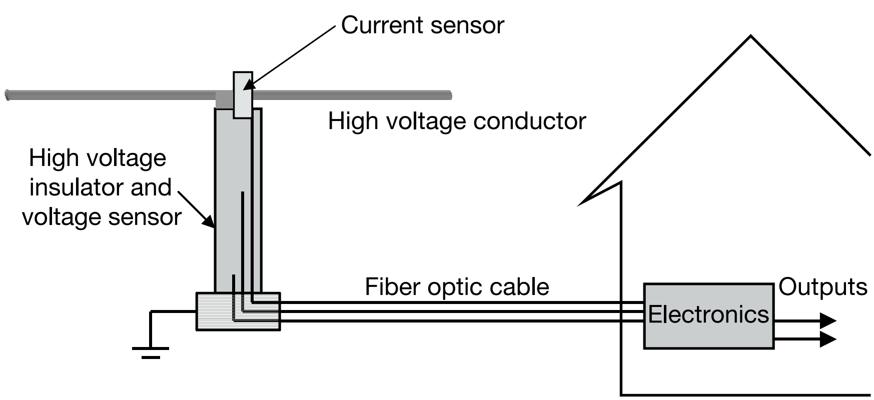


Figure 11-40. Schematic Diagram of Optical Current and Voltage Sensors.

Small, Lightweight Form Factor

For most optical designs, the equipment is significantly smaller and lighter than could be achieved with conventional wound iron-core insulation systems. The equipment requires less space in the substation and the amount of labor and equipment needed for installation is reduced. This lowers the total cost of ownership. Figure 11-41 depicts an example of a retrofit installation of optical current sensors into a 72 kV generator substation. Figure 11-42 depicts an example of optical voltage and current sensors (combined units) installed in a 362 kV substation. Figure 11-43 shows a 123 kV combined unit. Optical sensor elements, by virtue of their small size and weight, could be integrated into existing substation equipment such as circuit breakers and switches.

Figure 11-41. 72 kV Magneto-Optic Current Transducers at Substation.

Figure 11-42. 362 kV Optical Metering Units at Substation.

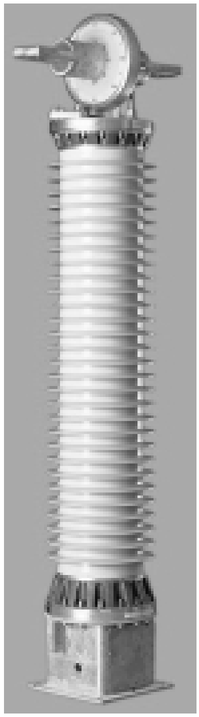


Figure 11-43. 123 kV Optical Metering Unit Prototype.

OPTICAL CURRENT SENSORS

Three broad classes of optical current sensors exist, where 'optical' refers to the use of optical fiber to convey measurands from high voltage to ground potential. As shown in Figure 11-44a, the bulk optic sensor uses a block of glass that surrounds the high voltage conductor. Light from an optical fiber travels inside the block in a closed path around the conductor, and is subsequently collected by a second optical fiber. Several manufacturers sell this type of current sensor. A large number of equipment years have been accumulated using this approach.

The second class of sensors, shown in Figure 11-44b, consists of multiple loops of optical fiber that encircle the conductor. In these all-fiber current sensors, light remains within the fiber at all times, and the light makes multiple trips around the conductor. There are several manufacturers of this design, with a small number of equipment years of experience.

In the third class of sensors, known as hybrid optical current sensors and shown in Figure 11-44c, a conventional current transducer such as an iron core surrounds the conductor (an air-core Rogowski coil, resistive shunt or other non-optical technology could also be used). For the case of an iron core, a secondary coil on the core generates a current that is proportional to the primary conductor current, in a manner identical to conventional current transformers. The secondary current is locally digitized and subsequently transmitted in serial fashion in an optical fiber that spans from the high voltage conductor to ground potential. Because electronics are present at the high voltage conductor, electrical power must be supplied to the sensor head. Commercial devices use a high power (>100 mW) infrared laser diode coupled into an optical fiber to carry optical power from ground potential to the sensor head. Efficient GaAs photocells convert the received optical power into electrical power to energize the electronics in the sensor head. The hybrid approach has been implemented for capacitor bank protection applications with many equipment years of experience. Several vendors are expecting to provide metering class accuracy.

The exterior appearances of all three classes of current sensors are more or less identical. A lightweight (<100 pounds) sensor pod is located at the high voltage conductor, and one or more optical fibers are brought from high voltage to ground using some form of post insulator, suspension insulator or shedded cable. In all three cases, an electronics chassis, usually located in the control house, supports the generation and detection of the optical signals affiliated with one or more three-phase sets of sensors.

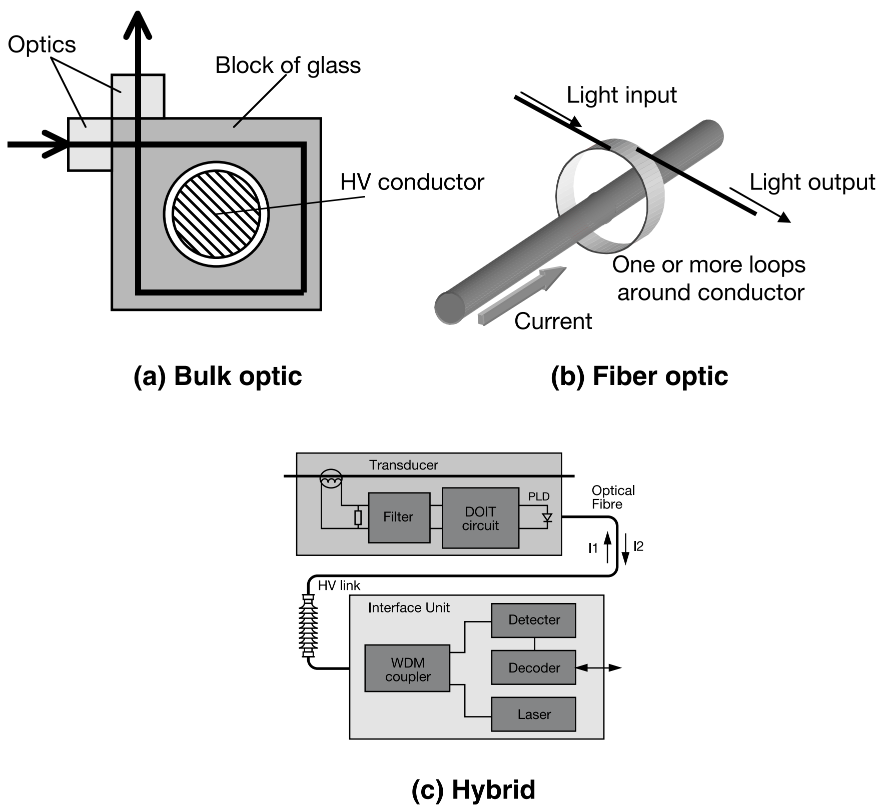


Figure 11-44. Optical Current Sensors.

The current sensor interface chassis can have several output signals, including;

1) Low-voltage analog output representation of the primary current;
2) Ampere-level current output representation of the primary current;
3) Digital parallel or serial output representation of the primary current.

The low voltage analog output can have various ratios, but many applications typically use a 2 Vrms or 4 Vrms output to represent nominal primary current. For example, an optical sensor with a marked ratio of 2400A:2V would generate a 2 Vrms output voltage when 2400 Arms are carried in the primary conductor.

The current output uses a Transconductance amplifier to generate an output current. The output current is usually specified in a manner identical to that found for conventional current transformers, although the output currents are typically 1 ampere at nominal primary current instead of the more common 5 ampere at rated primary current found with conventional current transformers. For example, an optical current sensor with a marked ratio of 2400:1 provides an output current of 1 Arms when 2400 Arms are flowing through the primary conductor. Since the compliance voltage of the amplifier can be limited through careful design, safety concerns surrounding open secondary windings of current transformers can be completely eliminated.

The digital interface is mentioned for future consideration, once interface standards have been selected and manufacturers of meters and optical sensors provide products that conform to these standards.

Optical sensor manufacturers can provide multiple outputs with different ratios using one sensing head. For example, a single optical current sensor at high voltage can provide a low voltage analog output of 2400A:2V for monitoring applications, a low voltage analog output of 2400A:0.2V for relaying or protection applications, and a current output (2400:1) for metering applications. Some manufacturers can provide two current outputs (2400:1 and 100:1) for metering applications.

SENSING MECHANISM IN OPTICAL CURRENT SENSORS

The bulk optic and all-fiber current sensors exploit the Faraday Effect and Ampere's Law to provide precision measurements of current. From basic Electromagnetic theory, Ampere's Law states that

$$\mathrm{i} = \oint \vec{\mathrm{H}} \bullet \vec{\mathrm{dl}}$$

where i is the current enclosed by the loop integral and H is the magnetic field present in the region of integration. Note that the path of integration does not matter, provided that it makes one or more complete closed loops around the primary conductor. The magnetic field is generated by electrical currents in the vicinity of the sensor. However, the integral is precisely equal to only the currents enclosed by the integration path.

The Faraday Effect describes a change in the refractive index of a material when exposed to a magnetic field. The change in refractive index causes the speed of light to be affected in the material. This variation can be detected by using Polarimetric or Interferometric methods. With the polarimetric approach shown in Figure 11-45, the Faraday Effect changes the polarization state of an optical beam in proportion to the magnetic field parallel to the optical beam path. The total rotation of the plane of polarization for linearly polarized light when the optical path encircles a conductor carrying current I is $\theta = \mu\mathrm{VNi}$, where N is the number of round trips traveled by the optical beam around the encircled

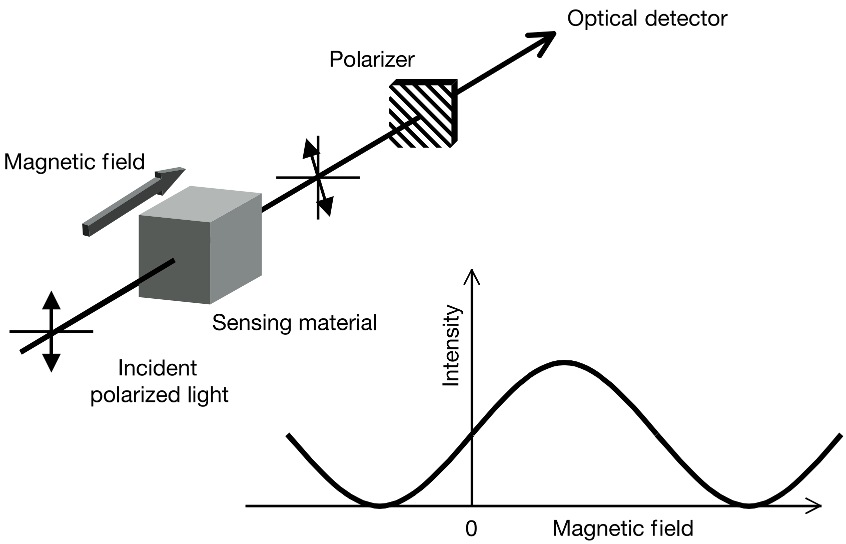


Figure 11-45. Polarimetric Optical Current Sensor.

conductor, V is the Verdet constant of the material, and μ is the magnetic permeability of the material. The change in polarization is detected using a linear polarizer, resulting in a signal that varies with the current.

With the interferometric approach, light traveling through the sensing material having one refractive index is interfered with another optical signal that experiences a different refractive index. In Figure 11-46, the two optical signals have orthogonal polarization states as they make one round trip through the fiber. When they interfere in the fiber polarizer, the optical phase shift between the two interfering waves generates an intensity variation at the detector. The detected signal varies with the strength of the applied magnetic field in the sensing fiber. By encircling the conductor with the optical path, an output signal is created that varies with the strength of the current in the encircled conductor.

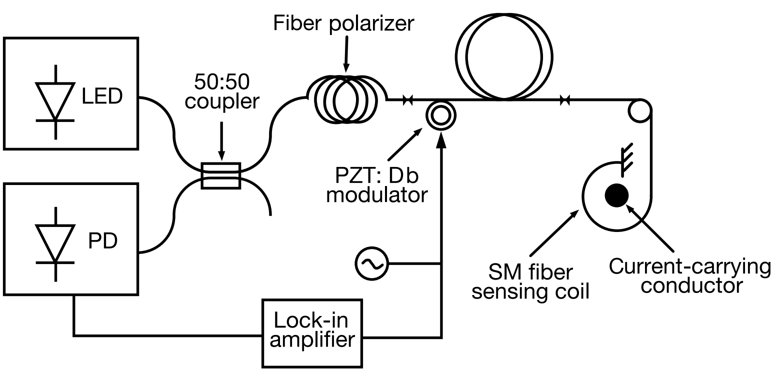


Figure 11-46. Interferometric Current Sensor.

The optical path in the sensor material must follow a closed path about the conductor, yet introduce no unwanted linear optical birefringence (a variation in the refractive index of a material with direction that changes the state of polarization) into the beam. Several methods are commercially used to accomplish this. The bulk optic sensor uses a block of glass that has been machined, finely annealed to remove linear strain birefringence, and optically polished. A curved reflector or lens is used to collimate the optical beam leaving an optical fiber. The collimated beam passes through a linear polarizer and enters the main sensor block. At each corner of the sensor block a pair of mirrors deflect the beam 90°. The complementary mirror pair is required to maintain the polarization state of the light at each right angle bend in the sensor. After making a single round trip in the glass, the beam is passed through a second polarizer and focused by a parabolic reflector or lens onto a receiving optical fiber. A large hole in the middle of the block permits the passage of the conductor through the optical loop formed in the sensor material. Precision machining of the block is required to maintain accurate alignment between the two multimode fibers.

The all-fiber sensor uses the fiber itself as the Faraday material. Single mode fiber is used, and strain-induced optical birefringence must be minimized or overwhelmed by other birefringence in order to construct a useful sensor. This is accomplished by using finely annealed single mode fiber or a deliberately twisted or spun single mode fiber. In all cases, the fiber must be carefully mounted in strain-relieving packaging to avoid temperature or vibration effects. With this approach, incident light can make many complete loops around the primary conductor, increasing the signal intensity at the receiver electronics. The modulated light can be reflected from the end of the fiber, recombined with the incident light in a coupler, or carried by a separate fiber. The fiber loop diameter can be adjusted to match the application requirements. As we will see shortly, the ability to create multiple optical loops around the conductor is important since the signal levels generated by useful Faraday materials are very small.

OPTICAL VOLTAGE SENSORS

Whereas optical current sensors have enjoyed power metering field use since 1986, optical voltage sensors are relatively new to the power-metering world. Three broad classes of optical voltage sensors exist, where 'optical' refers to the use of optical fiber to convey measurands from high voltage equipment to the control house.

As shown in Figure 11-47a, the electro-optic voltage sensor uses a cylindrical single crystal rod connected between high voltage and ground. Light from an optical fiber travels inside the rod between ground and high voltage, and is subsequently collected by a second optical fiber. A gas dielectric such as sulfur hexafluoride provides insulation around the rod. One manufacturer sells this type of voltage sensor, both for air-insulated and gas-insulated substation applications. A small number of equipment years have been accumulated using this approach.

The capacitive divider optical voltage sensor forms the second class of sensors. Shown in Figure 11-47b, it consists of a glass cylindrical rod connected electrically in series with a short single crystal rod. Light from an optical fiber travels inside the short crystalline rod, and is subsequently collected by a second optical fiber. A gas dielectric such as sulfur hexafluoride provides insulation around the two rods. The glass rod and the crystalline rod form a capacitive divider to reduce the primary high voltage to a value that can be measured optically using the short crystalline rod. The two rods are placed within a metallic pressure vessel to control the electric field distributions in the rods and contain the high-pressure dielectric insulation gas. One manufacturer offers this type of voltage sensor. A small number of equipment years have been accumulated using this approach.

In the third class, the distributed optical voltage sensor shown in Figure 11-47c, several optical point sensors are placed between high voltage and ground in a shedded high voltage insulator. Optical fibers carry light to and from the optical sensors. The vertical component of the electric field is measured at these points and the measurements are combined to estimate the potential difference between high voltage and ground. A gas dielectric such as nitrogen provides insulation around the sensors. One manufacturer offers this type of voltage sensor.

The exterior appearances of all three classes of voltage sensors are more or less identical. A hollow insulating column is located between the high voltage line and ground. The bottom of the column connects to a metallic enclosure. For the electro-optic voltage sensor, the optical sensor is placed inside the center of the insulator, and high voltage and ground electrodes are brought to the sensor from the ends of the column. The metallic enclosure at the base provides a means of containing and protecting the optical fiber connections and any monitoring equipment desired (typically a gas density alarm). The capacitive divider optical sensor is mounted in a metallic housing located at the base of the insulator. The distributed optical voltage sensor has optical sensors located along the inside of the column. The metallic enclosure at the base provides a means of containing and protecting the optical fiber connections and any monitoring equipment desired. In the first two cases, the column is pressurized with sulfur hexafluoride gas to ensure dielectric integrity. In the third case, the column is pressurized with dry nitrogen to preserve accuracy.

In all three cases, an electronics chassis, usually located in the control house, supports the generation and detection of the optical signals affiliated with one or more three-phase sets of sensors.

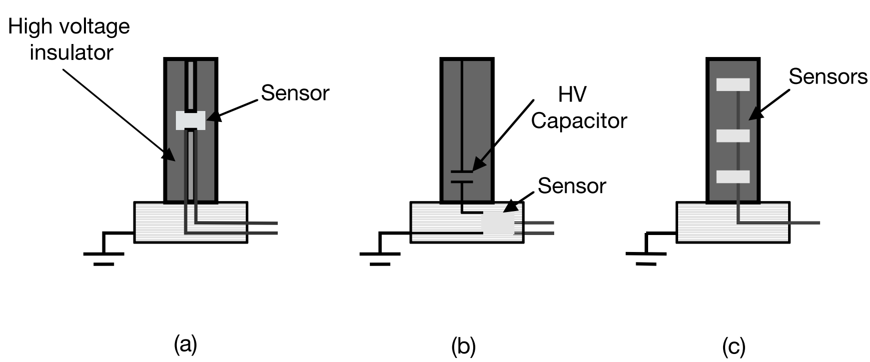


Figure 11-47. Schematic Diagrams of Three Different Optical Voltage Sensor Techniques.

The output of the voltage sensor interface chassis can have several output signals, including;

1. Low-voltage, low-burden analog output representation of the primary voltage;
2. Higher-voltage, higher-burden analog output representation of the primary voltage;
3. Digital parallel or serial output representation of the primary voltage.

The low-voltage analog output can have various ratios, but metering applications typically use a 4 Vrms output to represent nominal primary voltage. For example, an optical sensor with a marked ratio of 16,600:1 generates a 4 Vrms output voltage when the primary conductor is at 66,400 Vrms line to ground.

The higher-voltage output uses a voltage amplifier to generate an output voltage of 69 Vrms or 120 Vrms at rated primary voltage, with a burden capability of 10 VA – 100 VA. The output voltage is usually specified in a manner identical to that found for conventional voltage transformers, although the output burdens are typically <100 VA instead of the more common >100 VA burdens found with conventional voltage transformers. For example, an optical voltage sensor with a marked ratio of 1000:1 provides an output voltage of 69 Vrms when the primary conductor is at 69,000 Vrms.

The digital interface is mentioned for future consideration, once interface standards have been selected and manufacturers of meters and optical sensors provide products that conform to these standards.

Optical sensor manufacturers can provide multiple outputs with different ratios using one sensing column. For example, a single optical voltage sensor for use on a 115 kV three phase power line can provide a low voltage analog output of 16,600:1 for monitoring, relaying or protection applications, and a higher voltage output with a ratio of 2900:1 for metering applications.

SENSING MECHANISMS IN OPTICAL VOLTAGE SENSORS

From basic Electromagnetic theory, the voltage or potential difference is defined by

$$V_b - V_a = \int_a^b \vec{E} \bullet \vec{dl}$$

where E is the electric field vector, dl is the differential length of the integration path and V_a and V_b are the potentials at points a and b. Note that the integral is independent of the integration path, magnitude or direction of the electric field. The three optical voltage sensor designs approximate the integral shown above. In all three cases, the Pockels Effect in an electro-optic crystal is used. The variation in the polarization state of light traveling through an electro-optic crystal or Pockels cell is almost always linearly proportional to the local electric field vector. In addition to fast response compared with the measurement bandwidth desired, the response of the correctly selected material is relatively immune to other environmental effects such as temperature, magnetic fields, vibration, steady-state stress or strain, etc.

In all existing voltage sensor systems, the polarimetric technique is used to measure the optical phase shift induced by the applied voltage V_{b-a}. Linearly polarized light traversing an electro-optic crystal generates an intensity-modulated signal after passing through a quarter-wave wave-plate and a linear polarizer. The signal varies according to

$$I_m = \frac{I_o}{4}\{1 + \sin(\pi \frac{V_{b-a}}{V_\pi})\}$$

where I_o is the incident unpolarized optical intensity and V_π is a measure of the modulation efficiency of the electro-optic material.

The three voltage sensor designs use this measurement approach in slightly different ways. The electro-optic voltage sensor connects high voltage directly to one end of the crystal, and ground to the other end of the crystal. The optical signal generated by the sensor is directly proportional to the applied voltage difference. However, because the line voltages are typically much larger than V_π, a number of 'fringes' result in the output signal as the voltage increases or decreases with time. Signal processing is used to translate these fringing signals into a representation of the primary voltage. Since the line voltage and ground are applied directly to the crystal, the Pockels cell is insensitive to the electric field distributions surrounding it. For example, the Pockels cell can be located inside a hollow insulator pressurized with sulfur hexafluoride gas for dielectric insulation.

The capacitive divider sensor design connects the Pockels cell in parallel with the lower leg C_2 of a capacitive divider. The voltage imposed across the Pockels cell is then proportional to the primary voltage through the capacitive divider relation

$$V_{b-a} = V_{primary}\left\{\frac{C_1}{C_1 + C_2}\right\}$$

where C_1 is the high voltage capacitor (<50 pF), C_2 is the much larger low voltage capacitor, and C_2 is assumed to be much larger than the capacitance of the Pockels cell. If the capacitors C_1 and C_2 are stable and the electric field distribution in the region of the two capacitors is stable, then the resulting optical signal is proportional to the primary high voltage. Normally the capacitive divider is located in a grounded, metallic vessel to control the field distributions at the divider and provide dielectric insulation using pressurized sulfur hexafluoride gas.

The distributed voltage sensor uses multiple Pockels cells to measure the electric field at different locations along the high voltage insulator. Each Pockels cell measures a voltage drop that depends on the electric field strength in the local region of the cell, the dielectric properties of the materials from which the cell is fabricated, as well as the shape of the cell. This design is very sensitive to the shape of the electric field distribution between high voltage and ground. Selecting the locations of the cells and adding field-shaping resistors reduce the system's sensitivity to the field distribution. With signal processing to combine the sensor signals, a representation of the primary voltage is created.

UNIQUE ISSUES FOR OPTICAL SENSORS

Optical current and voltage sensors are radically different from conventional wound iron core current and voltage transformers, yet they must conform to existing utility standards and user expectations if they are to be installed. The standards to which instrument transformers must adhere must be carefully applied to optical sensors. Some of the quantitative requirements for instrument transformers exist because of known failure mechanisms. For example, the maximum temperature rise of a current transformer is set in part by the known rapid decomposition of high-voltage insulation (paper, polymer and oil) when a maximum operating temperature is exceeded for certain periods of time. Optical sensors will have similar maximum operating temperatures, but they may differ from those of conventional current transformers because of the different design used. Other requirements easily met by conventional transformers are more difficult challenges for optical sensors. For example, the maximum allowed ratio calibration factor (RCF) deviation over a wide operating temperature range is easily met by conventional instrument transformers—due to the intrinsic nature of their design. With optical sensors, however, the sensing elements, packaging materials, fiber optic cables and interface electronics all have temperature dependencies that must be controlled or removed. The unique characteristics of optical sensors that should be carefully assessed are discussed below.

Accuracy over Temperature

The Faraday Effect in materials used for optical current sensors has an intrinsic variation of about 0.7 to 1.5% per 100°C. If every other part of the optical current sensor functions perfectly, this temperature dependence remains. The Pockels cells normally used in optical voltage sensors also have temperature dependencies of 1.5% per 100°C.

The temperature dependence of the sensor element is compensated using three techniques. The first approach, known as passive temperature compensation and used in the bulk optic current sensor and capacitive divider voltage sensor, introduces a second temperature dependence in the optical path at the sensor head which compensates the temperature dependence of the Verdet constant or the Pockels Effect. The resulting sensor heads typically display ±0.2% RCF variations from −55 to +85°C, which is suitable for revenue metering.

A second approach, known as active temperature compensation, measures the temperature at or near the sensor, estimates the actual sensor temperature and electronically corrects the system output. This method is employed in the electro-optic voltage sensor and the all-fiber current sensor.

The third approach, known as hybrid temperature compensation, measures a secondary parameter of the Pockels cell or the current sensor head by processing the optical signals returned to the receiver electronics. The estimate of the temperature at the sensor is then used to electronically correct the system output. This approach is used in the all-fiber current sensor and the distributed optical voltage sensor.

The system accuracy also depends on the calibration accuracy of the interface electronics over temperature. Many installations, although provided with a control house for weather protection, are not temperature controlled. Installations will generally involve mounting of the electronics in a rack or enclosure, where temperatures can rise 30°C above ambient. The light sources, power amplifiers, photodiodes, low noise analog amplifiers, analog to digital and digital to analog converters all have critical parameters that vary with temperature.

The optical losses of optical fiber cables and connectors also vary over temperature and time. The interface electronics are normally designed to accommodate some variations in optical insertion loss while maintaining accuracy.

Temperature compensation is a routine test for optical voltage and current sensors. This is never included in the routine test report of a conventional instrument transformer. Normally, the sensor head is temperature cycled while the electronic receiver is kept at a fixed temperature, or synchronously cycled over a reduced temperature range. The range of testing temperatures is important, but typically should include −50°C to +90°C. For example, a sensor head mounted in the Southwestern United States can experience an ambient temperature of 50°C, combined with a 5 to 15°C solar load and a thermal rise of 15 to 30°C due to rated primary current flow of 2400 Amps. In this steady state condition, the sensor head could experience temperatures exceeding 90°C. Likewise, an installation in Northern Maine or Canada may have a primary current of 20 Amps, an ambient temperature of −50°C and a wind velocity of 30 mph. Following this temperature cycle, the electronics chassis can be temperature cycled while the sensor head is kept at a fixed temperature. Typically, an industrial temperature range of −40°C to +70°C is used for this temperature cycle. Compensation must be verified on every system and documented in the routine test report provided by the manufacturer.

Dynamic Range and Noise of Optical Current Sensors

Optical current sensors can maintain accuracy over a wide dynamic range of currents. This characteristic merits attention, since the signal-to-noise ratio of an optical current sensor output is typically poorer than a conventional current transformer. This is caused by the presence of white noise superimposed on the current measurement. The effects of this noise must be carefully considered for metering applications.

Many optical current sensors use fused silica as a sensing material, which provides an optical modulation (for near-infrared light) of approximately $I_m / I_o = 1 - 5 \times 10^{-6}$ per Amp-turn, where turn refers to the number of turns taken by the optical path around the primary conductor. Usually the light is sent in both directions around the conductor, which doubles the sensitivity to $2 - 10 \times 10^{-6}$ per Amp-turn. This is a small modulation depth, and typically a single turn, double-pass optical current sensor provides a noise floor on the interface electronics output of 0.05 to 0.3 Arms/(Hz)$^{0.5}$ of primary current. With a noise-equivalent bandwidth of 5 kHz, this represents a noise floor of 3 to 20 Arms. Since this is usually Gaussian white noise, the full-bandwidth primary current indicated by the optical current sensor output never drops below 3 to 20 Arms, creating measurement errors at low primary current levels when using a wide-bandwidth ammeter.

The all-fiber current sensor has the ability to complete multiple closed optical loops around the primary conductor by simply looping more optical fiber around the conductor. For an N-turn all-fiber optical sensor, the noise floor is reduced by a factor of N. For example, a typical all-fiber current sensor with N=20 fiber turns provides a noise floor equivalent to 0.15 to 1 Arms of primary current.

The trade-off occurs when considering large currents. The single turn sensor can accurately measure currents as large as 400 kA peak when proper signal processing is included in the interface electronics. This is suitable for all relaying and protection applications. For the N=20 all-fiber current sensor, the largest currents that can be measured are reduced to 20 to 40 kA peak, which is insufficient for many relaying and protection applications. For all-fiber optical current sensor applications that require both metering and protection functions in one system, three choices are available:

1. A trade-off is made on the number of optical turns N to meet both needs;
2. Two separate optical fiber loops with different values of N are included in one sensing head to meet both requirements;
3. Additional signal processing is included in the interface electronics to accommodate a larger dynamic range.

Evidently there is a large improvement in the noise floor when using an all-fiber current sensor with multiple turns of optical fiber. However, even this performance is not sufficient to accurately monitor very small primary currents using a wide-bandwidth ammeter. When used for metering applications, the noise may or may not be an issue, depending on how the selected meter calculates power, and what power flow parameters are of interest.

A power meter can be considered a synchronous detector if the meter performs a multiplication of real-time or time-shifted current and voltage waveforms and integrates the result over some period of time. The integration process narrows the effective bandwidth of the meter, and the multiplication prior to integration effectively removes contributions from any frequency components that do not simultaneously and synchronously exist in both the current and voltage waveforms. This type of meter can provide excellent power metering accuracy even with a poor signal to noise ratio on the output of the optical current or voltage sensor. One manufacturer reported maintaining 0.2% metering accuracy when the primary current signal was ten times smaller than the noise floor of the optical current sensor. The ability to effectively average through the noise depends, however, on the detailed signal processing carried out by the meter.

Meters that compute the rms values of current and voltage separately and then multiply the two results to calculate apparent power will not average out the contributions from the noise, and erroneous apparent power and active power readings will result. Depending on the algorithm used to determine power factor, erroneous power factor readings may also result.

Some electronic meters calculate power quantities by multiplying the instantaneous voltage and current and averaging over time, and separately calculate the voltage and current rms values. These meters can provide correct power readings, but display erroneous voltage and current values, depending on the noise present on the voltage and current waveforms. This can lead to very confusing situations.

The proposed standard IEEE 1459-2000 provides a way to describe the effect of noise on the reported power flows measured by a meter that calculates rms values of voltage and current before multiplying these values to calculate apparent power. Although specifically fashioned to quantify harmonic and non-harmonic power flows on the power system, it is directly applicable to the case at hand. The voltage and current waveforms have rms values V and I, with total harmonic distortion levels defined by $THD_V = V_H / V_1$ and $THD_I = I_H / I_1$, where V_1 and I_1 are the fundamental (60 Hz) voltage and current rms values, and V_H and I_H are the non-fundamental voltage and current rms values, including all integer and non-integer harmonics (i.e., noise). The apparent power that results (a single-phase analysis is used for simplicity) is

$$S^2 = (VI)^2 = S_1^2 + S_1^2 = S_1^2 + D_I^2 + D_V^2 + S_H^2$$

where S is the total apparent power, S_1 is the fundamental (60 Hz) apparent power, D_I is the current distortion power, D_V is the voltage distortion power, $S_H = S_1\ (THD_V)(THD_I)$ is the harmonic apparent power and S_N is the non-fundamental apparent power. The distortion powers are given by $D_V = S_1\ THD_V$ and $D_I = S_1\ THD_I$. For distortion-free current and voltage waveforms, $D_V = D_I = S_H = 0$ and the apparent power $S = S_1$, as expected.

When noise generated by the sensor is included but limited to THD_V <5% and THD_I <200%, then the total apparent power S can be approximated by

$$S^2 \approx S_1^2\left[1 + (THD_V)^2 + (THD_I)^2\right]$$

Similarly, for THD_V <5%, THD_I <40%, and assuming that current waveform distortions dominate over other sources of distortion, the power factor P_F can be approximated by

$$P_F \approx \frac{P_{F1}}{\sqrt{1 + (THD_I)^2}}$$

where P_{F1} is the fundamental (60 Hz) power factor.

For a meter that calculates the rms values of voltage and current separately before calculating the total apparent power, both results will have considerable error as the noise levels on the voltage and current waveforms increase. Three examples are given here.

1. An undistorted primary voltage of 200 kVrms is monitored by an optical voltage sensor with noise, creating a THD_V = 1%. An undistorted primary current of I_1 = 50 Arms is monitored by a bulk optic current sensor with a noise floor of 20 Arms, giving a THD_I = 20/50 = 40%. The apparent power reported by the meter will be 10.77 MVA, but the true apparent power is 10 MVA, giving an error of 7.7%. The power factor will also appear to be 92.8% of its actual value.
2. An all-fiber optic current sensor with a noise floor of 1 Arms monitors the same power line described above. In this case, THD_V = 1%, THD_I = 1/50 = 2%, and the apparent power reported by the meter will be 10.0025 MVA, or an error of 0.25%. The reported power factor will be within 0.02% of its actual value.
3. As a final example, an all-fiber optic current sensor with a noise floor of 1 Arms is used to meter an undistorted primary current of I_1 = 1 Arms. An optical voltage sensor monitors the 200 kVrms primary voltage with no additional noise. Here, THD_I = 1/1 = 100% and THD_V = 0%. The reported apparent power will be 282 kVA, as compared with the true apparent power of 200 kVA.

As can be seen by these three examples, even very high performance optical sensors may create metering errors, *depending on the algorithm used in the meter*. Since new electronic meter designs, algorithms and features are constantly being introduced, the best course of action for an optical system user is to request the optical sensor system manufacturer to furnish type test results when the optical sensor is operating with the user's meter of choice. The tests should be conducted over the full range of metered currents. If harmonic content is needed for power quality measurements, then type test results for harmonic content should also be requested. Often, only the optical current sensor needs to be verified with a particular meter, since optical voltage sensors have very small noise contributions at rated primary voltage, and metering usually does not occur when the primary voltage differs appreciably (>20%) from nominal values. Alternatively, if resources are available, these type tests can be performed at the user's meter testing facilities.

Effects of Pollution, Ice, and Condensation on RCF

Pollution class requirements for high voltage switchgear are normally specified to ensure dielectric integrity of the equipment over prolonged exposure to a polluting environment. The principle effect of pollution is a time-dependent fluctuation in the electric field distribution along an insulating, polluted surface, even within a single power frequency cycle. The field re-distributions can lead to large field enhancements and local or line-to-ground dielectric breakdown. However, the RCF's of well-designed iron-core current and voltage transformers are completely immune to pollution effects, and no requirements are specified in IEEE C57.13 for testing RCF under polluted conditions.

The situation is different for one type of optical voltage sensor. The distributed optical voltage sensor is sensitive to electric field distributions along the insulating column. Use of this type of optical voltage sensor for metering applications should be certified for operation under the pollution class selected by the user. The certification must include verification of RCF under clean and polluted conditions.

Furthermore, the lowest pollution class still allows for continuous layers of ice (frozen solid or having a melted surface) or condensed fog on the outer insulator surface (this differs from the salt-fog conditions found in some coastal climates). Here again, the electric field distribution along the insulator can vary dramatically over time. Type tests must be performed on distributed optical voltage sensors to verify that the RCF remains within the accuracy class claimed while exposed to clean fog and iced conditions. The user should request the manufacturer to provide this type test report.

Long-Term Drift and Calibration Requirements

Nearly 100 years of experience with conventional wound iron-core instrument transformers have provided a level of comfort that the RCF of a particular piece of conventional equipment will remain accurate over the operating life of the unit. This can amount to many decades of service with virtually no required maintenance. Some of the comfort level originates in the physical sensing mechanism used in the transformer. Once assembled, the transformer turns ratio, burden capability, internal impedance and core losses remain virtually unchanged. Internal dielectric failure can result in shorted turns in a voltage transformer, but the rate of occurrence is small.

The reliability (i.e., the accuracy over a period of time) of a metering installation then falls to the characteristics of the meter. While electromechanical meters have provided decades of service with good accuracy, almost all substation installations today use electronic meters to provide additional functionality and communications capability. Carefully designed and manufactured electronic meters can provide reliable metering operation over more than 20 years of service. Usually, however, meter accuracy is verified on a routine basis every 1 to 16 years, depending on location, accuracy class, and revenue flow through the meter. Government certification requirements can play a major role in defining the time period between verifications.

A similar situation exists with the optical sensors available today. An optical link provides dielectric isolation between high voltage and an interface electronics package, which then interfaces with an electronic meter. The most desirable situation is one in which the sensor head has a proven track record of maintaining RCF over decades of service. This eliminates the need to routinely verify the RCF of the equipment connected to the high voltage line.

Unfortunately, optical sensor technologies are too new to provide a sufficient installed base in equipment-years to warrant the same level of comfort enjoyed by conventional iron-core instrument transformers. The oldest commercial optical sensor systems are bulk optic current sensors, some of which have been in service since 1986. Although these units presumably continue to provide accurate metering performance, their number is not sufficient to claim long-term stability of a particular sensor head design. This lack of comfort is exacerbated by a number of factors that can influence the RCF of an optical sensor, although manufacturers have engineered optical sensors to minimize these influences.

Equipment-years of installed optical systems are rapidly accumulating due to the large number of bulk optic current and voltage sensor systems installed between 1997 and 2001. Once long-term accuracy data is reported, routine field calibration may no longer be required to ensure revenue class accuracy of optical voltage and current sensors. Field calibration is common with capacitive voltage transformers (CVT or CCVT) used for relaying and protection applications. For CVT, CCVT, and optical voltage sensors, this normally involves taking the unit out of service, energizing the sensor with a portable test set, and measuring the RCF at the output of the interface electronics as compared with an accepted standard such as a precision potential transformer. Indeed, several government agencies currently insist on frequent (every 1 or 2 years) calibration verification of optical sensors to certify use in revenue metering, although efforts are underway to relax or eliminate this requirement.

A second issue associated with optical sensors is the interplay that exists between the sensor head and the interface electronics. Manufacturing tolerances prevent sensor heads from having precisely the same RCF. This is due to variations in materials properties in the sensor head, as well as variations in the optical source used for each sensor head. Two sensor heads may have RCFs that differ by >0.3% when connected to the same interface electronics board. Likewise, two interface electronics connected to the same sensor head may provide RCF differences of >0.3%. Given the more likely situation that the interface electronics fail long before the sensor head, replacement of the interface electronics without removing or replacing the sensor head is a desirable feature for optical sensors.

Three scenarios are possible. In the first two, the interface electronics can fail while the sensor head remains functional, or the sensor head can fail while the interface electronics remains functional. In either case, two responses are currently in use by manufacturers. In the direct approach, the sensor head and interface electronics are both replaced with a new, calibrated set. This involves replacing the sensor head from the high voltage line. Serial numbers are used to maintain matching of an optical sensor head with a particular set of interface electronics.

A second approach provides a programmable set of calibration factors in each electronics interface. The calibration factors provide information about the sensor head and the interface electronics. Replacing the interface electronics can then be accomplished by loading the calibration factors of the existing sensor head into some new interface electronics. The sensor head does not need to be removed from the high voltage line. Likewise, the sensor head can be replaced and its calibration coefficients loaded into the existing interface electronics.

A third scenario is possible in which the fiber cable breaks while the interface electronics and the sensor head both remain intact. In almost all cases, the cable can be replaced without changing the sensor head or the interface electronics. Verification of the RCF is usually not required. If a single fiber breaks within the cable, the system can usually be repaired using one of the spare fibers that have been included within the cable. However, with all-fiber current sensors, the polarization properties of the fiber optic cable also contribute to the overall RCF of the sensor system. In this case, the RCF may need to be verified in the field.

Calibration of optical sensors presents some new metrology challenges for the utility metering community. Optical current and voltage sensors must meet all of the accuracy requirements listed elsewhere in this book for conventional current and voltage transformers. Standard calibration techniques are suitable for calibrating the 1 Arms output of an optical current sensor, or the 69 or 120 Vrms output of an optical voltage sensor. However, the low voltage analog outputs of these sensor systems are not compatible with most of the traditional calibration equipment. Many alternative methods have been proposed and/or employed, but no standard technique has yet been selected. IEC 60044-8, a recently approved standard for non-conventional current transducers, provides suggestions for calibrating low voltage analog output signals.

A commercially available calibration aid is the Model 931A manufactured by Arbiter Systems, Inc. In addition to measuring ratios and phase angles between conventional current or voltage transformers, it also provides accurate measurements of low voltage analog outputs compared with conventional current and voltage transformers. In addition, wide-bandwidth or narrow-bandwidth measurements of rms voltages and currents can be made. These are very useful features when trying to provide traceable calibration measurements of optical sensors.

Fiber Optic Cabling

Although usually considered a mundane component of a measurement system, the fiber optic cabling between the sensor head and the interface electronics is crucial to long term reliability of an optical sensor system. Almost all early failures in optical sensors involved a failure related to the fiber cabling. Cabling usually involves the fiber optic run between the control house and the location in the substation where the optical sensor is installed, the fiber run up to the sensor elements, and the connectors or splicing techniques used to connect the cable into the sensor head and the interface electronics. Manufacturers usually supply the optical cable as part of the total system. Some manufacturers must provide the cable to ensure that the RCF is maintained after installation.

The telecommunications industry has provided very strict standards (known as Bellcore standards) that, if followed, will ensure trouble-free fiber cable service. Some of the issues involved with fiber cabling include:

1. Water is an optical fiber's enemy. Over long-term exposure and under tension, an optical fiber develops surface micro-cracks that eventually cleave the fiber. Manufacturers usually recommend a fiber cable that can be directly buried. This applies even when running fiber cable in conduit, because conduit cannot be made waterproof.
2. Rodents love the taste of fiber cables. A kevlar-armored fiber cable with rodent deterrent is usually preferable for direct bury applications.
3. When the optical sensor system manufacturer provides the fiber cable, it is usually cut to a user-specified length and fiber connectors are often installed on the ends of the cable. The connectors are protected by pulling sleeves. While being handled, the ends of the fiber cable are extremely fragile. Training of installation personnel is usually advisable to avoid costly time delays due to accidents (i.e., fiber cables can be pulled through conduit much more easily if the connectors are snipped off first).
4. Ultraviolet light is the enemy of fiber cable jackets. If the cable must be installed above ground, a metal conduit is highly preferred to provide ultraviolet light shielding.
5. Fiber optic connectors must be kept meticulously clean. Cleaning kits are available from many fiber optic supplies stores and are highly recommended.
6. Ports into which fiber connectors are inserted must be kept meticulously clean. If contaminated, they are very difficult to clean without disassembling the equipment. To avoid this, see item #5 above.
7. Optical sensor manufacturers use several different fiber sizes. In general, standard singlemode fiber is the least expensive, followed by multimode fiber and finally polarization maintaining single mode fiber. Multimode fiber is much more tolerant to mechanical misalignments than single mode fiber.
8. The polarization maintaining property of polarization maintaining single mode fiber (known as the extinction ratio) is sensitive to stresses and bends placed on the cable. For this type of fiber, avoid tight bend radii.
9. Some manufacturers provide optical systems with fiber that can be fusion spliced. This can be advantageous for repairing a cut cable. Some manufacturers supply fiber that cannot be fusion spliced. For this type of fiber, one manufacturer uses mechanical splices for field repairs.

CHAPTER

12

METER WIRING DIAGRAMS

DIAGRAMS OF INTERNAL CONNECTIONS for watthour meters and the associated form numbers are in accordance with ANSI C12.10.

INDEX FOR ILLUSTRATIONS

Symbols used are in accordance with ANSI Y32.2 except where none are listed.

For typical meter wiring diagrams of kiloVAR and kilovoltampere metering, refer to Chapter 9. Refer to previous editions of the *Electrical Metermens Handbook* for AC, two-phase, and DC meter wiring diagrams.

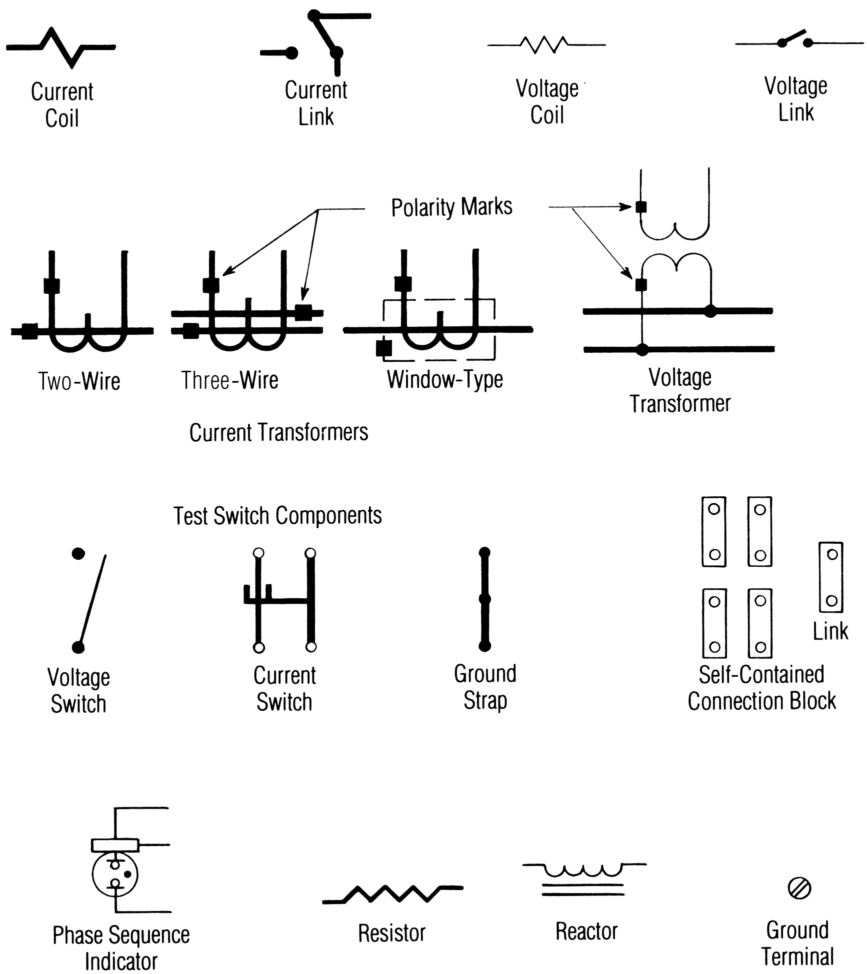
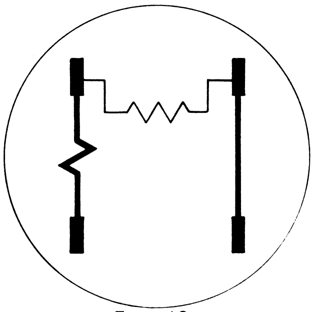
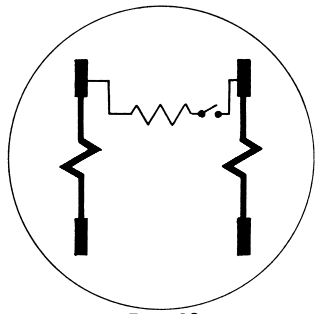


Figure 12-1. Symbols.

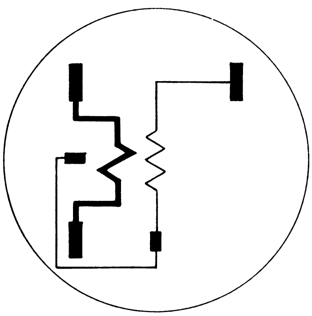
Internal Connections of Type "S" Meters
Front Views



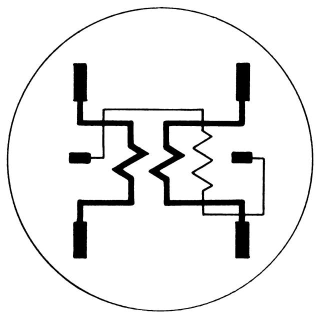
Form 1S
Two-Wire Self-Contained



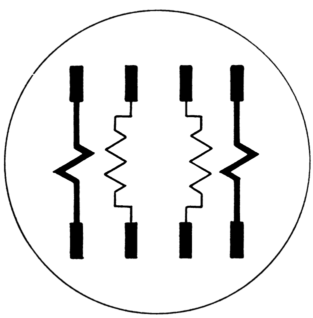
Form 2S
Three-Wire Self-Contained



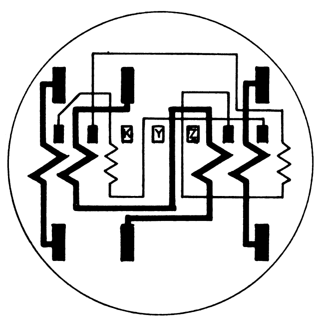
Form 3S
Two-Wire Transformer-Rated



Form 4S
Three-Wire Transformer-Rated



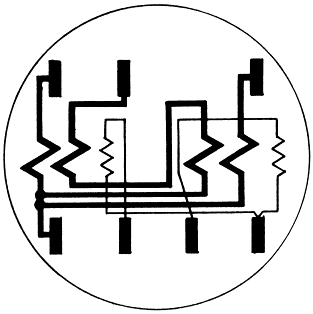
Form 5S
Two Stator Transformer-Rated
Two-Phase, Three- or Four-Wire
Three-Phase, Three-Wire



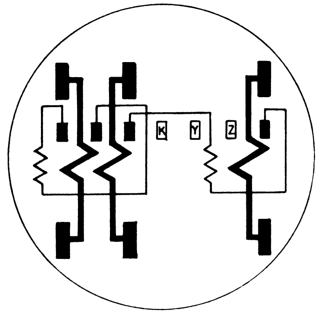
Form 6S
Two Stator Transformer-Rated
Three-Phase, Four-Wire Wye

Figure 12-2. Form Numbers 1S, 2S, 3S, 4S, 5S, and 6S.

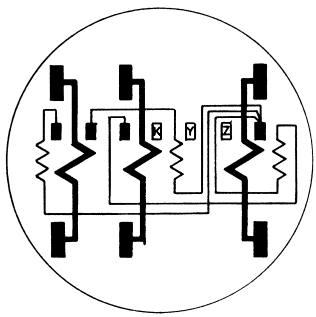
Internal Connections of Type "S" Meters
Front Views



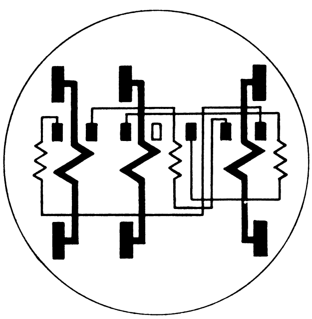
Form 7S
Two Stator Transformer-Rated
Three-Phase, Four-Wire Wye
(Alternative)



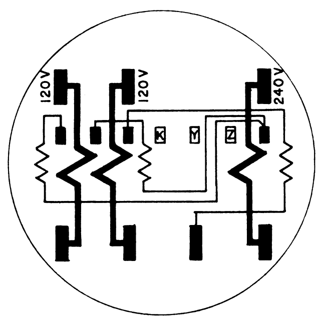
Form 8S
Two Stator Transformer-Rated
Three-Phase, Four-Wire Delta



Form 9S
Three Stator Transformer-Rated
Three-Phase, Four-Wire Wye



Form 10S
Three Stator Transformer-Rated
Three-Phase, Four-Wire Wye
(Alternative)

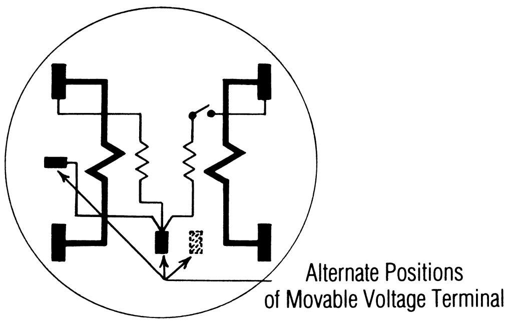


Form 11S
Three Stator Transformer-Rated
Three-Phase, Four-Wire Delta

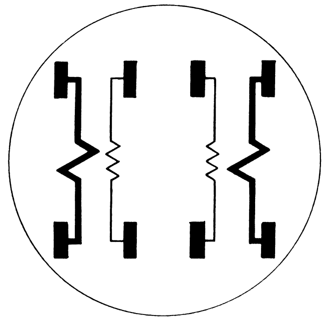
Figure 12-3. Form Numbers 7S, 8S, 9S, 10S, and 11S.

Internal Connections of Type "S" Meters

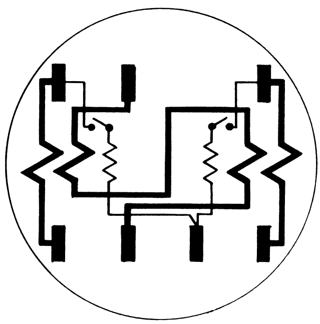
Front Views



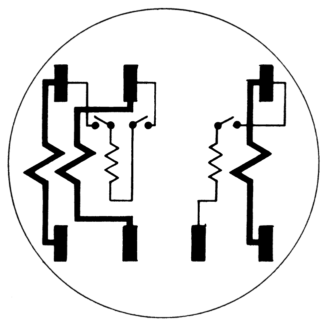
Form 12S
Two Stator Self-Contained
Three-Wire Network



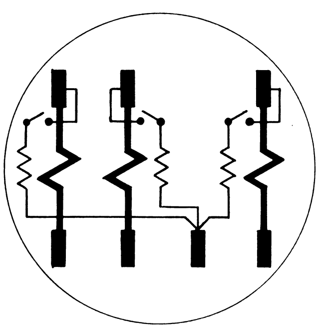
Form 13S
Two Stator Self-Contained
Two-Phase, Three- or Four-Wire
Three-Phase, Three-Wire



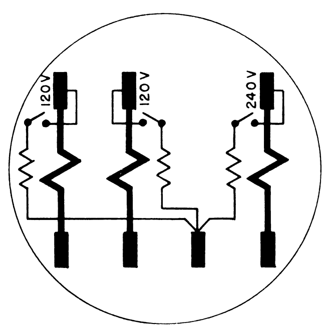
Form 14S
Two Stator Self-Contained
Three-Phase, Four-Wire Wye



Form 15S
Two Stator Self-Contained
Three-Phase, Four-Wire Delta



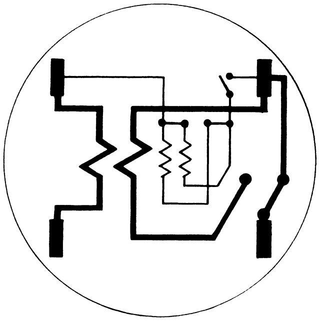
Form 16S
Three Stator Self-Contained
Three-Phase, Four-Wire Wye



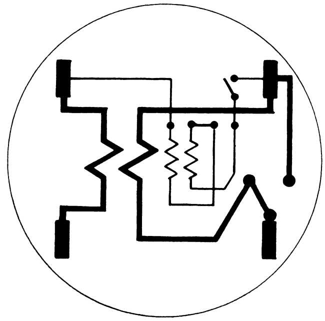
Form 17S
Three Stator Self-Contained
Three-Phase, Four-Wire Delta

Figure 12-4. Form Numbers 12S, 13S, 14S, 15S, 16S, and 17S.

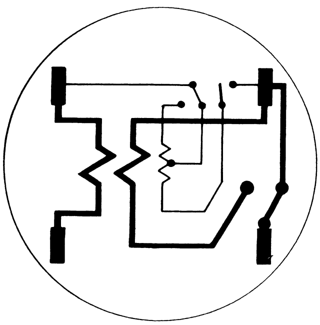
Internal Connections of Type "S" Meters
Front Views



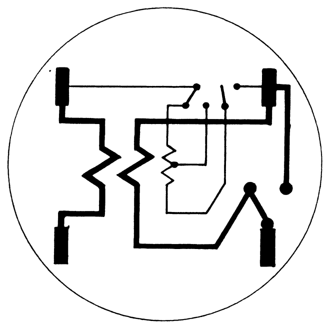
Form 19S-2
Two- or Three-Wire Single Stator
Self-Contained Two-Wire Connection



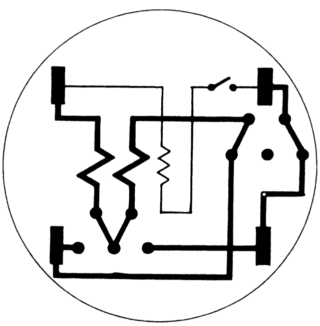
Form 19S-3
Two- or Three-Wire Single Stator
Self-Contained Three-Wire Connection



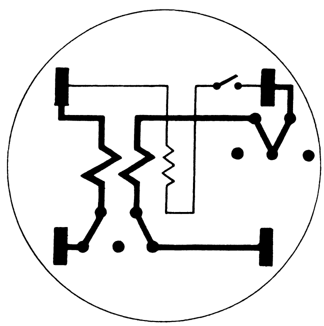
Form 20S-2
Two- or Three-Wire Single Stator
Self-Contained Two-Wire Connection



Form 20S-3
Two- or Three-Wire Single Stator
Self-Contained Three-Wire Connection



Form 21S-2
Two- or Three-Wire Single Stator
Self-Contained Two-Wire Connection

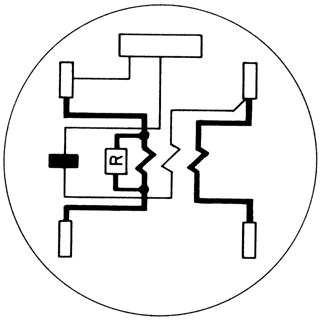


Form 21S-3
Two- or Three-Wire Single Stator
Self-Contained Three-Wire Connection

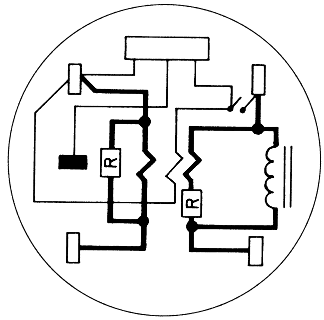
Figure 12-5. Form Numbers 19S-2, 19S-3, 20S-2, 20S-3, 21S-2, and 21S-3.

Internal Connections of Type "S" Meters

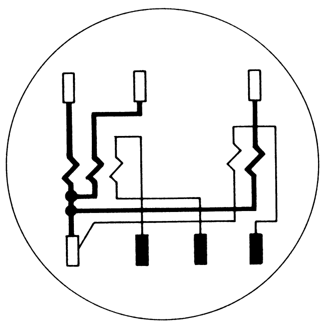
Front Views



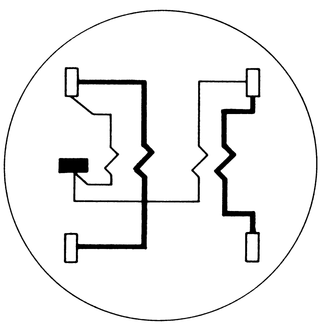
Form 22S
Three-Wire Self-Contained
(Network Only)



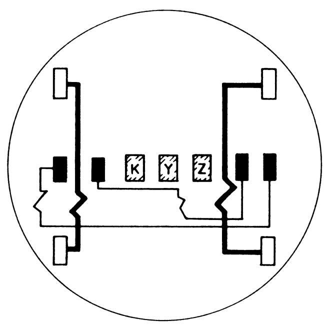
Form 23S
Three-Wire Self-Contained
(Network Only)



Form 24S
Two Stator Transformer-Rated
Three-Phase, Four-Wire Delta
(Seven Terminals)



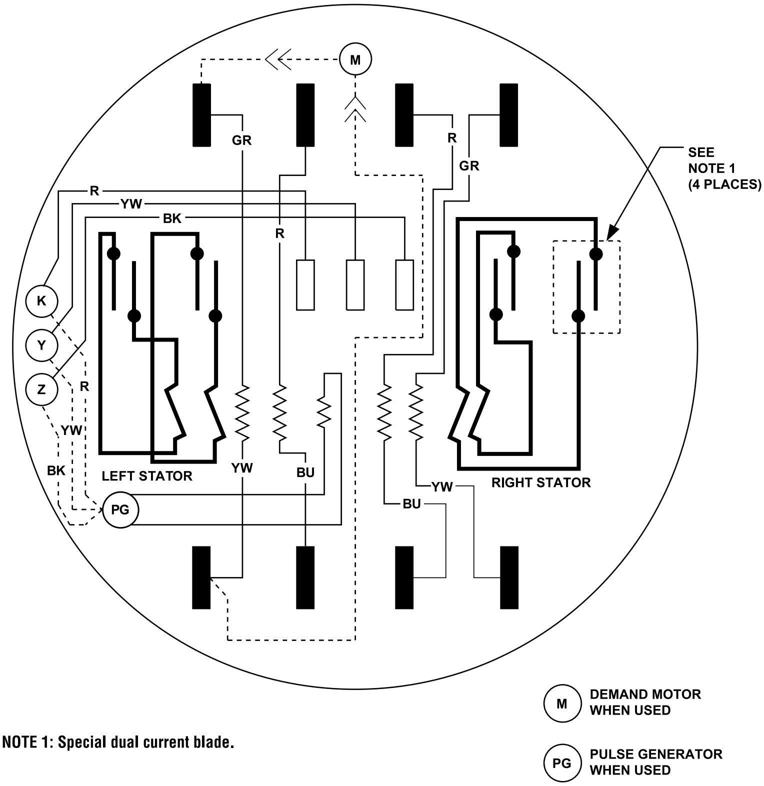
Form 25S
Two Stator Self-Contained
Three-Wire Network



Form 26S
Two Stator Transformer-Rated
Three-Phase, Three-Wire

Figure 12-6. Form Numbers 22S, 23S, 24S, 25S, and 26S.

Internal Connections of Type "S" Meters
Front View

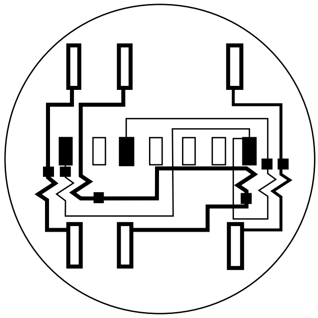


NOTE 1: Special dual current blade.

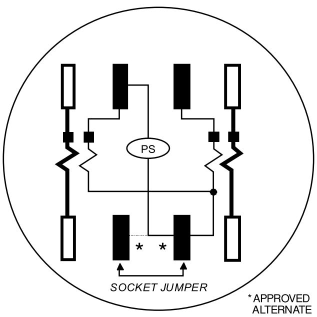
Form 28S
Two Stator Universal
Three-Phase, Three-Wire

Figure 12-7. Form Number 28S.

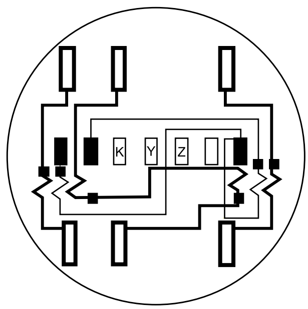
Internal Connections of Type "S" Meters
Front View



Form 29S
Two Stator Transformer-Rated
Three-Phase, Four-Wire Wye



Form 35S
Two Stator Transformer-Rated
Three-Phase, Three-Wire

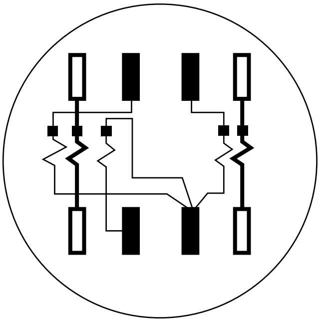


Form 36S
Two Stator Transformer-Rated
Three-Phase, Four-Wire Wye

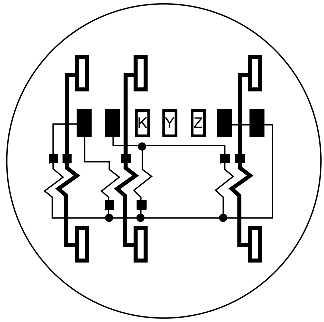
Figure 12-8. Form Numbers 29S, 35S, and 36S.

Internal Connections of Type "S" Meters

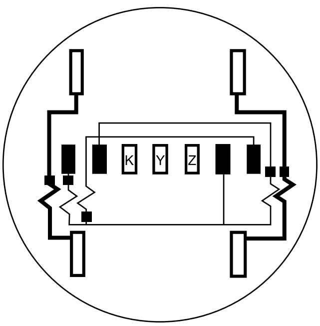
Front View



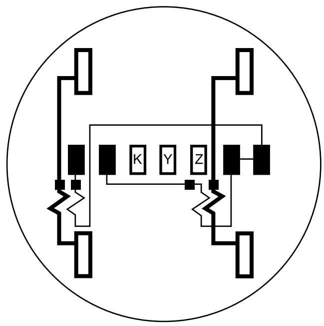
Form 45S
Two Stator Transformer-Rated
Three-Phase, Three-Wire



Form 46S
Two Stator Transformer-Rated
Three-Phase, Four-Wire Wye



Form 56S
Two Stator Transformer-Rated
Three-Phase, Three-Wire Wye



Form 66S
Two Stator Transformer-Rated
Three-Phase, Three-Wire Wye

Figure 12-9. Form Numbers 45S, 46S, 56S, and 66S.

Internal Connections of Type "A" Meters

Front Views (Except Terminals)

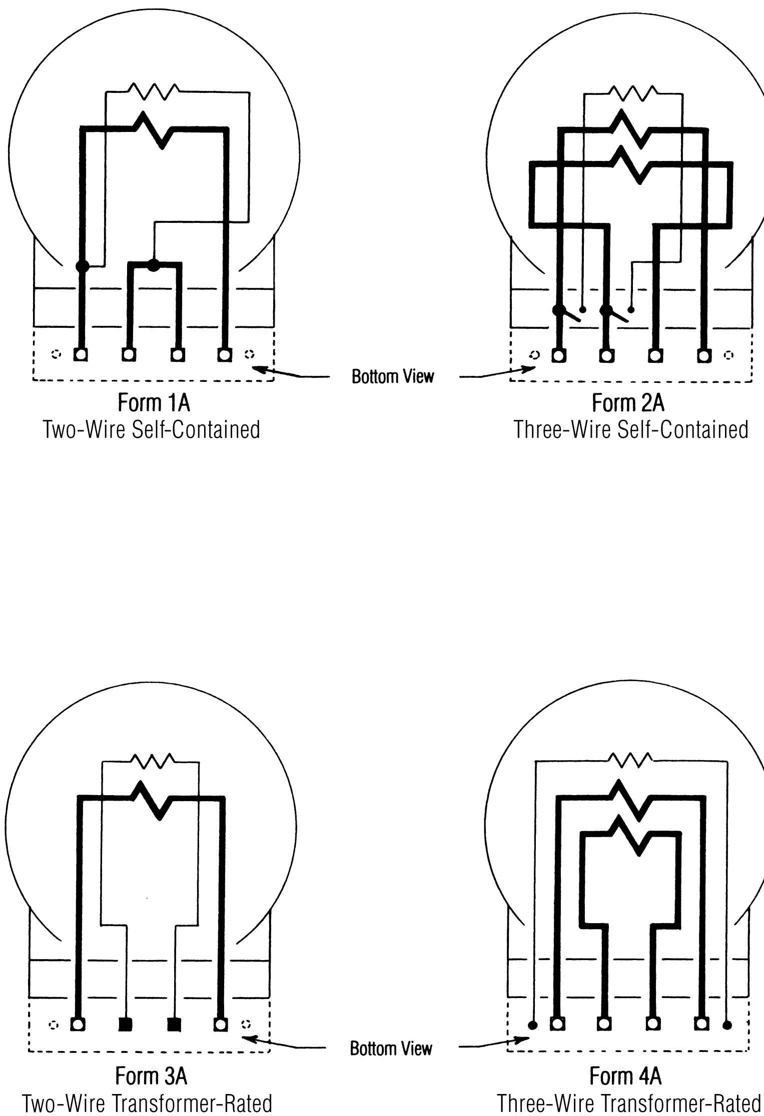
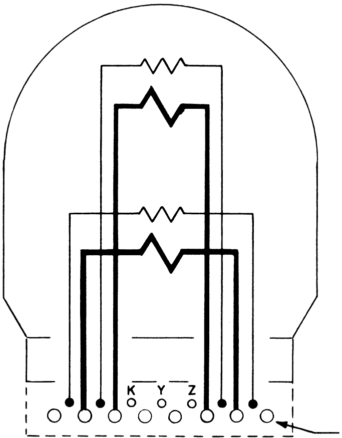


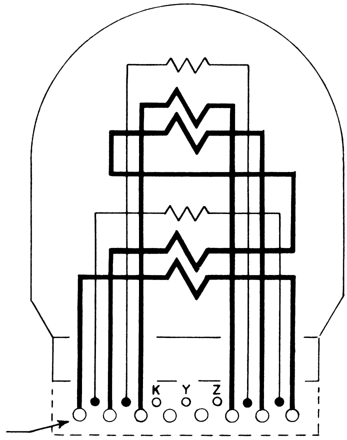
Figure 12-10. Form Numbers 1A, 2A, 3A, and 4A.

Internal Connections of Type "A" Meters

Front Views (Except Terminals)

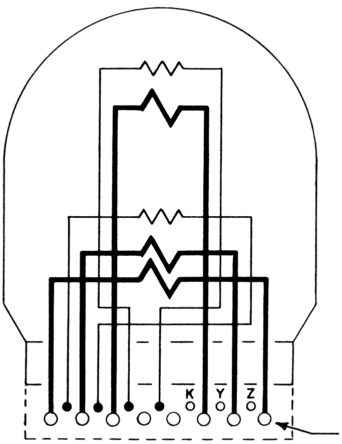


Bottom View

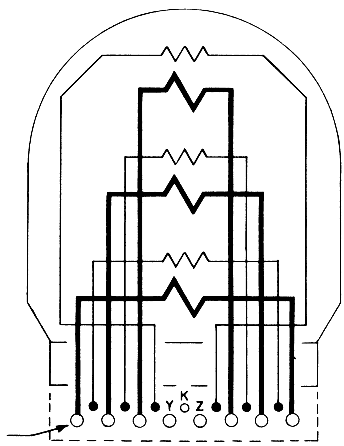


Form 5A
Two Stator Transformer-Rated
Two-Phase, Three- or Four-Wire
Three-Phase, Three-Wire

Form 6A
Two Stator Transformer-Rated
Three-Phase, Four-Wire Wye



Bottom View



Form 8A
Two Stator Transformer-Rated
Three-Phase, Four-Wire Delta

Form 9A
Three Stator Transformer-Rated
Three-Phase, Four-Wire Wye

Figure 12-11. Form Numbers 5A, 6A, 8A, and 9A.

Internal Connections of Type "A" Meters
Front View

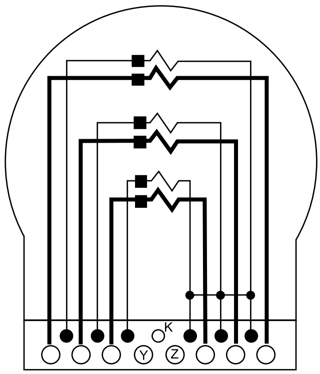
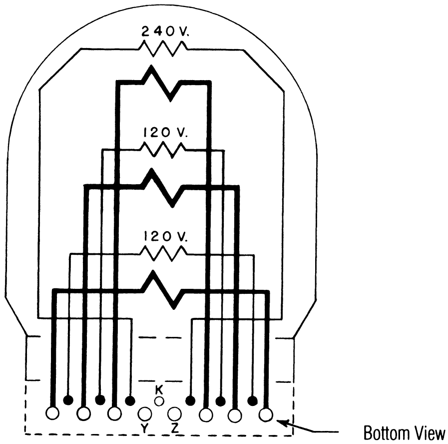


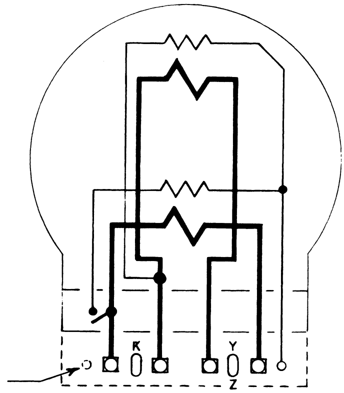
Figure 12-12. Form Number 10A.

Internal Connections of Type "A" Meters

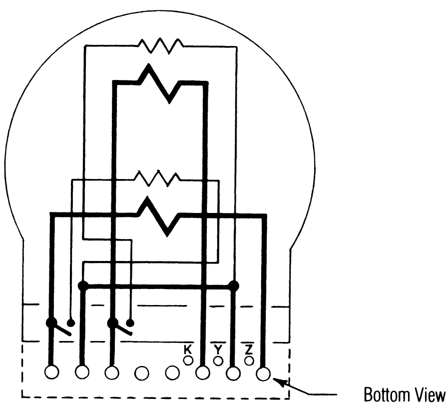
Front Views (Except Terminals)



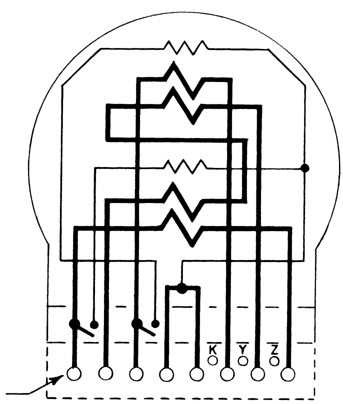
Form 11A
Three Stator Transformer-Rated
Three-Phase, Four-Wire Delta



Form 12A
Two Stator Self-Contained
Three-Wire Network



Form 13A
Two Stator Self-Contained
Two- or Three-Phase, Three-Wire

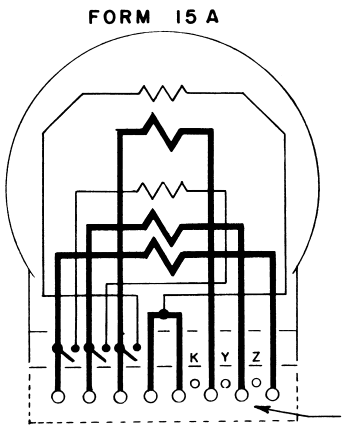


Form 14A
Two Stator Self-Contained
Three-Phase, Four-Wire Wye

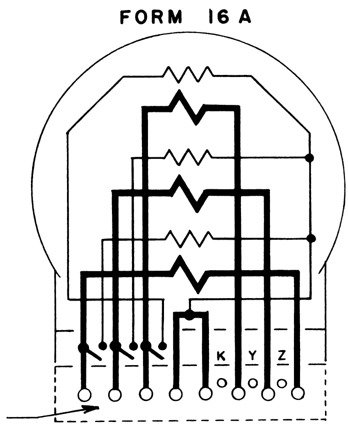
Figure 12-13. Form Numbers 11A, 12A, 13A, and 14A.

Internal Connections of Type "A" Meters

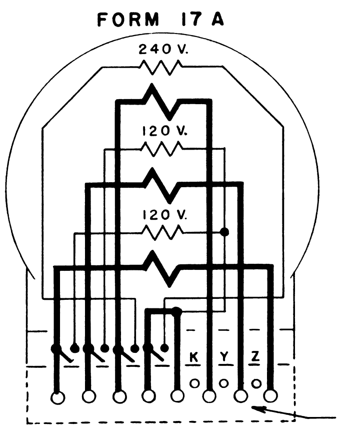
Front Views (Except Terminals)



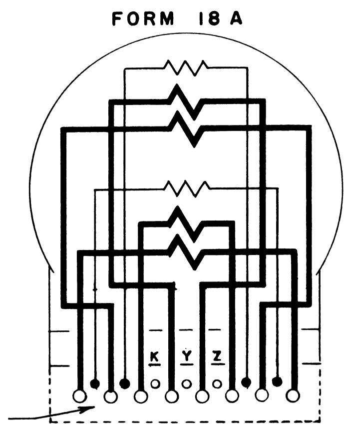
Form 15A
Two Stator Self-Contained
Three-Phase, Four-Wire Delta



Form 16A
Three Stator Self-Contained
Three-Phase, Four-Wire Wye



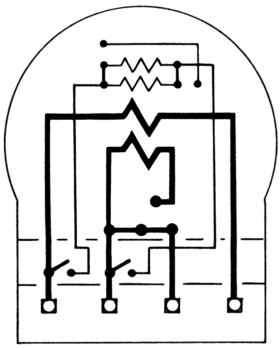
Form 17A
Three Stator Self-Contained
Three-Phase, Four-Wire Delta



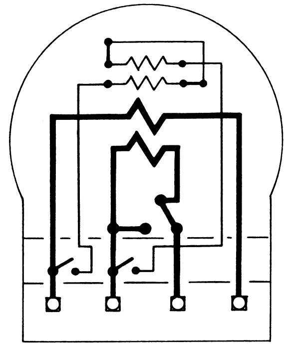
Form 18A
Two Stator Self-Contained
Two-Phase, Five-Wire

Figure 12-14. Form Numbers 15A, 16A, 17A, and 18A.

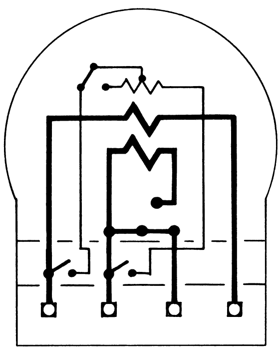
Internal Connections of Type "A" Meters
Front Views



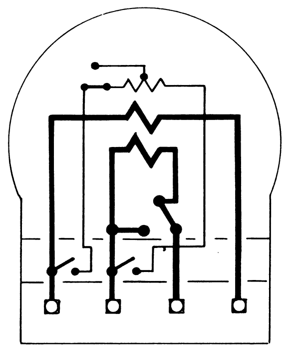
Form 19A-2
Two- to Three-Wire Single Stator
Self-Contained Two-Wire Connection



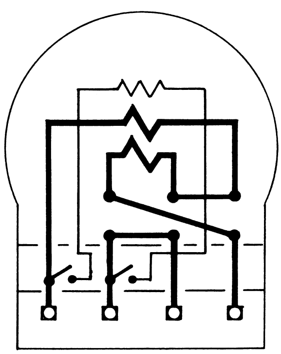
Form 19A-3
Two- to Three-Wire Single Stator
Self-Contained Two-Wire Connection



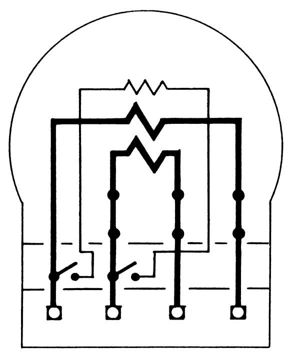
Form 20A-2
Two- to Three-Wire Single Stator
Self-Contained Two-Wire Connection



Form 20A-3
Two- to Three-Wire Single Stator
Self-Contained Three-Wire Connection



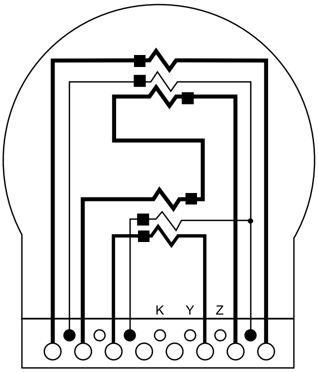
Form 21A-2
Two- to Three-Wire Single Stator
Self-Contained Three-Wire Connection



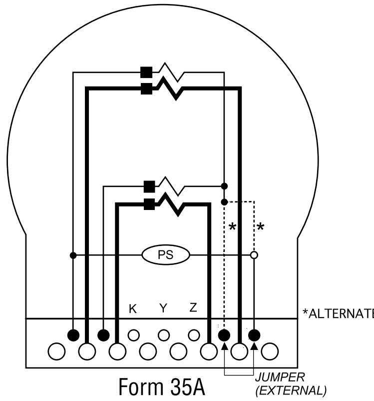
Form 21A-3
Two- to Three-Wire Single Stator
Self-Contained Three-Wire Connection

Figure 12-15. Form Numbers 19A-2, 19A-3, 20A-2, 20A-3, 21A-2, and 21A-3.

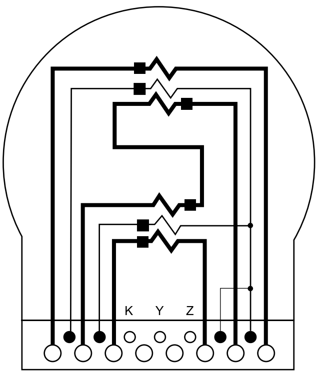
Internal Connections of Type "A" Meters
Front View



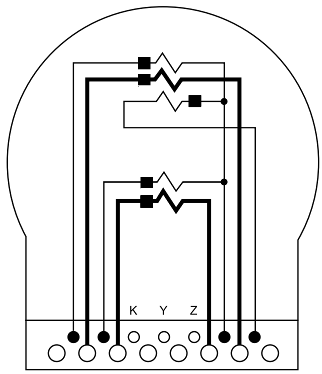
Form 29A
Two Stator Transformer-Rated
Three-Phase, Four-Wire Wye



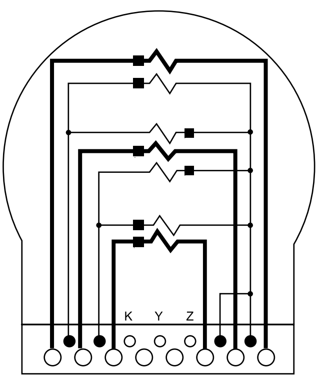
Form 35A
Two Stator Transformer-Rated
Three-Phase, Three-Wire



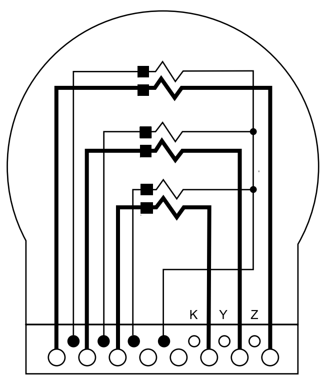
Form 36A
Two Stator Transformer-Rated
Three-Phase, Four-Wire Wye



Form 45A
Two Stator Transformer-Rated
Three-Phase, Three-Wire



Form 46A
Two Stator Transformer-Rated
Three-Phase, Four-Wire Wye

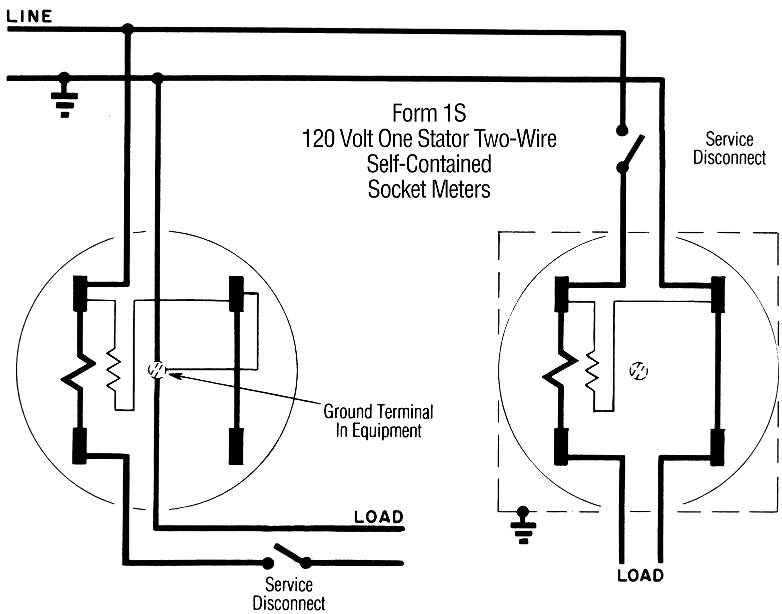


Form 48A
Two Stator Transformer-Rated
Three-Phase, Four-Wire

Figure 12-16. Form Numbers 29A, 35A, 36A, 45A, 46A, and 48A.

Single-Phase, Two-Wire Circuits

Front Views



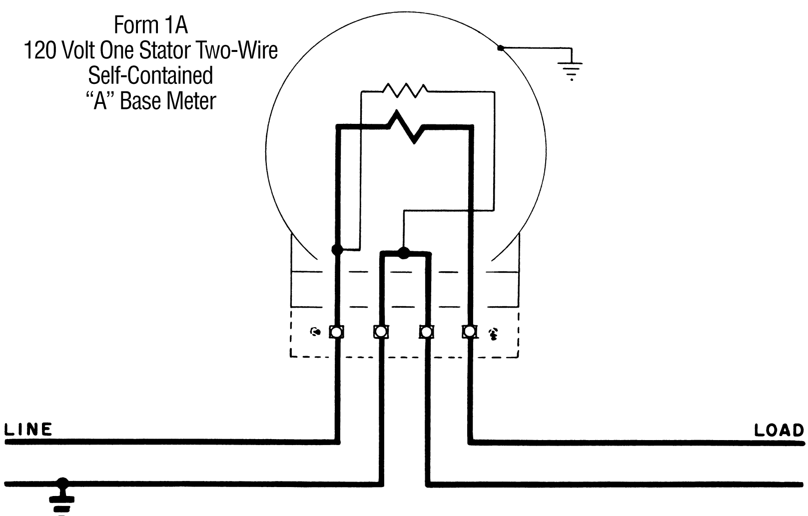
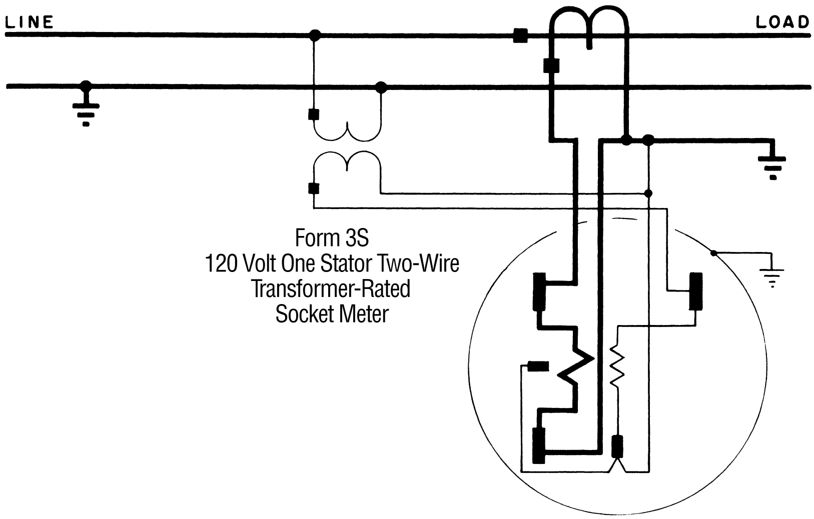


Figure 12-17. Self-Contained.

Single-Phase, Two-Wire Circuits
Front Views



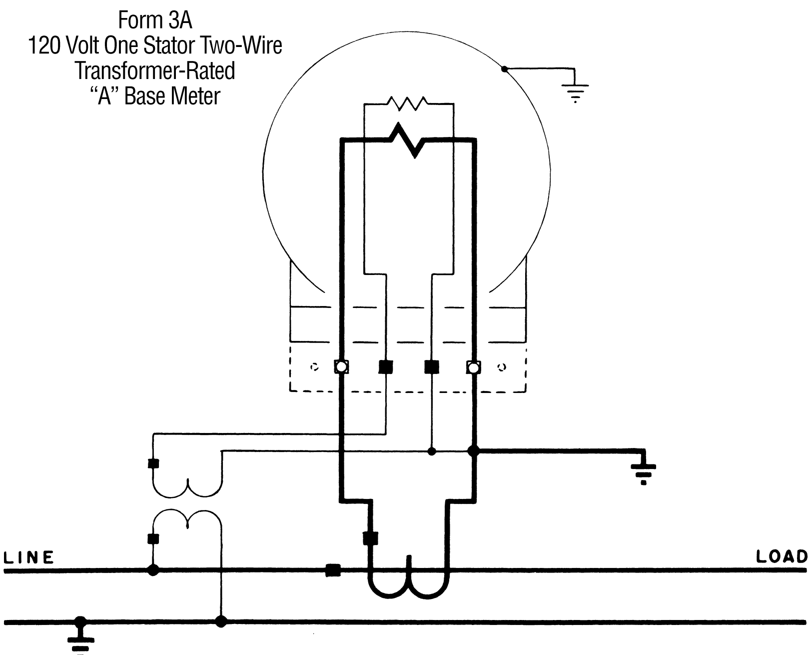
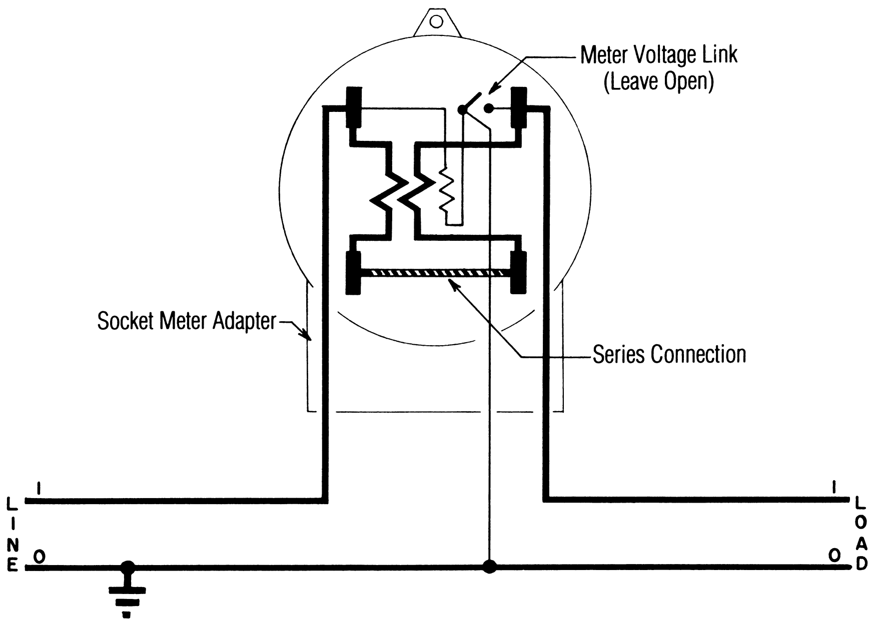


Figure 12-18. Current and Voltage Transformers.

Single-Phase, Two- or Three-Wire Circuits (Three-Wire not shown)
Front View

Form 2S
240 Volt One Stator Three-Wire
Self-Contained Socket Meter
Connected to Single-Phase Two-Wire 120 Volt Service
Using an "A" Base Socket Meter Adapter



Note: Socket meter adapter to be wired with the line wire (live) connected to the upper-left terminal, the load wire (live) connected to the upper-right terminal. Series-connect lower-left terminal to lower-right terminal. With meter voltage link open, connect neutral (ground) wire to the voltage coil terminal (link) screw on the meter.

Figure 12-19. Self-Contained with Socket Adapter.

Single-Phase, Two- or Three-Wire Circuits

Front Views

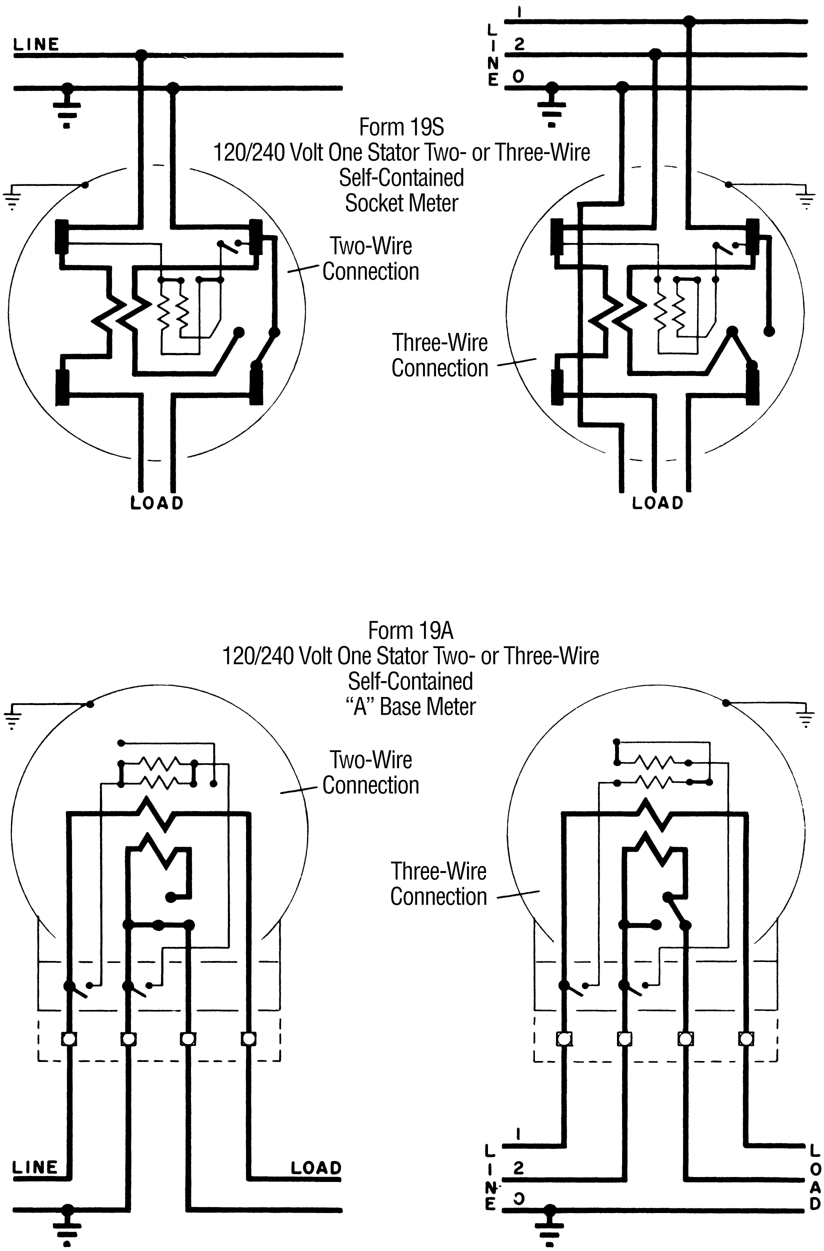


Figure 12-20. Self-Contained.

Single-Phase, Two- or Three-Wire Circuits
Front Views

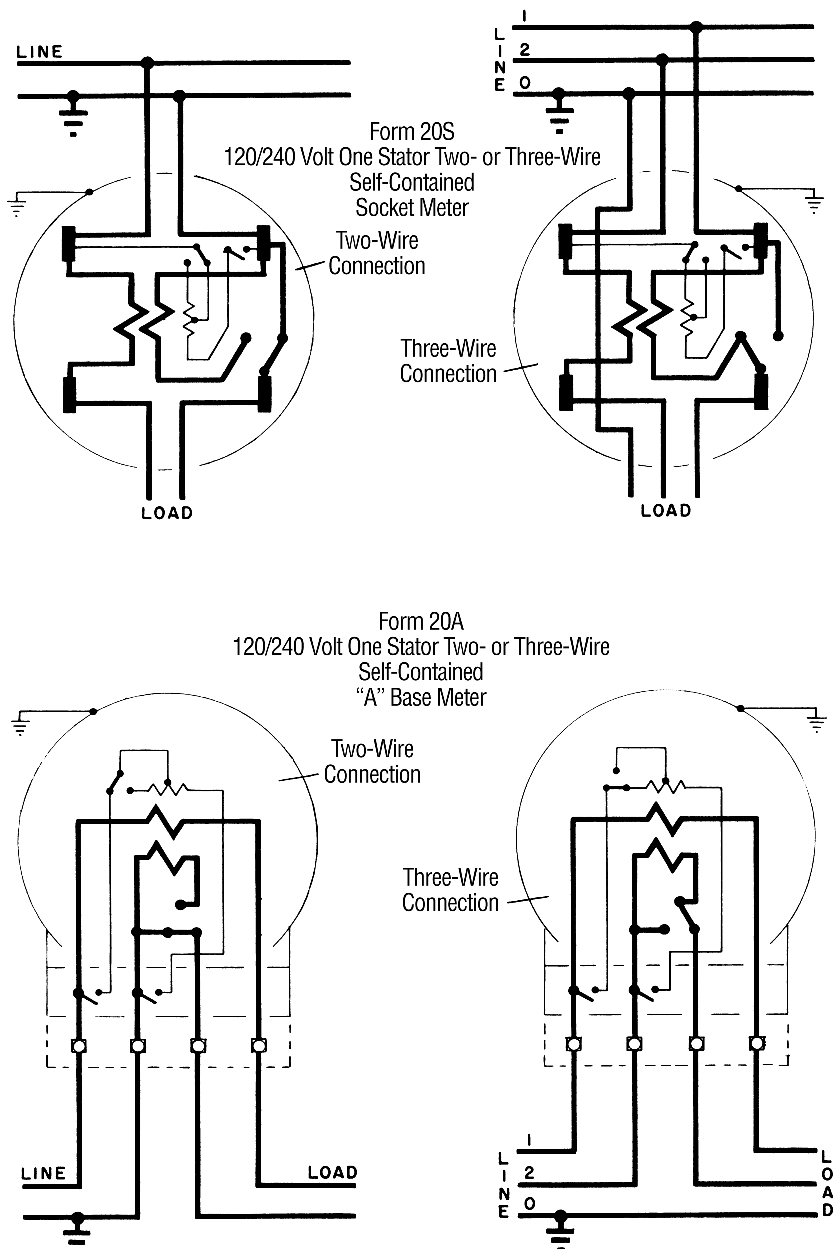


Figure 12-21. Self-Contained.

Single-Phase, Two- or Three-Wire Circuits
Front Views

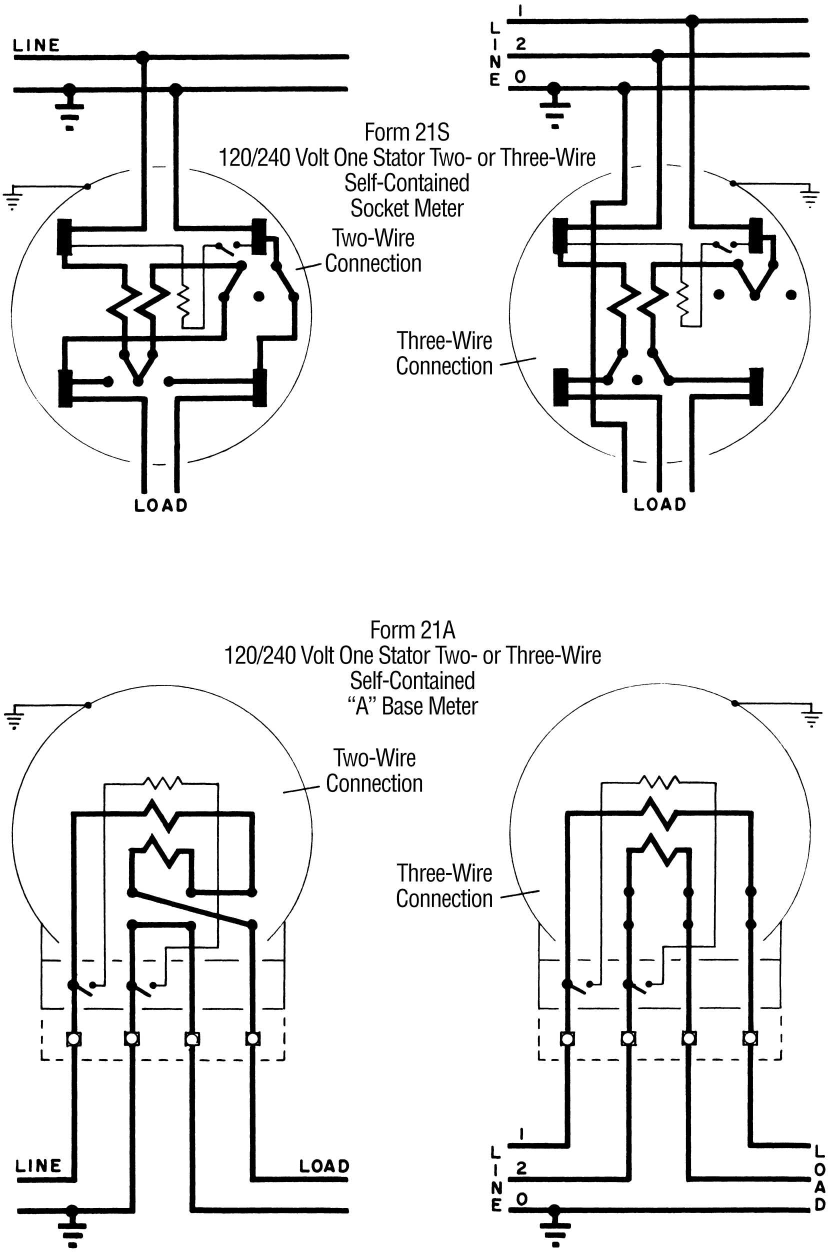
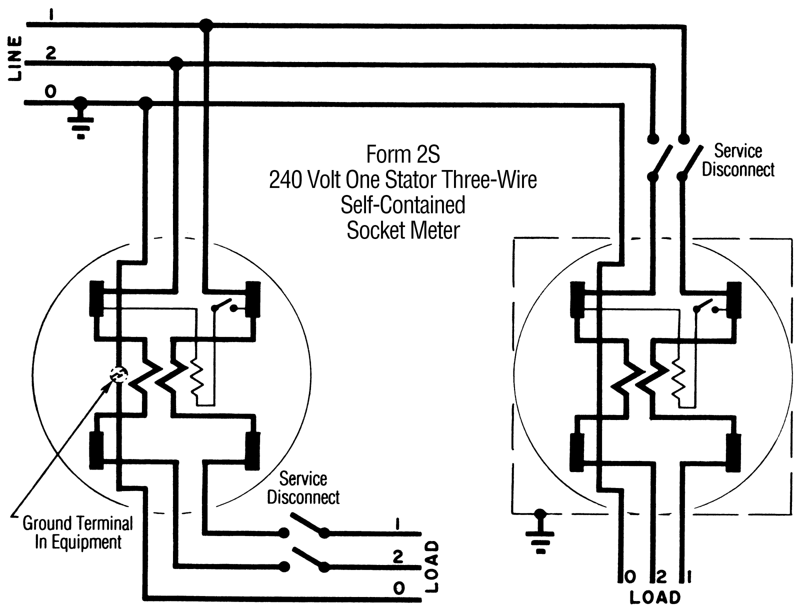


Figure 12-22. Self-Contained.

Single-Phase, Three-Wire Circuits
Front Views



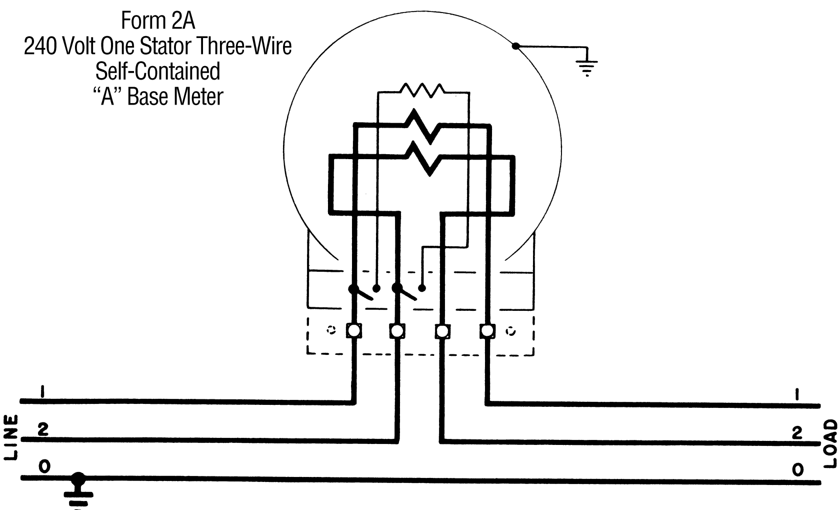


Figure 12-23. Self-Contained.

Single-Phase, Three-Wire Circuits
Front Views

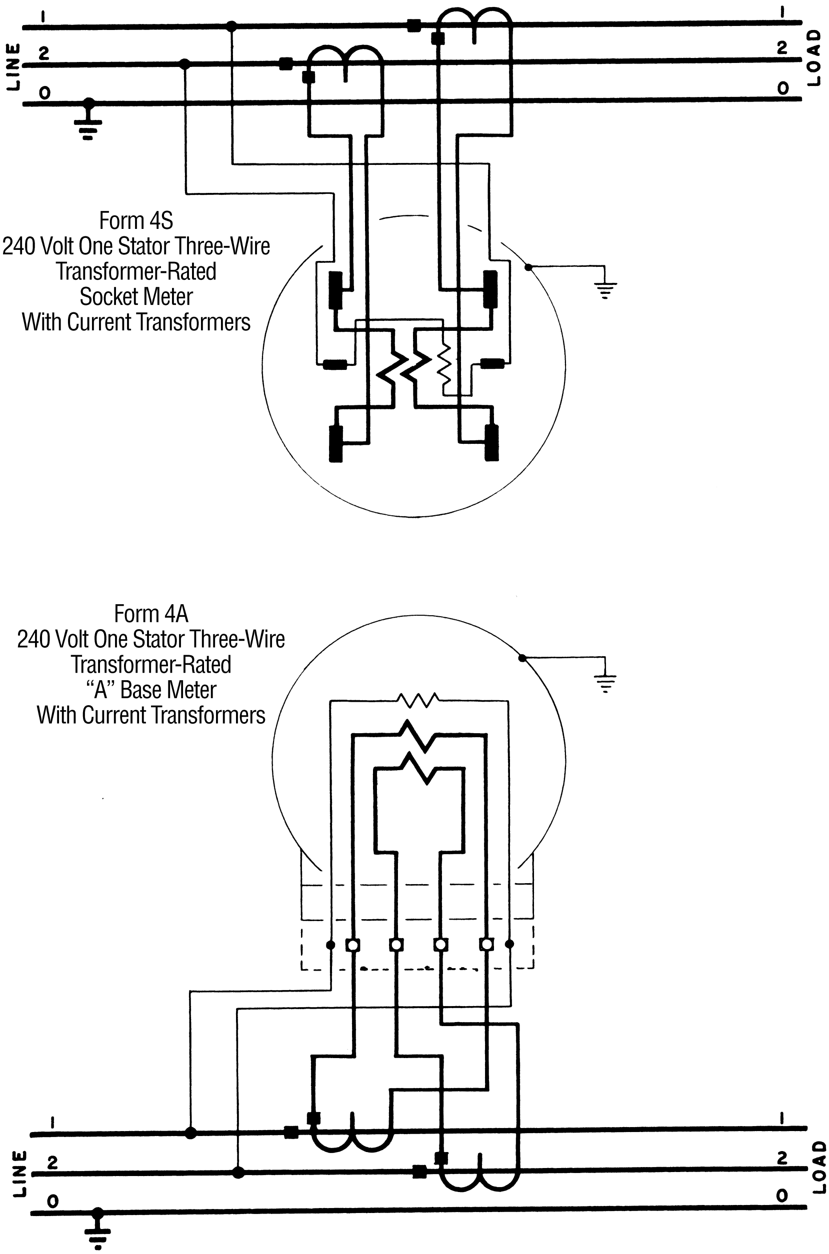
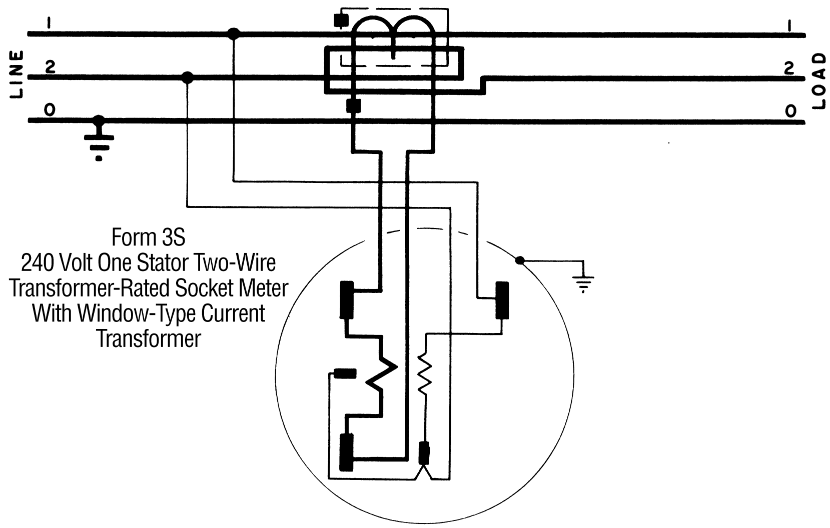


Figure 12-24. Current Transformers.

Single-Phase, Three-Wire Circuits
Front Views



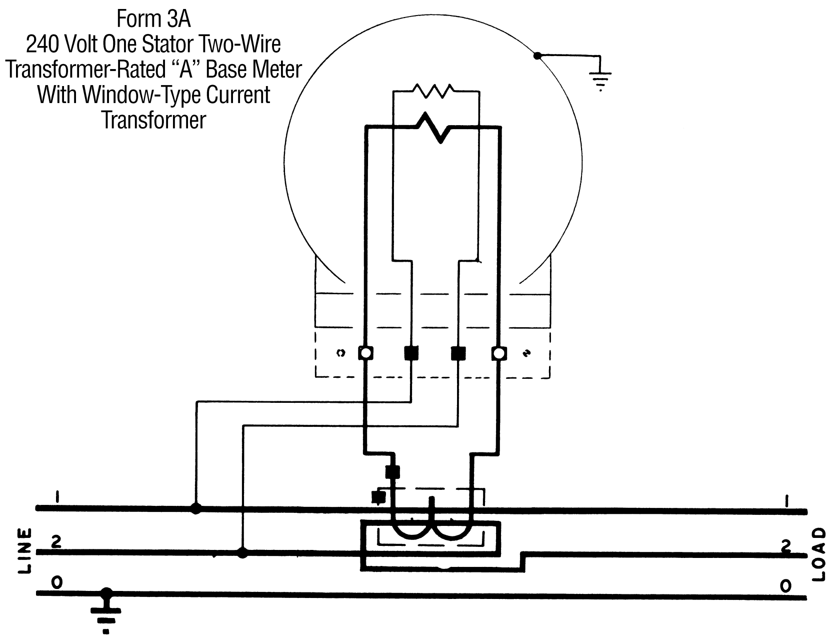
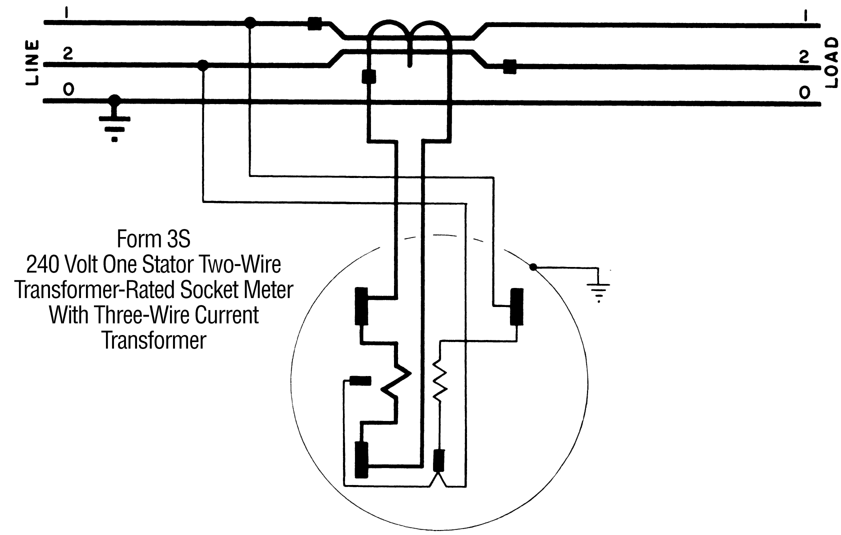


Figure 12-25. One Window-Type Current Transformer.

Single-Phase, Three-Wire Circuits

Front Views



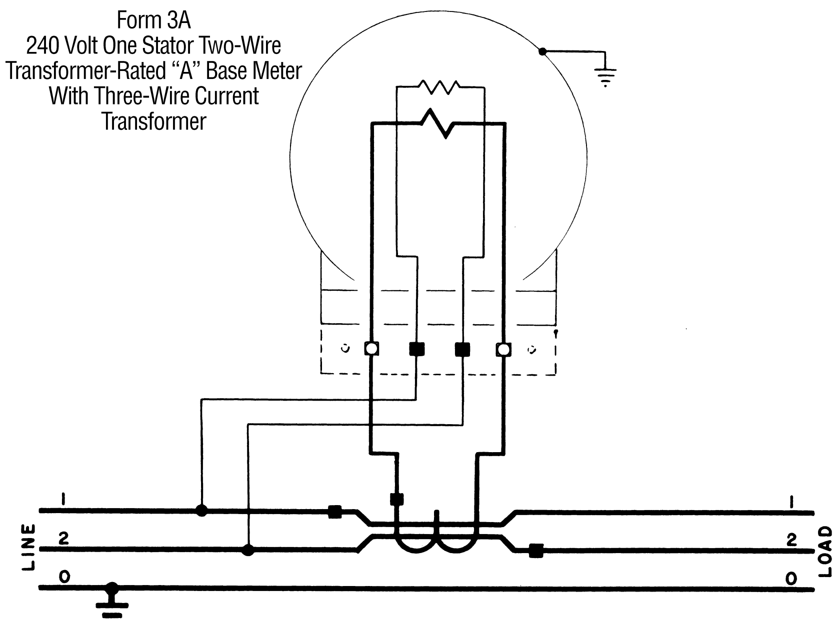
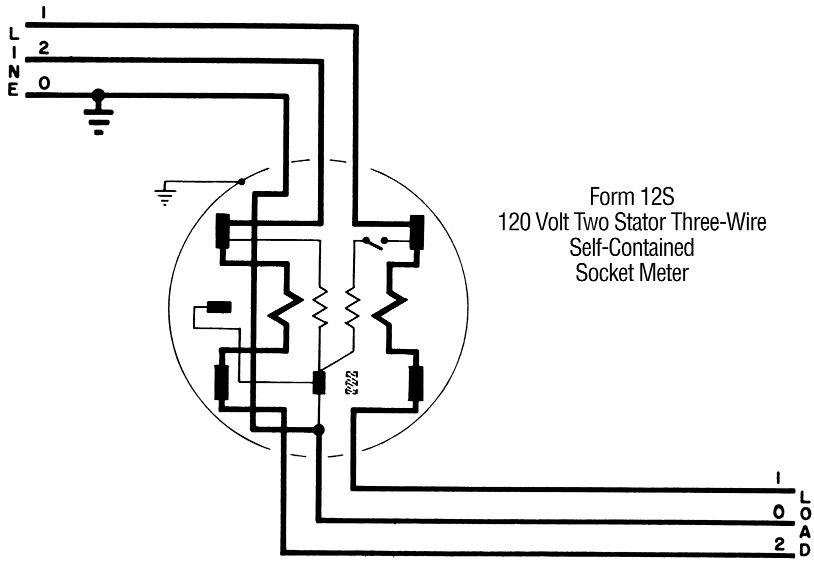


Figure 12-26. Three-Wire Current Transformer.

Three-Wire Network Circuit

Front Views



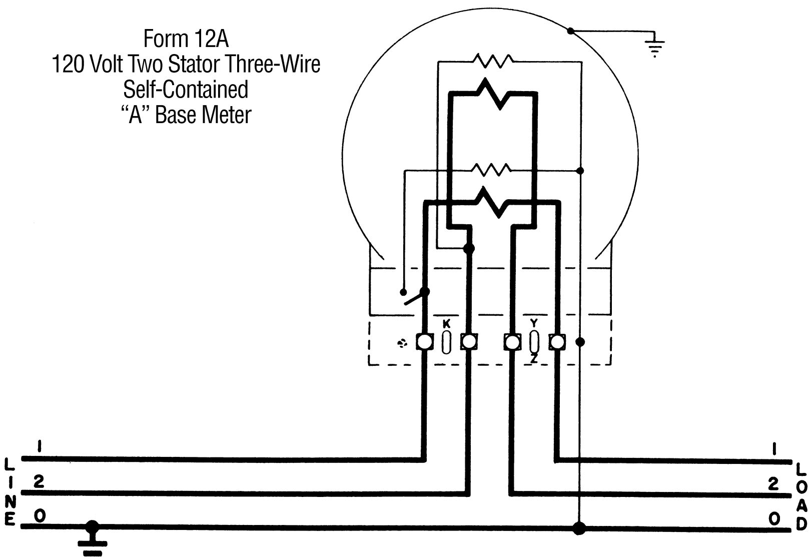


Figure 12-27. Self-Contained.

Three-Wire Network Circuit

Front Views

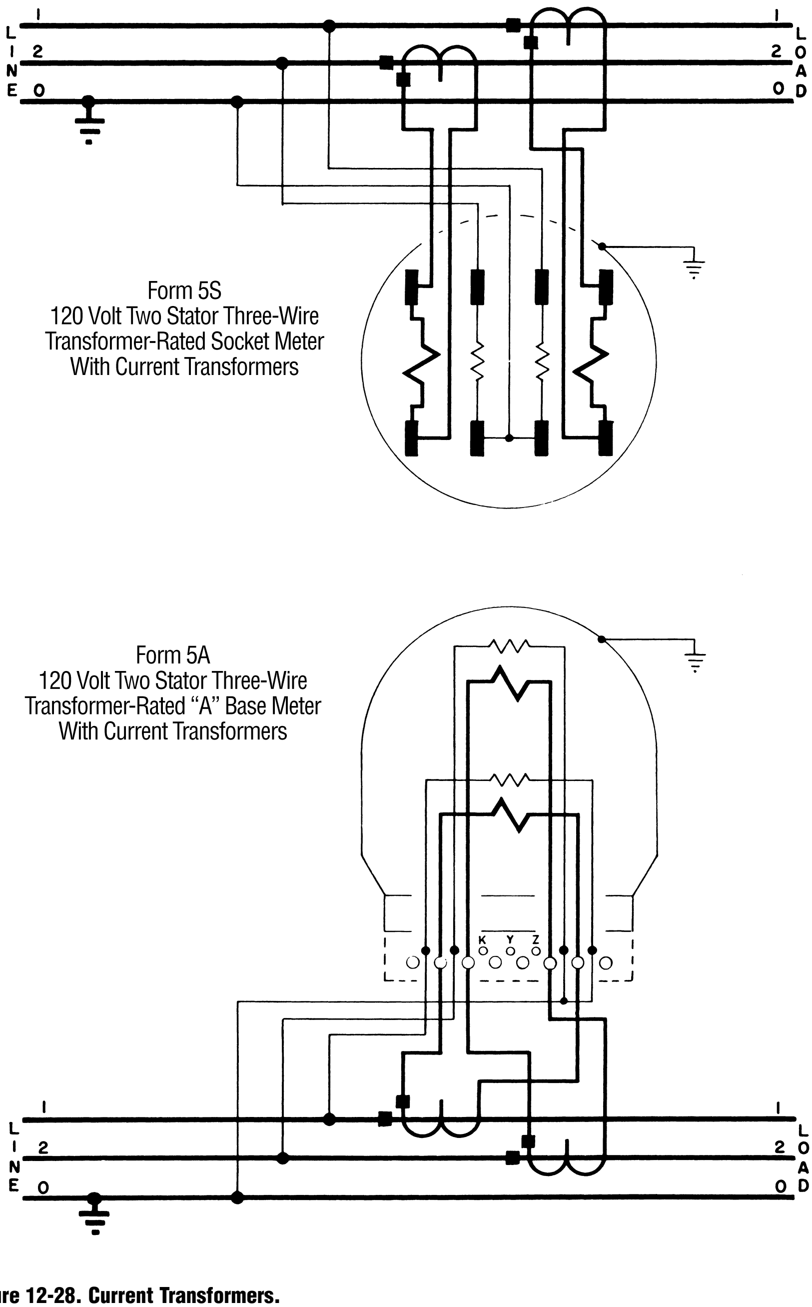


Figure 12-28. Current Transformers.

Three-Wire Network Circuit

Front Views

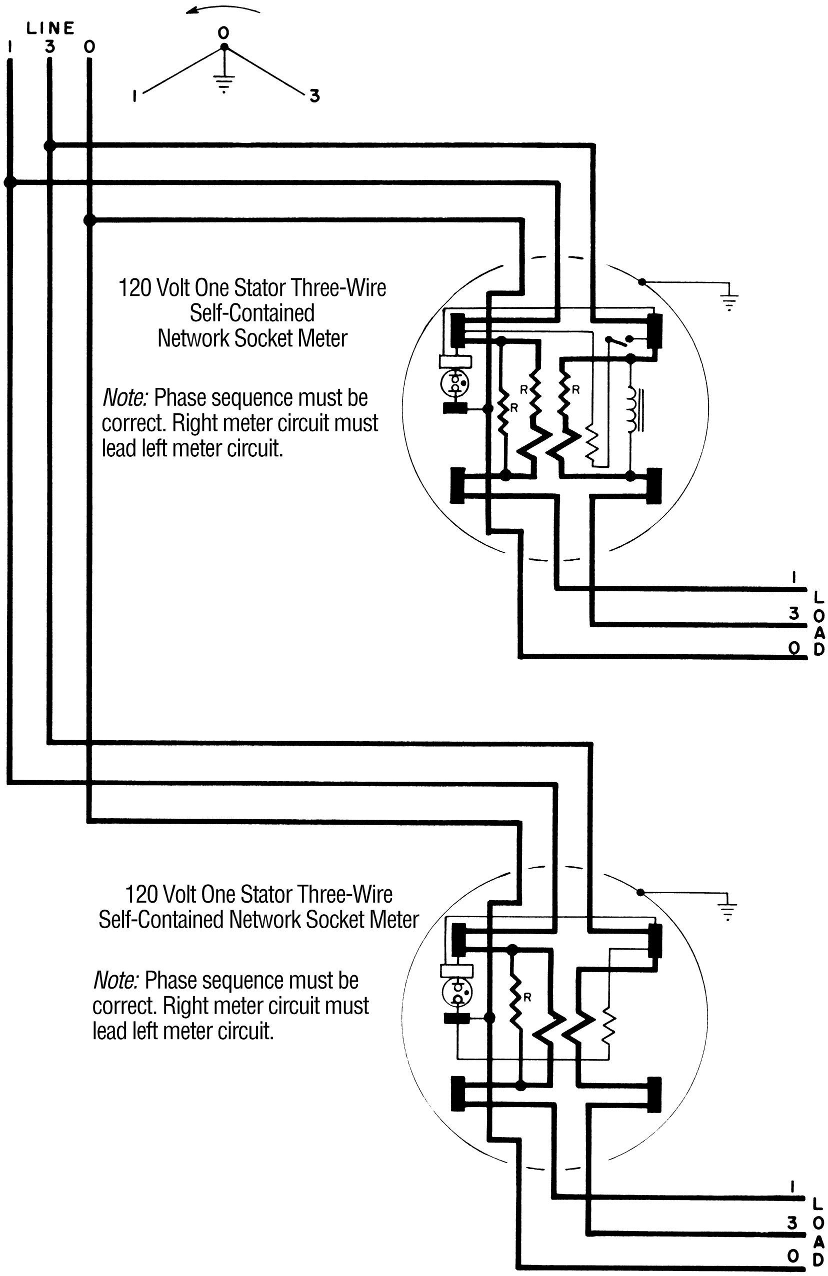
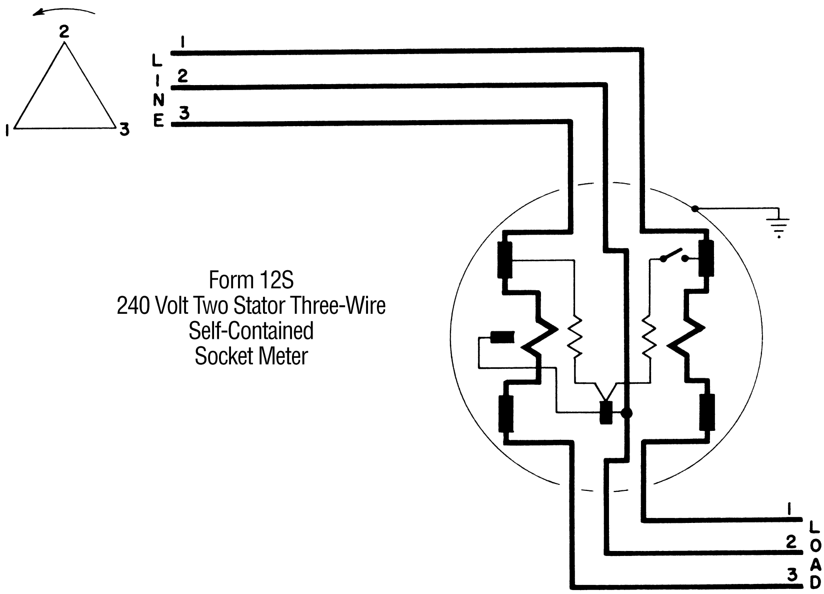


Figure 12-29. Self-Contained, One Stator Meter (for Network Only).

Three-Phase, Three-Wire Circuits

Front Views



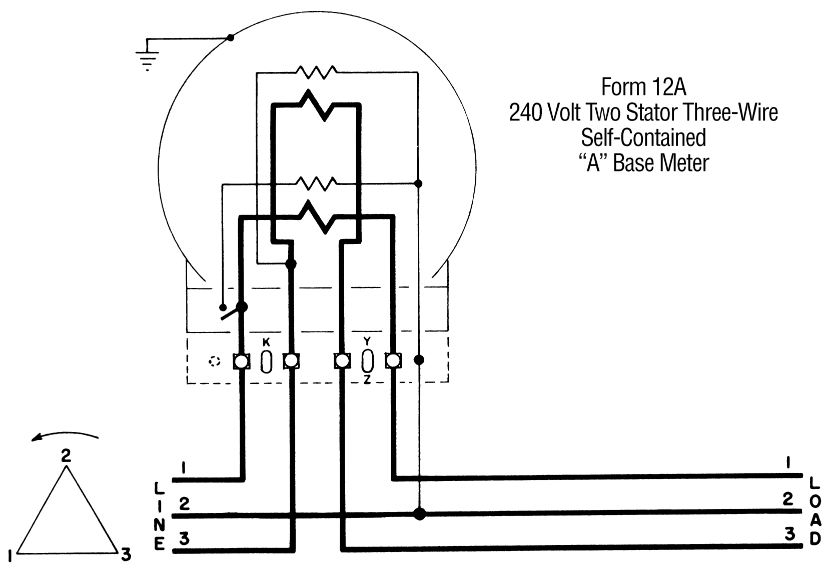


Figure 12-30. Self-Contained, Five-Terminal Meter.

Three-Phase, Three-Wire Circuits

Front Views

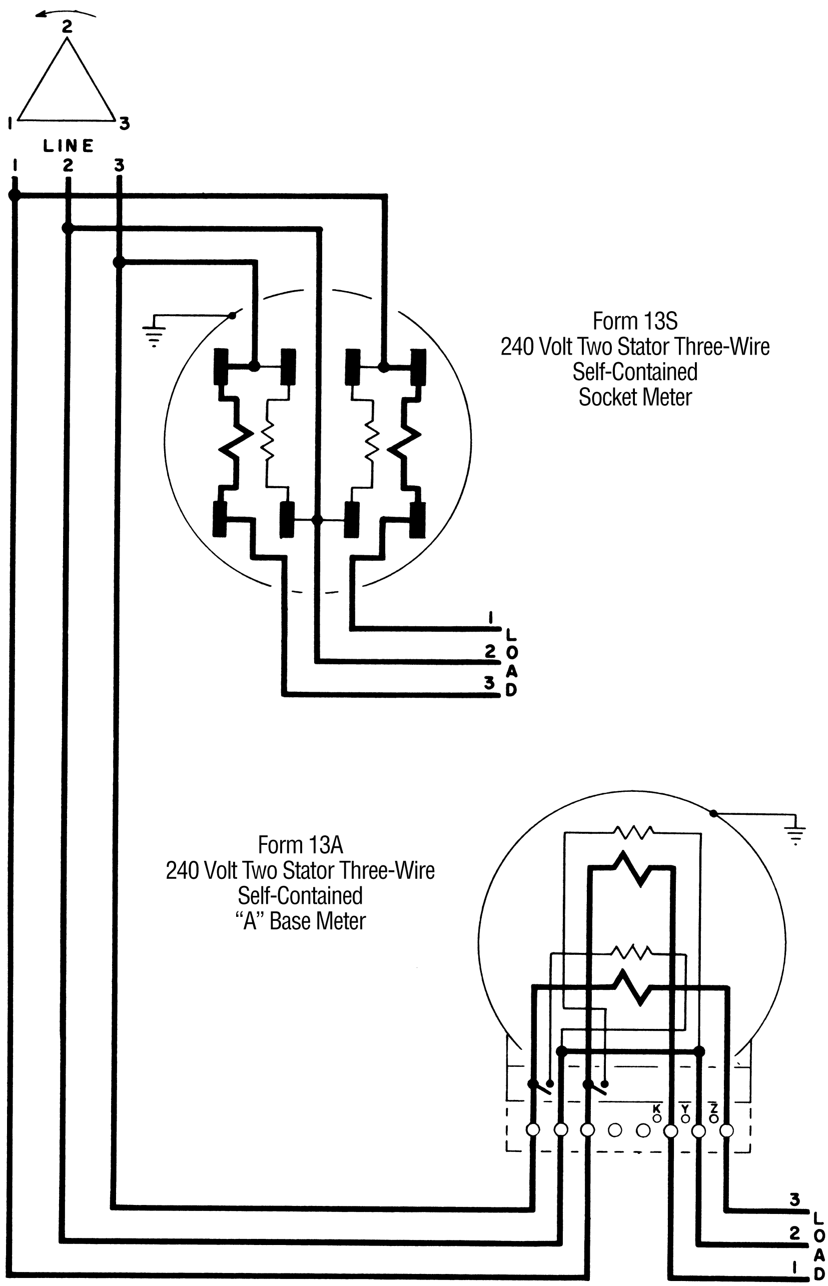


Figure 12-31. Self-Contained.

Three-Phase, Three-Wire Circuits
Front View

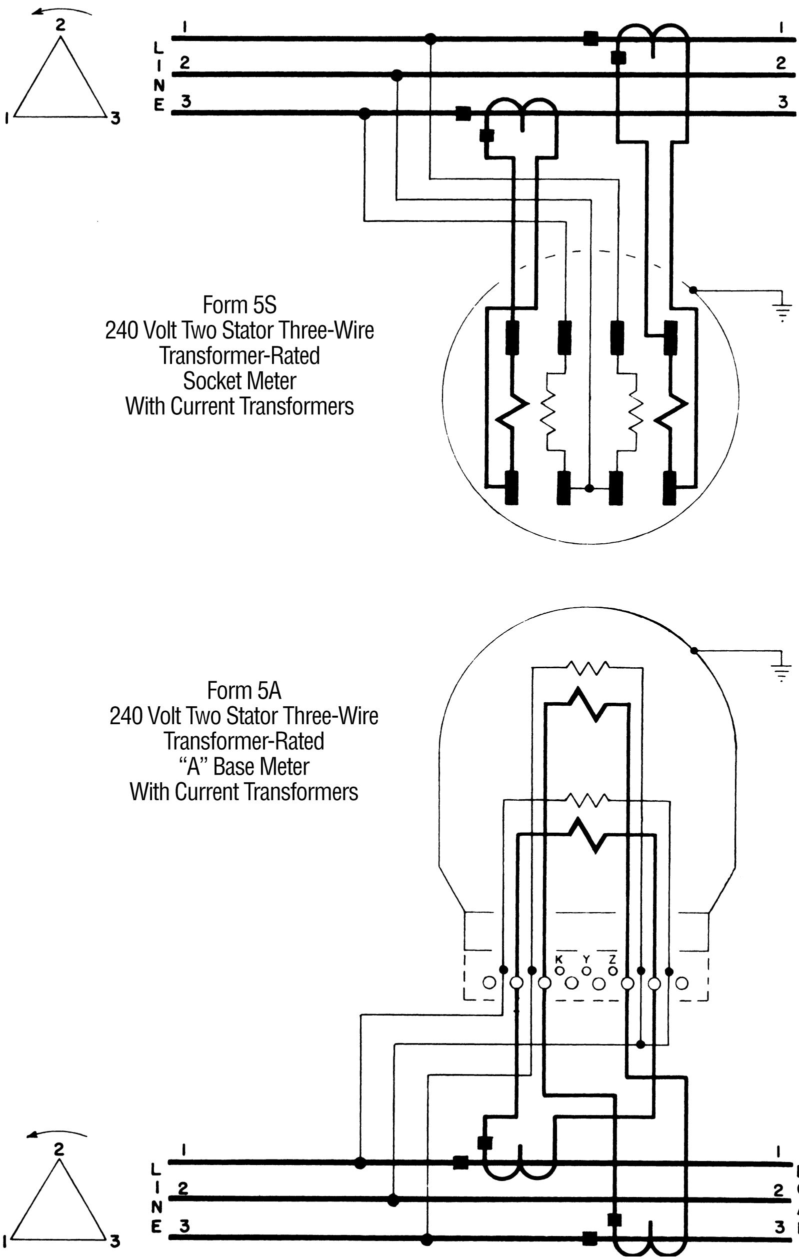


Figure 12-32. Current Transformers.

Three-Phase, Three-Wire Circuits
Front View

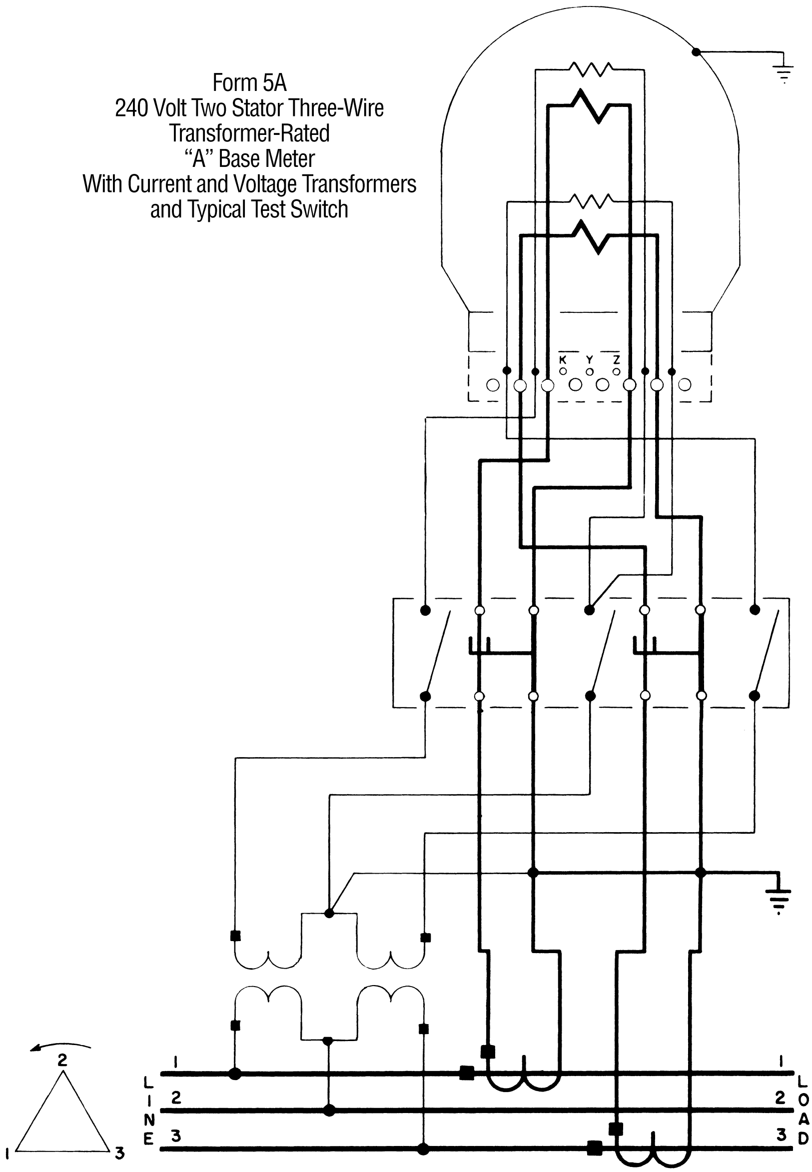


Figure 12-33. Current and Voltage Transformers and Typical Test Switch.

Three-Phase, Three-Wire Circuits

Front Views

Form 5A
240 Volt Two Stator Three-Wire Meters
With Current and Voltage Transformers, and Test Switches

Typical circuit of metering "Out" and "In" current flow,
showing current circuits of "In" meter reversed.

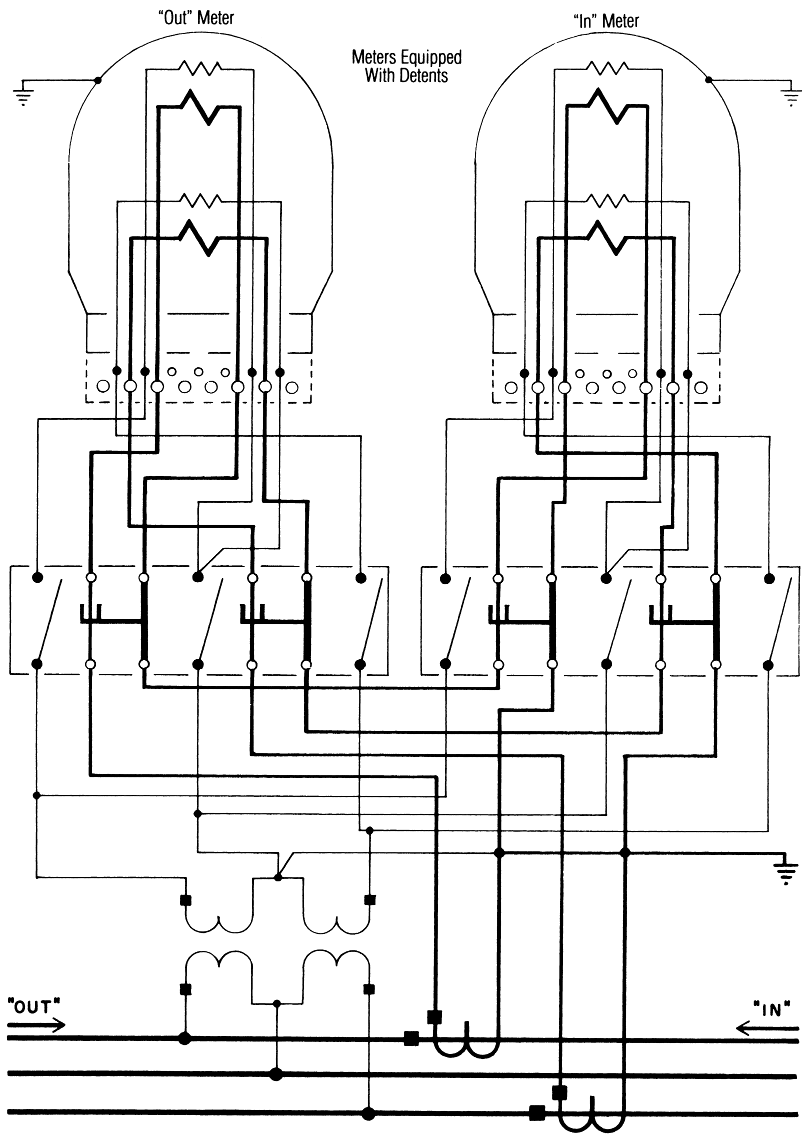


Figure 12-34. "Out" and "In" Metering, Current and Voltage Transformers, and Test Switches.

Three-Phase, Four-Wire Wye Circuits

Front Views

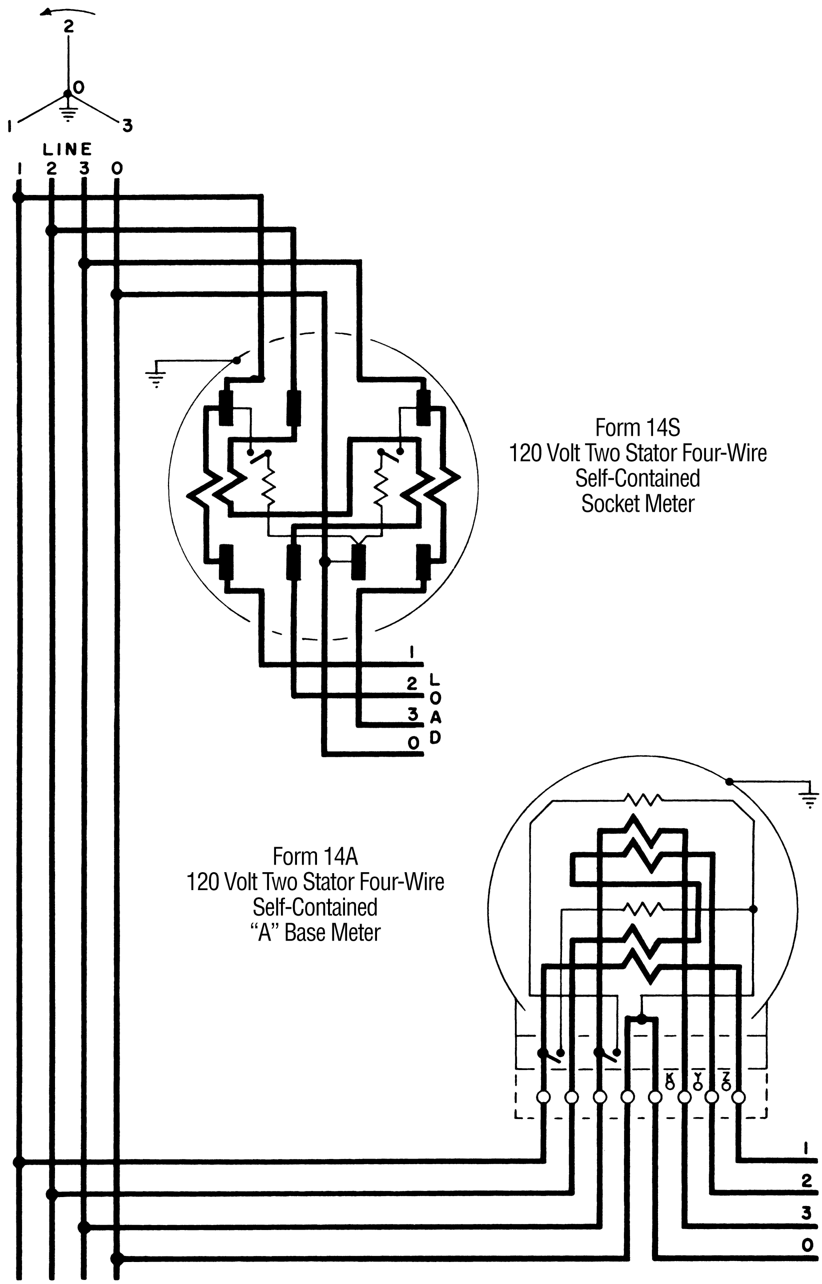


Figure 12-35. Self-Contained.

Three-Phase, Four-Wire Wye Circuits

Front View

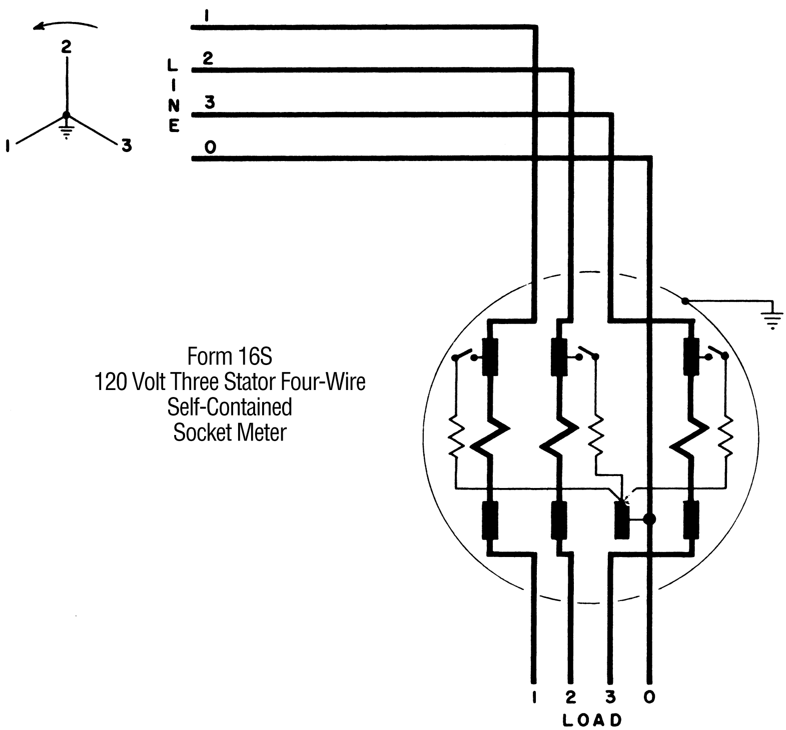


Figure 12-36. Self-Contained.

Three-Phase, Four-Wire Wye Circuits

Front View

Form 16A
240 Volt Three Stator Four-Wire
Self-Contained
"A" Base Meter
Showing typical self-contained
connection blocks with wiring connected in
Line-Load, Line-Load, Line-Load sequence.

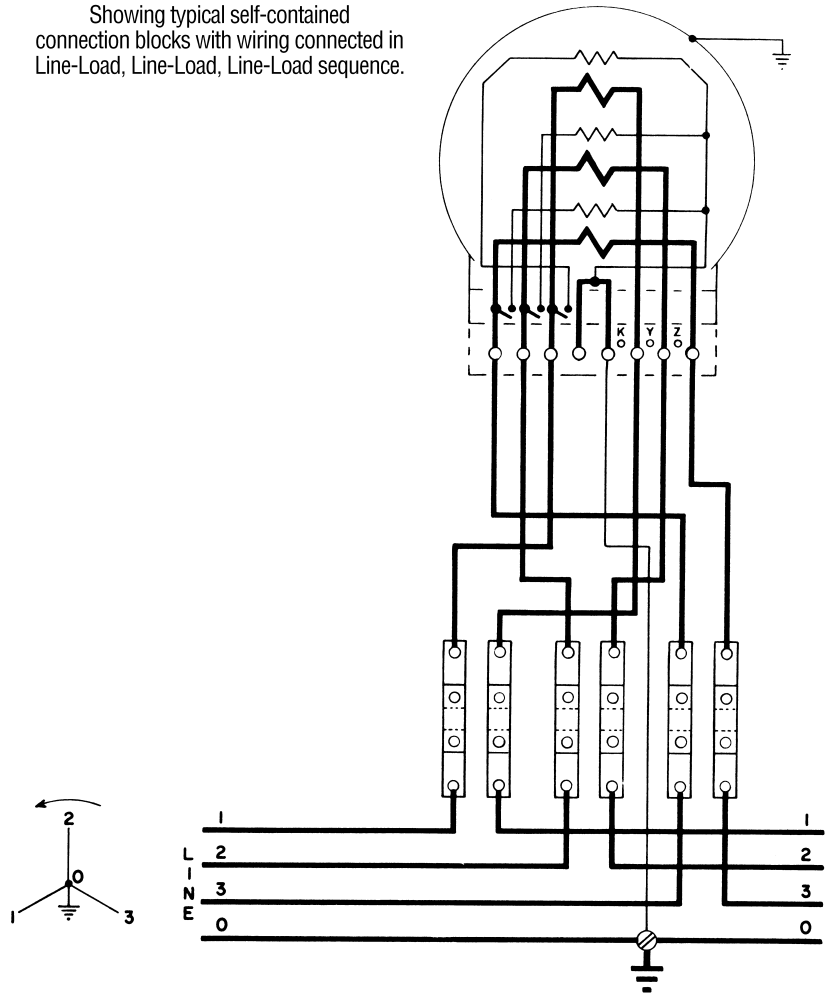


Figure 12-37. Self-Contained with Connection Blocks.

Three-Phase, Four-Wire Wye Circuits
Front View

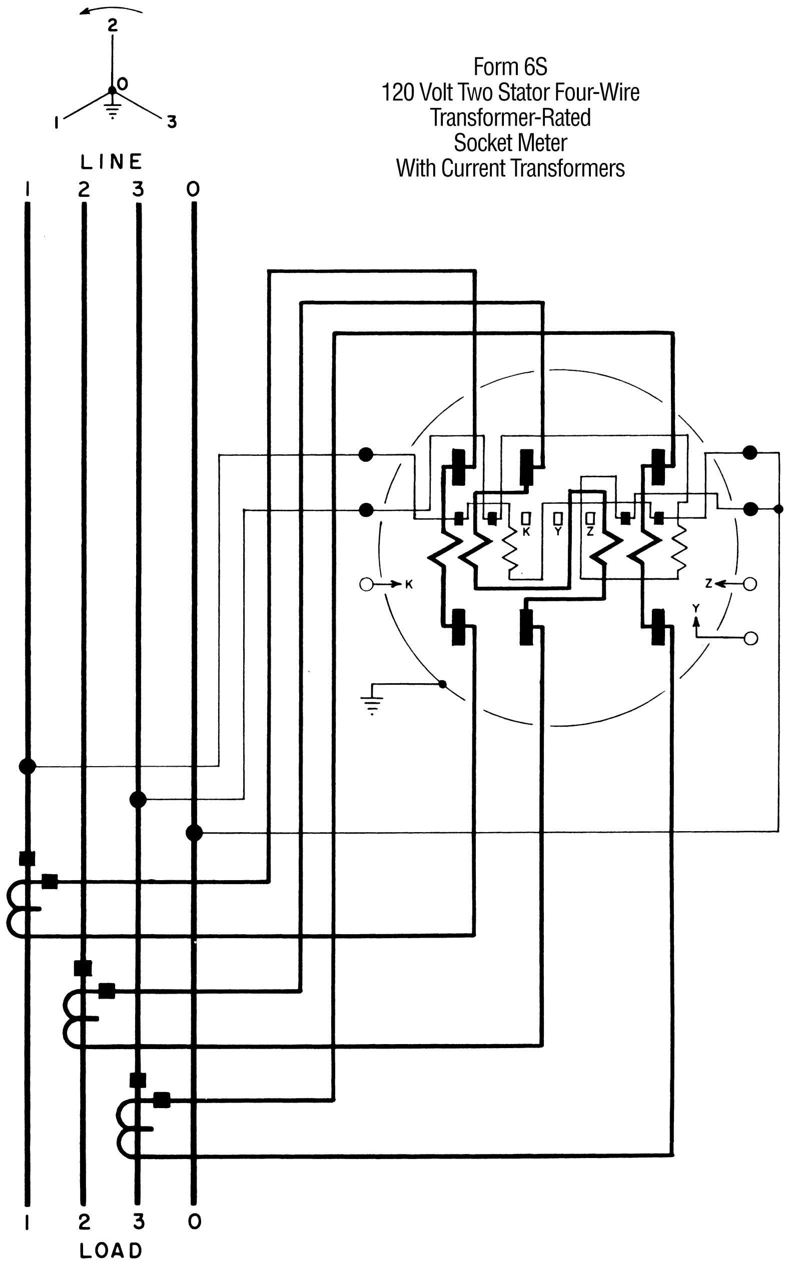


Figure 12-38. Current Transformers.

Three-Phase, Four-Wire Wye Circuits
Front View

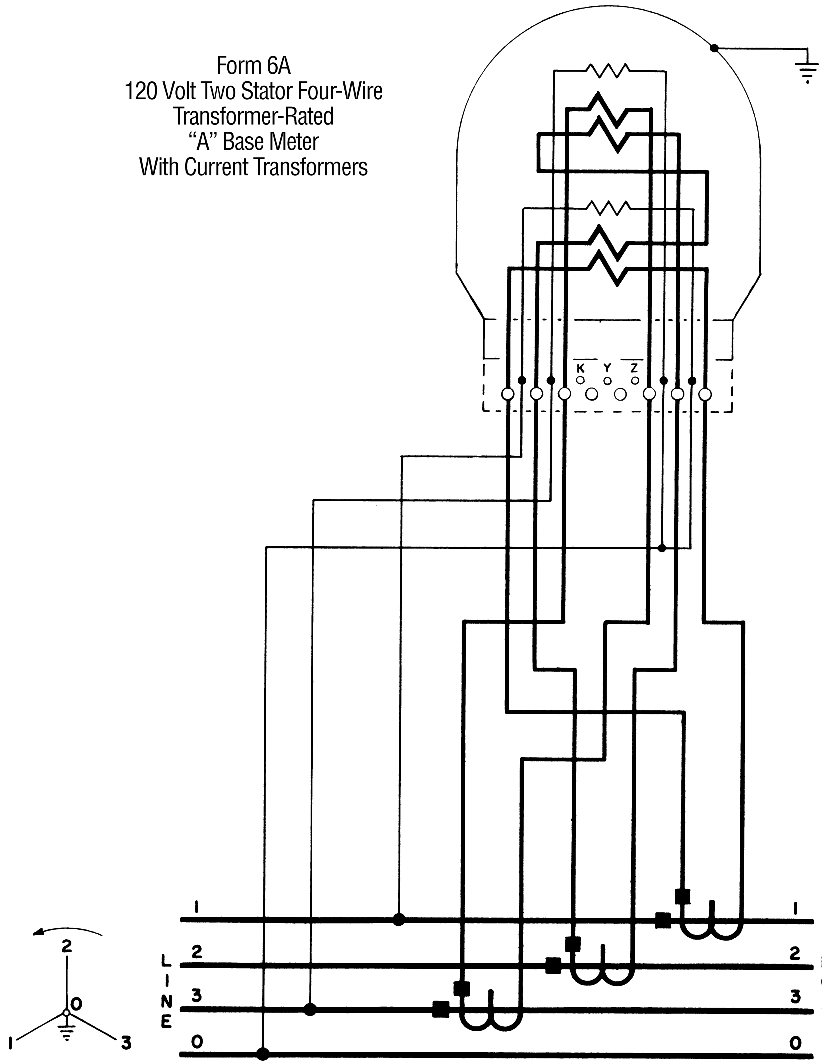


Figure 12-39. Current Transformers.

Three-Phase, Four-Wire Wye Circuits

Front View

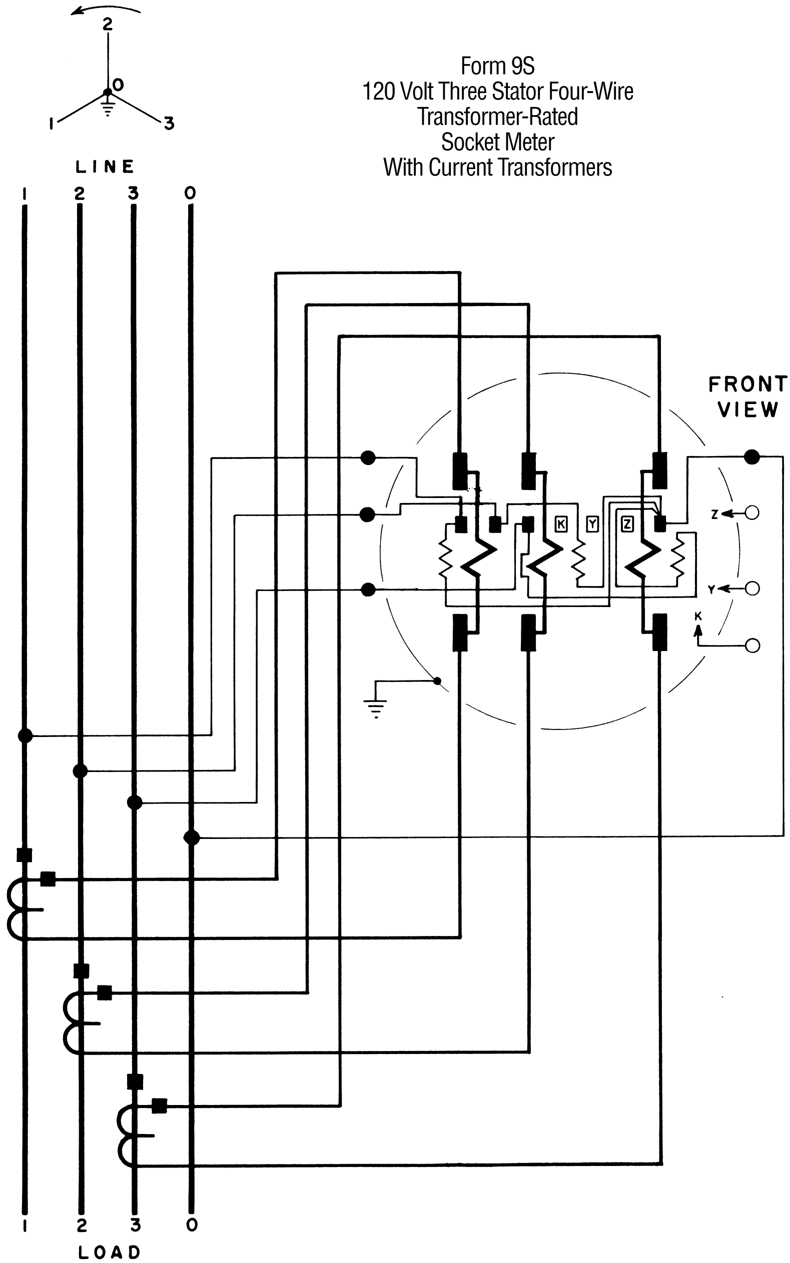


Figure 12-40. Current Transformers.

Three-Phase, Four-Wire Wye Circuits
Front View

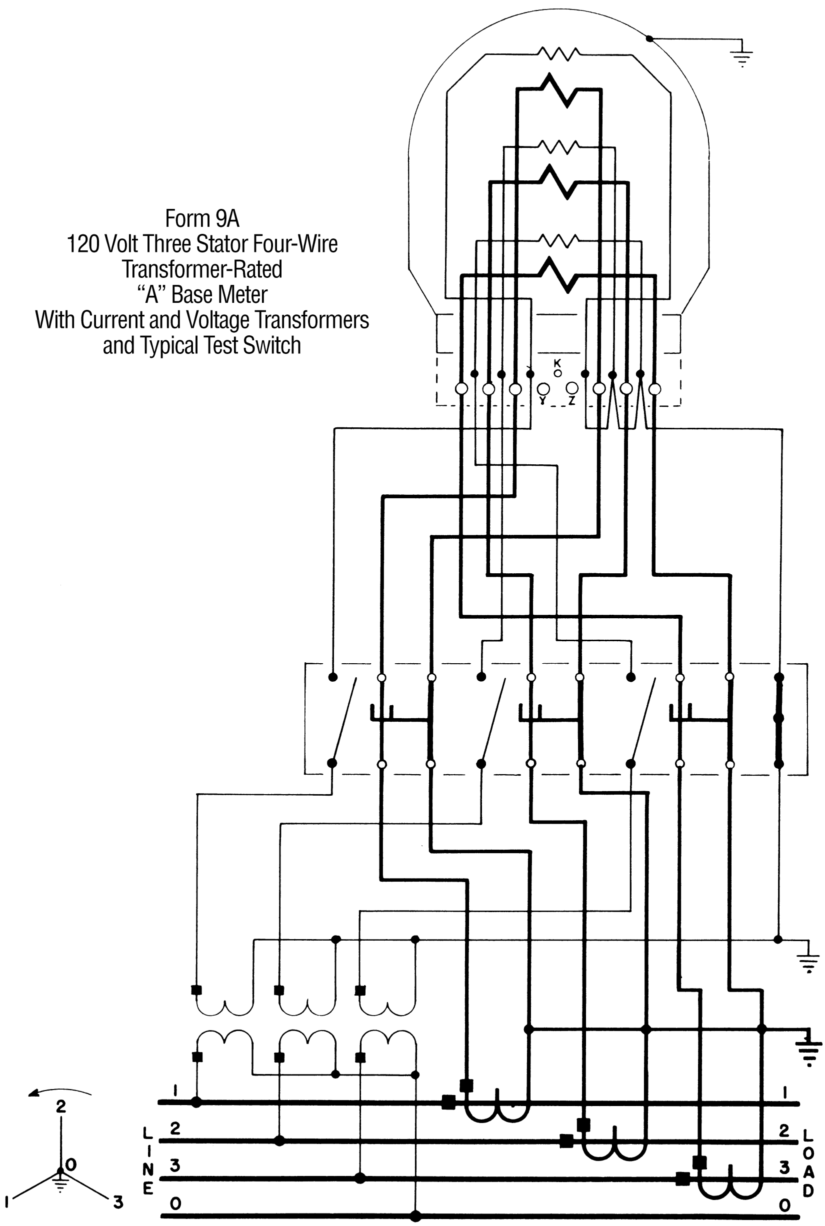


Figure 12-41. Current and Voltage Transformers and Typical Test Switch.

Three-Phase, Four-Wire Delta Circuits

Front Views

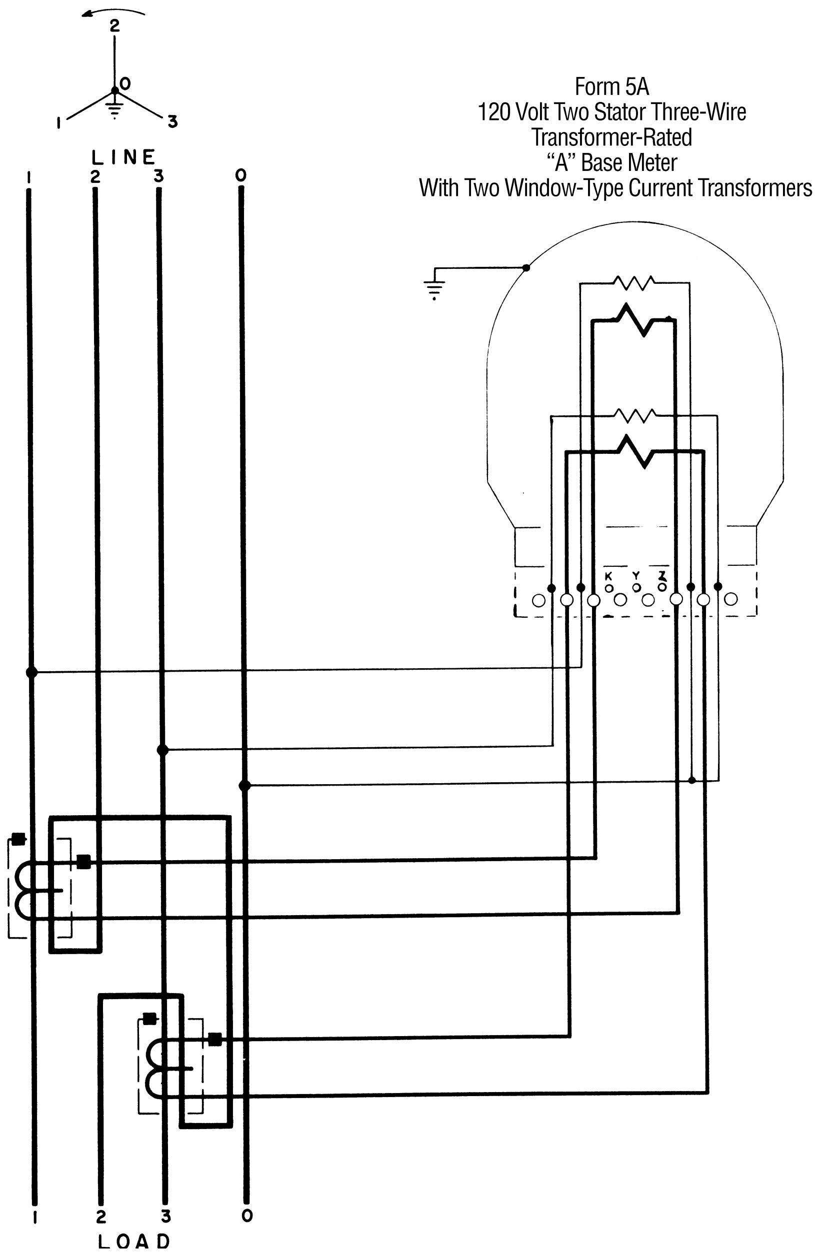


Figure 12-42. Two Window-Type Current Transformers.

Three-Phase, Four-Wire Wye Circuits
Front View

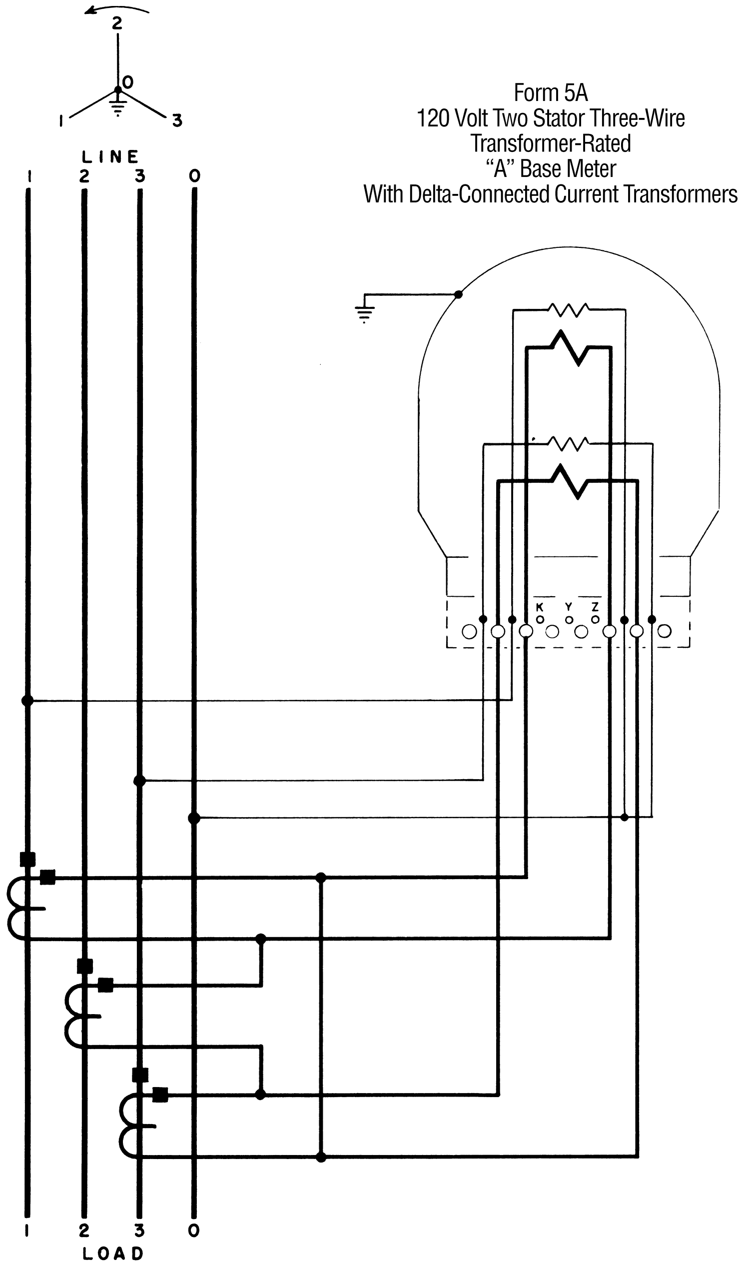


Figure 12-43. Delta-Connected Current Transformers.

Three-Phase, Four-Wire Delta Circuits

Front Views

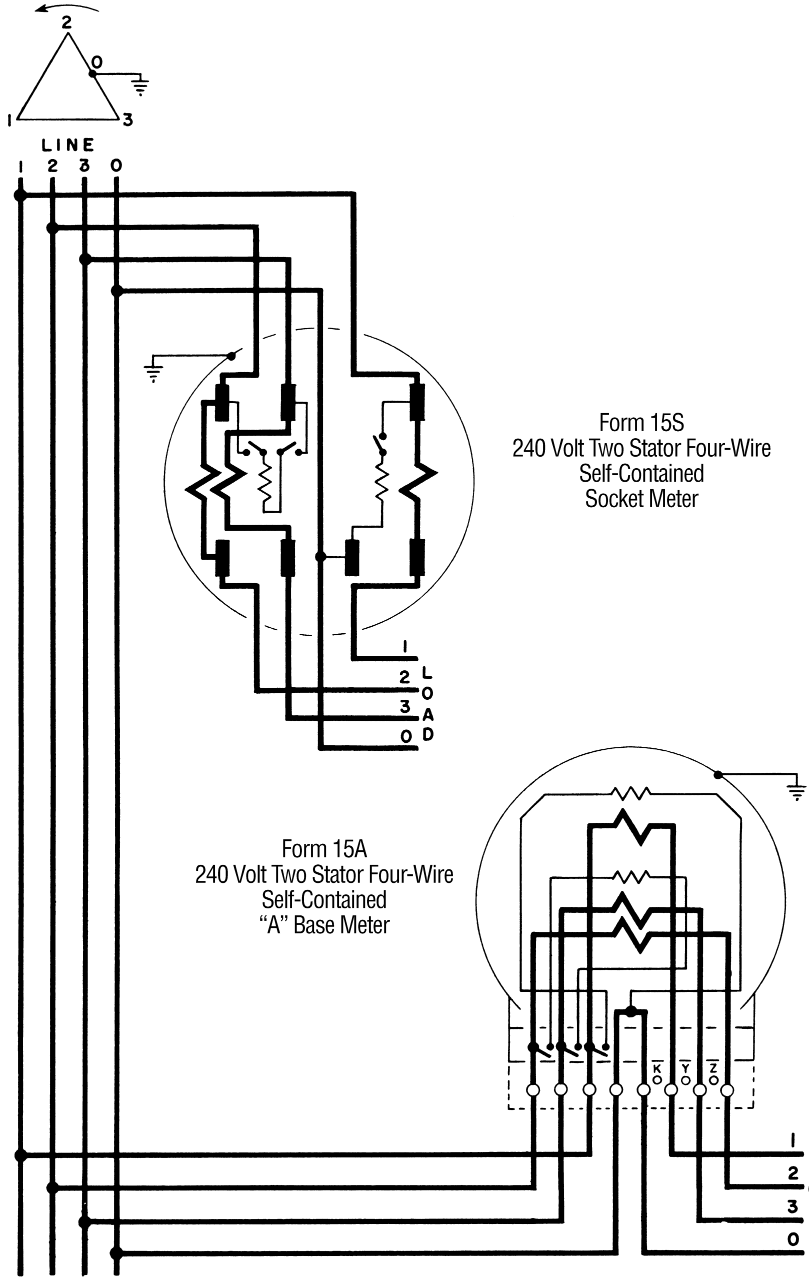


Figure 12-44. Self-Contained.

Three-Phase, Four-Wire Delta Circuits

Front Views

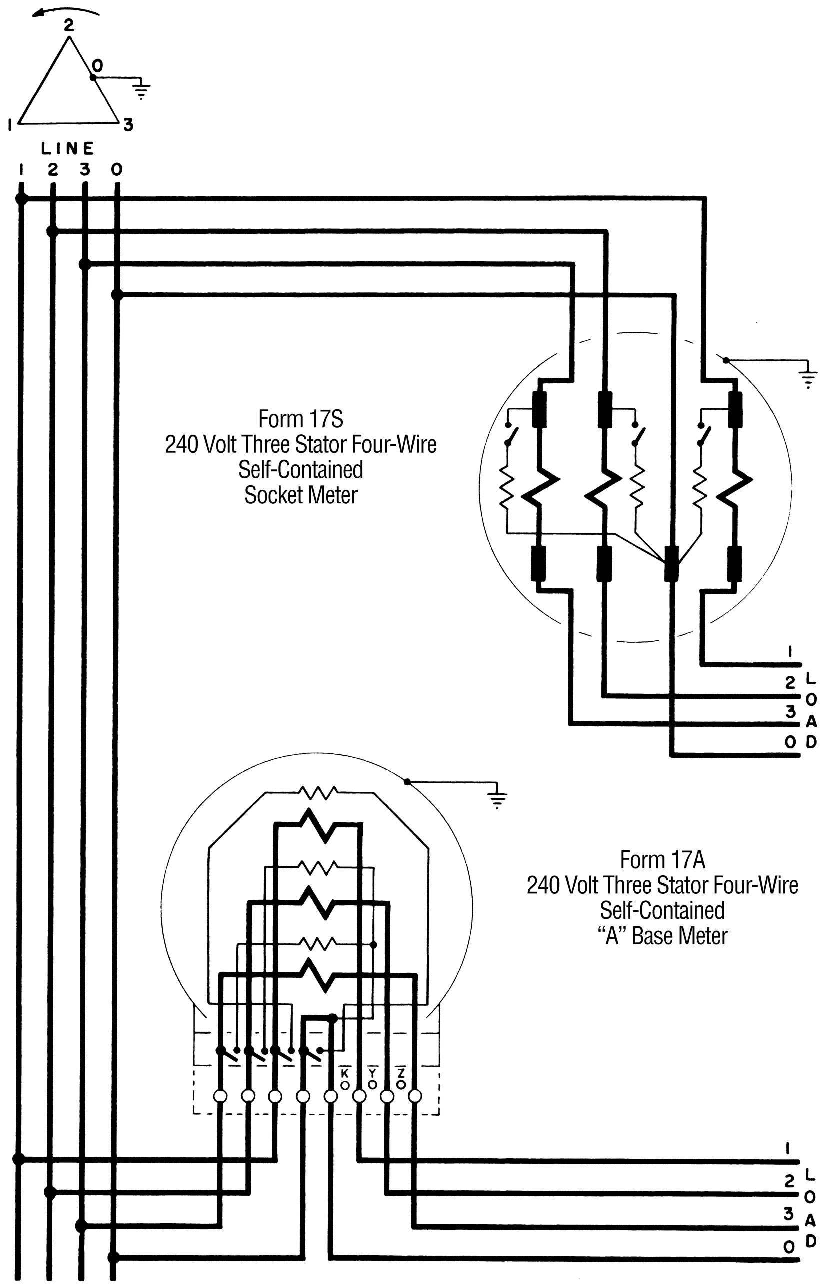


Figure 12-45. Self-Contained.

Three-Phase, Four-Wire Delta Circuits
Front Views

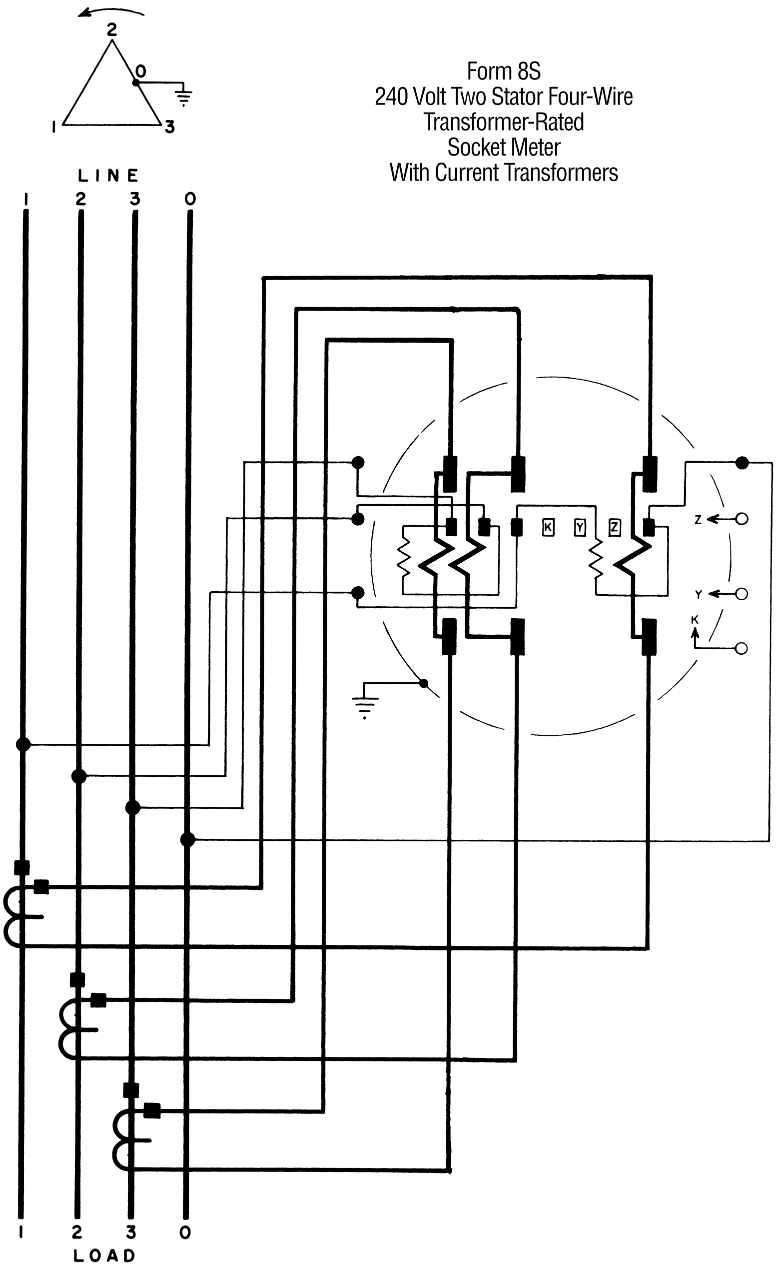


Figure 12-46. Current Transformers.

Three-Phase, Four-Wire Delta Circuits
Front View

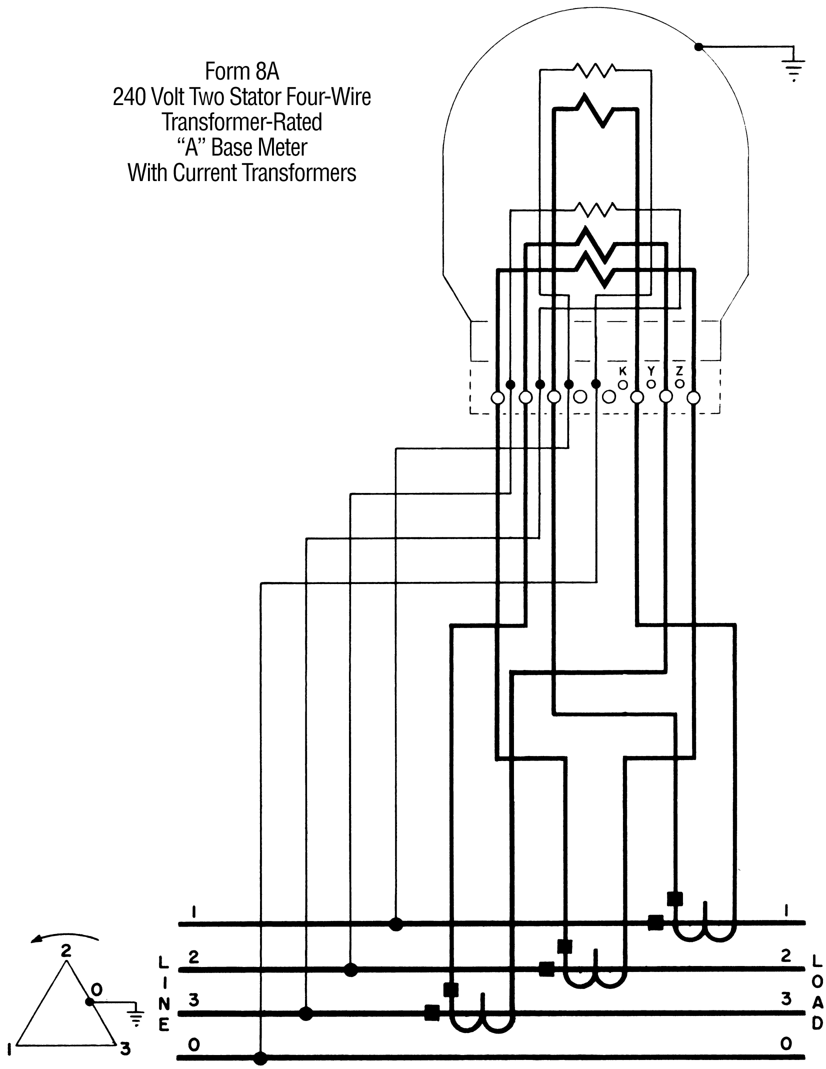
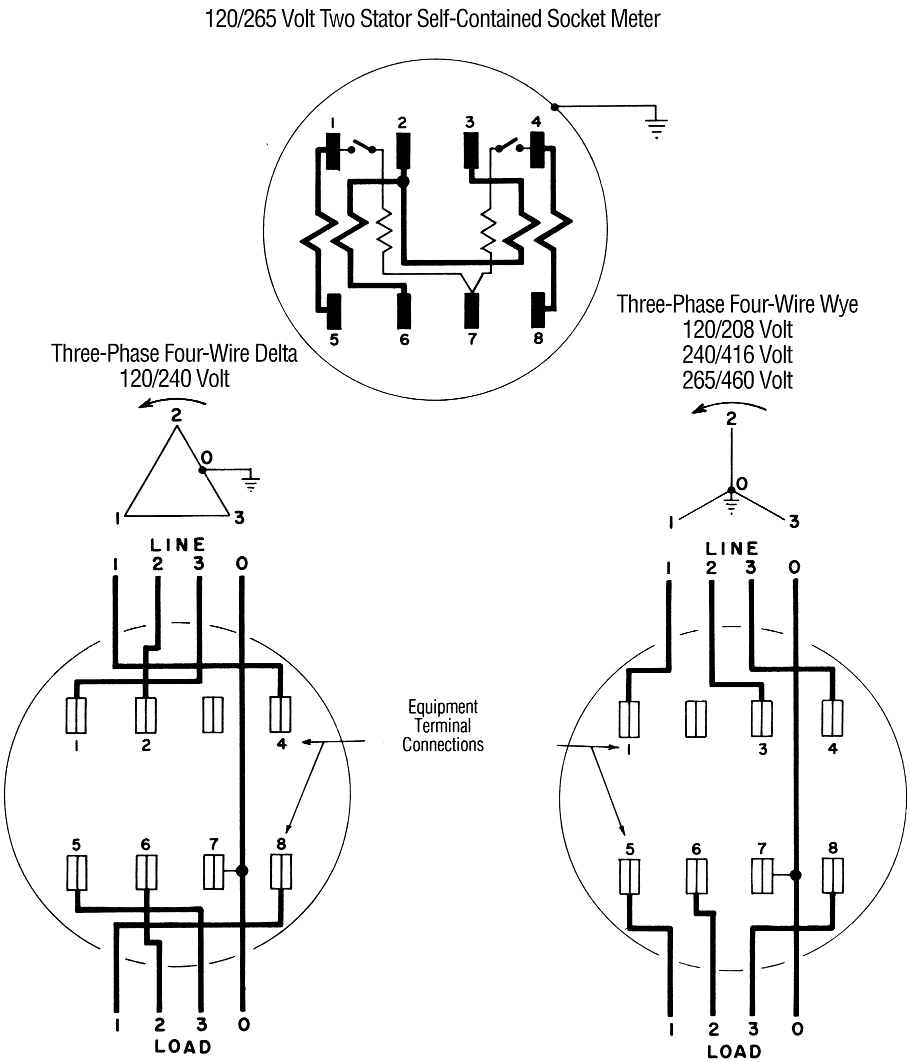


Figure 12-47. Current Transformers.

Universal Meter

For Use on Three-Phase Four-Wire Delta, and Three-Phase Four-Wire Wye Circuits
Front Views



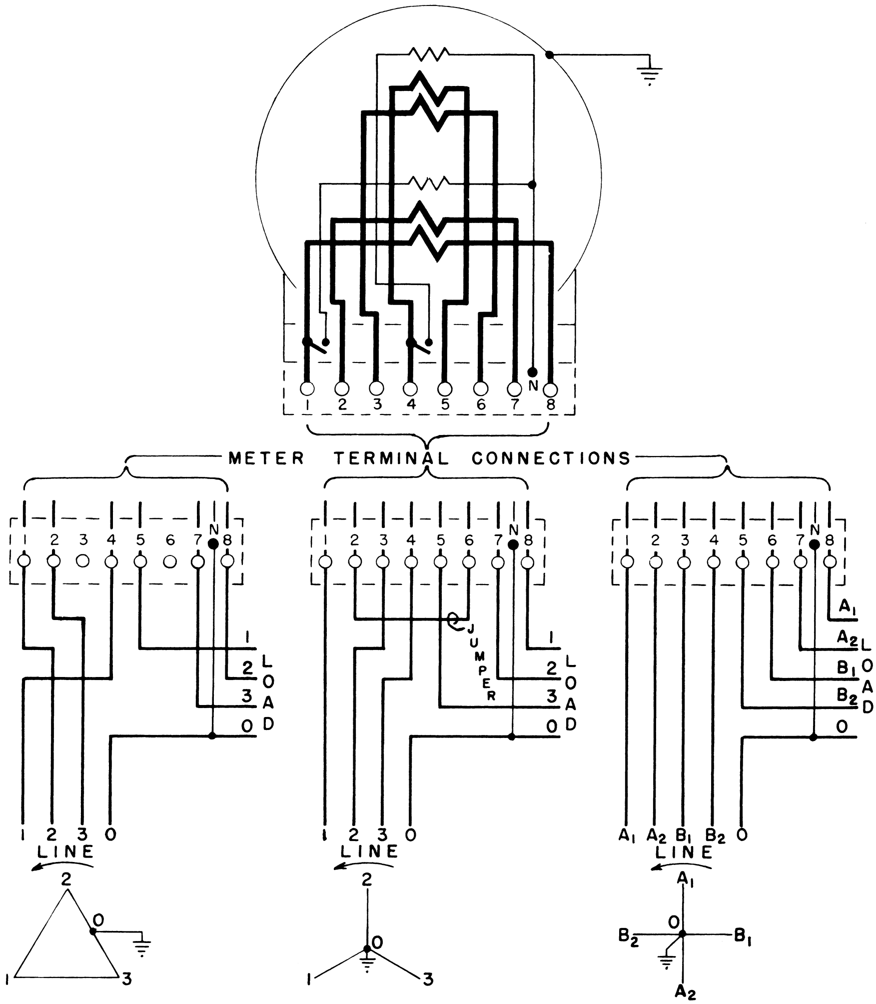
Note: Voltage coils suitable for from 120 volts to 265 volts.

Figure 12-48. Self-Contained "S" Type.

Universal Meter

For Use on Three-Phase Four-Wire Delta, Three-Phase Four-Wire Wye, and Two-Phase, Five-Wire Circuits
Front View

120/265 Volt Two Stator Self-Contained "A" Base Meter



Three-Phase Four-Wire Delta 120/240 Volt

Three-Phase Four-Wire Wye 120/208 Volt 240/416 Volt 265/460 Volt

Two-Phase Five-Wire 120/240 Volt 240/480 Volt

Note: Voltage coils suitable for from 120 volts to 265 volts.

Figure 12-49 Self-Contained "A" Type.

CHAPTER 13

THE CUSTOMERS' PREMISES, SERVICE AND INSTALLATIONS

THE PURPOSE OF THIS CHAPTER is to discuss certain fundamentals concerning the utility's service to the customer and present information which may be of value to the meter installer, tester, or troubleshooter.

Although metering employees are not commonly called on to serve as wiring inspectors and they should not except under specific instructions from their supervisors discuss wiring deficiencies with the customer, a knowledge of the basic principles of service wiring should be of assistance in discovering hazardous conditions and in understanding all aspects of the work. Each utility company has its own service rules which provide specifications of materials and workmanship. It is not intended here to treat such details. When performing work on energized equipment review OSHA 1910.269 and your company's safety practices when performing any work. Safety should be utmost concern.

THE CUSTOMER'S SERVICE

The Service Drop

The service drop is the connection between the customer's wiring and the company's distribution line. The drop may be open wire or cable. Considerations of current-carrying capacity, voltage drop, and mechanical strength control the material and wire size. Mechanical strength is important since the conductors may be subject to ice loading and wind pressure. Some slack is necessary to avoid excessive strain on the service bracket which is the attachment on the customer's house. The point of attachment must be high enough to provide proper clearances. According to the 1990 *National Electrical Code*, services must have the following clearances: 10 feet above sidewalks, finished grade, or platforms; 12 feet over residential driveways and commercial areas not subjected to truck traffic; 15 feet over commercial and other areas subjected to truck traffic; and 18 feet over public streets, alleys, and roads.

The underground service conductor is the connection between the customer's wiring and the electrical company's secondary distribution system.

The connection may be owned by the customer or by the electric company. If the customer owns the underground service conductor, it must be installed in accordance with the *National Electrical Code*.

The Service Entrance

The service entrance conductors are those wires, generally on the outside of the building, from the service drop support to the customer's service equipment. The *National Electrical Code* describes minimum specifications for service entrances and these are often supplemented by rules of the city or town inspectors. In some areas, service drop and service entrance conductors are installed as a continuous run of cable without a break at the point of attachment.

It is obviously impossible for the company to assume responsibility for the various hazards that may result from either faulty wiring or improper use of equipment which has been installed and is maintained by the customer. Normally the responsibility of the company ends at the point of attachment of the service drop-wires to the customer's premises or at the terminal point of company-owned equipment. As a protection for the customer, the company has the right to refuse service to any customer where wiring hazards are known to exist.

Classes of Service

Two-wire service may be taken from a two-wire, three-wire, or four-wire distribution system. Almost without exception, one wire of such service is grounded by the company near the transformer and by the electrical contractor or customer at the customer's service equipment.

Three-wire, single-phase service may be supplied from either a single-phase or a polyphase distribution system. One conductor is normally grounded and the nominal voltage for this service is 240 volts between the ungrounded conductors and 120 volts from each of the ungrounded conductors to the grounded conductor. Some street services are three-wire 480 volts, 240 volts from line to ground and 480 volts from line to line.

Three-wire network service is supplied from a four-wire, wye distribution system. One line is always grounded. The nominal voltage for this circuit is 208 volts between the ungrounded conductors and 120 volts between each of the ungrounded conductors to the grounded conductor. Note that 208 volts is the phasor resultant, not the algebraic sum, of the two line-to-ground voltages.

Three-wire, three-phase service may be supplied from either a closed-delta or an open-delta transformer bank. The difference between these two connections is largely one of capacity. The output of an open-delta bank is 58% of the output of a closed delta where the individual transformers are similar.

Four-wire, three-phase, delta service is often used for combined power and lighting. It is a delta service with one transformer center tapped to provide 120 volts for lighting. The center tap must be grounded. In this case, the voltage between any two phase wires is 240 volts; the voltage between the grounded wire and either of two phase wires is 120 volts; but between the grounded line and the third phase wire the voltage is 208 volts. The transformer bank may be either open-delta or closed-delta.

Four-wire, three-phase, wye service is also used for combined power and lighting. Under balanced load conditions, the grounded neutral carries no current.

If the voltage from neutral to phase conductor is 120 volts, the voltage between any two-phase wires is 208 volts. Likewise, if the voltage from the neutral to the phase conductor is 277 volts, the voltage between any two-phase wires is 480 volts.

Primary service is service above 600 volts where the customer owns the transformers which reduce the service voltage from the primary level to the operating level requested by the customer. The metering is done with instrument transformers, normally installed at the point where the customer facilities are connected to the electric utility.

How to Distinguish between Three-Wire Network and Three-Wire, Single-Phase Services

Elsewhere in this *Handbook* it has been shown that the requirements for network metering are not met by the meter normally used on single-phase services.

To distinguish between a three-wire network service and a three-wire, single-phase service, any of the following three methods may be used.

Voltmeter Check

In a single-phase circuit, the voltage across the ungrounded wires is equal to the sum of the voltages between the grounded conductor and each of the other two lines. In a network service, the voltage across the ungrounded wires is equal to about 87% of the sum of the voltages between the grounded conductor and the ungrounded lines.

Example (with imbalanced voltages):

	Three-Wire, Single Phase	Three-Wire Network
Voltage between grounded wire and live leg A	116 volts	116 volts
Voltage between grounded wire and live leg C	122 volts	122 volts
Voltage between A and C	238 volts	207 volts

This test requires a voltmeter rather than a voltage tester since it is necessary to determine relatively small differences among voltages.

Phase-Sequence Indicator

In a single-phase circuit, the rotating-disk type of phase-sequence indicator will give no indication. On either three-wire network or three-phase circuits, the disk will rotate.

Test Lamps

One method for identifying a network service is to connect two identical test lamps in series across the two outside wires. If both lamps brighten perceptibly when the center tap between the two lamps is touched to the neutral, the circuit is a wye network. This is because each lamp has the voltage applied changed from 104 volts to 120 volts. If the lamps remain at the same brilliancy or if one dims and the other brightens slightly due to imbalanced voltages, the circuit is single-phase. Since the test lamp method is not without hazard, it is no longer commonly used. See Figure 13-1. Be aware that some street lighting voltages are 480 volt three-wire single phase and the bulb may explode if connected from line to line.

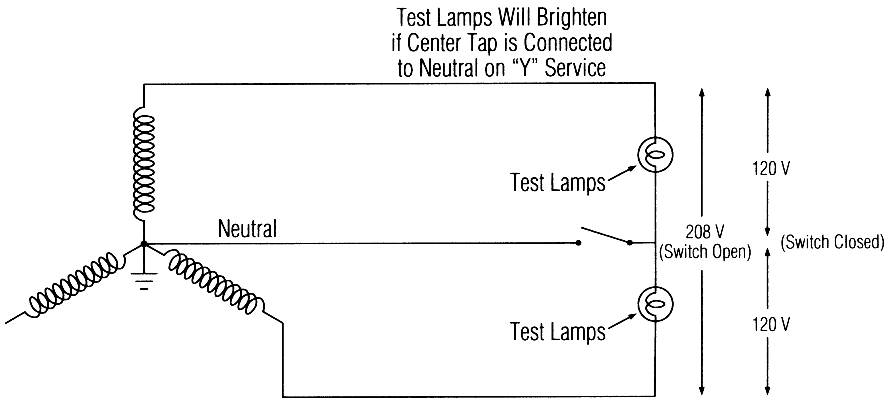


Figure 13-1. Test-Lamp Check.

To Distinguish between Four-Wire Delta and Four-Wire Wye Service

A voltmeter check is sufficient for this purpose. First determine which is the grounded conductor. Then check voltages between the grounded conductor and each of the phase wires and phase to phase.

In a wye service, each of these voltages will be 120 volts phase-to-ground and 208 volts phase-to-phase (or 277 volt phase-to-ground and 480 volts phase-to-phase). In a delta service, only two of these voltages will be 120 volts, the third will be 208 volts to ground and 240 volts phase-to-phase.

OVERHEAD SERVICE TO LOW HOUSES

The current popularity of ranch-type houses poses a real problem in maintaining proper clearances of the service drop. This is particularly true when the distribution line and the residence are on opposite sides of the street. One method of maintaining clearances is by a service pole set on the house side of all public ways, driveways, and sidewalks. Another is the use of a service mast attached to the building. A pipe mast of rigid steel conduit from two to three inches in diameter makes a neat extension when properly installed.

CIRCUIT PROTECTION

Lightning Arresters

Lightning arresters are designed to protect circuits and connected equipment by providing a by-pass to ground when the supply circuit voltage rises above safe limits. Basically, the arrester consists of a fixed gap connected between each ungrounded line conductor and ground. Normal line voltages are not capable of arcing across the gap. In electronic meters, metal oxide varistors (MOVs) or air gap spacing on the circuit boards are often used as protection against lightning.

An example of a simple arrester may be found in the relief gaps of modern socket-type watthour meters. In one type of meter there are two relief-gap pins protruding inside the meter base. When the meter is assembled, the current-coil leads are located near but not in contact with these pins. If lightning or a system disturbance of any kind causes a sudden surge of high voltage which might break down the meter insulation, an arc will be established across one or both relief air gaps. The surge will then go through the pins to the stainless-steel straps on the back of the base, into the socket, and then to ground.

Fuses and Circuit Breakers

In general, fuses are designed to open a circuit when the current flowing in it is above a safe limit. The fuse is an over-current protection and must be coordinated with the size of wire it protects. Excessive current may be due to an overload caused by appliances drawing current beyond the current-carrying capacity of the wire or to a short circuit resulting from a failure of insulation. In the latter case, the current may reach very high values. A fuse must be able to open a circuit under either of these conditions.

Overloaded conductors become a source of fire hazard because of conductor heating. Heat is a form of energy rather than of power and, as such, is a function not only of the current in the wire but of the time during which the current flows.

A fuse consists of a strip of metal which has a low melting temperature enclosed in a screw plug or a cartridge. This is placed in series with the load. When the current passing through the fuse exceeds the ampere rating of the fuse, the heat produced due to the flow of current will cause the metal to melt opening the circuit.

Since the fuse link is melted by heat energy and since heat energy is a function of both current and time, the fuse will open either on a very high current existing for a short period of time or a current moderately in excess of rated capacity for a longer period. This time-current characteristic is designated as inverse-time. That is, operation of the fuse occurs in progressively shorter intervals as the current increases. As an example, a 15 ampere fuse may carry 30 amperes for several seconds but will open in about a tenth of a second should 150 amperes occur in the circuit.

Circuit breakers are used in place of fuses as protective devices in many instances. They too will open circuits when overloads or fault currents develop. Breakers have many advantages—one of them being that they can be reset and used again.

Time-Delay Fuses

Many small motors have a starting inrush current several times the normal running current. This inrush current is of such short duration that, although it may cause an annoying voltage dip, it does not result in a serious fire hazard. The time-delay fuse or circuit breaker permits the passage of such starting currents without opening. However, should this high current last for more than the normal starting period of the motor, as might be the case if the motor stalled, the fuse or breaker will open and clear the circuit. Time-delay fuses or circuit breakers will eliminate many "no-light" trouble calls by reducing unnecessary circuit openings.

GROUNDING

A ground is a conducting connection between an electric circuit or equipment and the earth. Such a connection may refer to the grounding of the neutral wire of a circuit or to the connection between such hardware as meter sockets or switch cabinets and the earth.

When and how to ground are questions which do not always have simple answers. Conditions of use, location of equipment, and other considerations have a bearing on methods of grounding. *Grounding at any one location must conform to company policy which has been established for the whole utility system.*

Residential Wiring Grounds

Responsibility for adequate grounding on the customer's premises lies with the customer and not with the utility company.

Grounding is one of the most important subjects covered by the *National Electrical Code* and this code is very clear in regard to the purposes of grounding. It reads:

> Circuits are grounded to limit excessive voltages from lightning, line surges, or unintentional contact with higher voltage lines and to limit the voltage to ground during normal operation.

The *National Electrical Code* requires the grounding of one conductor of electrical systems in which the voltage to ground does not exceed 150 volts. One of the wires in a single-phase, three-wire system, and also in a four-wire wye system is called the neutral conductor and is grounded within the company distribution system. This same conductor, whenever brought onto the customer's premises, must again be connected to a ground at a point as close to the entrance to the structure as possible, but at no other point. Since a two-wire system comprises the neutral conductor and one line conductor, the grounding of the neutral in the two-wire system follows the same rules as those applied in the three-wire system.

Grounding at one point only on the customer's premises guards against the possible hazards due to difference in ground resistance. Also, with only one ground, it is easy to check the presence and adequacy of the grounding circuit.

In residential wiring systems, not only must the neutral conductor be grounded, but exposed metal such as cabinets and conduits which might come in contact with ungrounded current-carrying wires must also be grounded.

Most commonly, the ground connection to the neutral wire is made in the first switch, distribution panel, or meter mounting device installed as a part of the service equipment. The ground connection must be made on the supply side of the customer's switch.

At this point, the neutral wire is connected to the metal enclosure, meter socket, or switch box and grounding of both neutral wire and "non-current-carrying parts" of the system is effected by one grounding conductor. There is, however, an important distinction. On the supply side of the service-disconnecting device, the grounded conductor may be used for grounding the meter socket or trough and service equipment. On the load side, this grounded conductor shall not be used to ground equipment or conductor enclosures. Exceptions to this rule are made only for the frames of 120/240 volt electric ranges and electric clothes dryers which may be grounded to the neutral conductor of a three-wire circuit.

In city areas where there is a public water system, the grounding wire is connected to the water pipe near the point it enters the building.

To avoid corrosion, connectors for use on copper pipe should be made of copper; those for use on galvanized pipe should be made of galvanized iron.

In areas not served by an extensive public water system or where plastic pipe is used, there can be difficulty getting a dependable ground connection. A satisfactory ground connection is one which presents a low resistance to the flow of electric current. Such a ground connection usually consists of a rod, at least eight feet in length, driven into the ground adjacent to the building served.

Identification of Grounded Conductor

Soil conditions vary widely with location and weather. This means that the resistance of grounds can vary widely and may reach very high ohmic values. Under these conditions the correct identification of the grounded secondary conductor is difficult when the service connection is being completed. If a mistake is made and a "live" line conductor is connected to the grounded service wire, a short circuit will develop when the pole ground resistance drops in value during wet weather conditions. It is essential to correctly and permanently identify the grounded conductor when the service connection is made.

One method of identifying the grounded conductor is the use of a high-resistance voltmeter, such as a rectifier type with 1,000 ohms per volt.

After the customer's load has been disconnected by opening the main switch or, when the meter is ahead of the switch, by removing the meter, voltage checks are made as in Figure 13-2. Voltmeter readings should be zero for all combinations of service drop to entrance wires except A to N=, and B to N=. Readings of approximately 120 volts identify N= as the customer's grounded conductor.

CAUTION: If the service is underground, a cable test might indicate ground on all conductors due to capacitance of the cable. Such cases should be checked with a low-resistance meter or a small lamp. (Be aware of voltage rating of the bulb and the service you are connecting to the bulb).

To be effective, grounding should maintain the voltage of the grounded conductor at the same level as that of the ground. Perfect grounding implies zero resistance of the grounding conductor, zero voltage, and zero current flowing in this conductor.

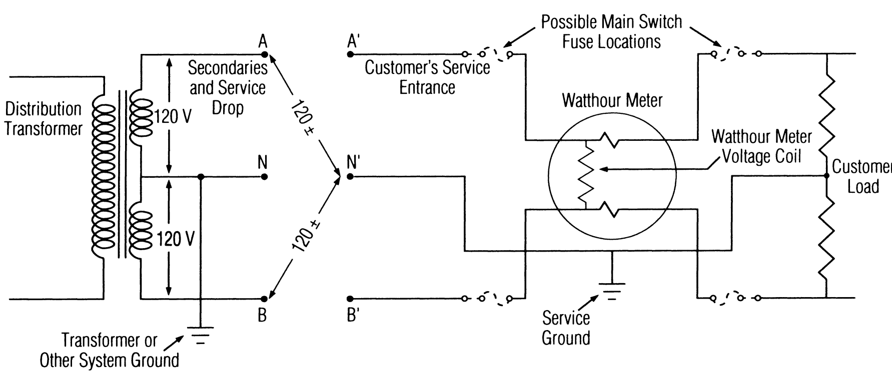


Figure 13-2. Identification of Grounded Conductor.

Two points in regard to grounding must be remembered:

1. The earth's crust is not a good conductor. Because of this fact, differences in ground voltage, particularly under conditions of high current flow such as lightning, may occur. Such voltage differences may exist within distances of a few feet. For instance, in pole metering installations it is wise to have grounding electrodes completely surrounding the area on which a meterman might stand when working;
2. Grounding is not the answer to all electrical safety problems. In some instances, isolation is safer than grounding. For instance, some companies do not ground pole-top metal enclosures because such grounding may be hazardous to personnel working on live conductors.

Conductor Identification by Color

The *National Electrical Code* specifies the color markings of certain insulated conductors in interior wiring systems, and these markings may be helpful in identifying conductors. These specifications require that:

1. Grounded insulated conductors of No. 6 or smaller size shall have identification of white or natural gray color;
2. Grounded insulated conductors larger than No. 6 shall have an outer identification of white or natural gray color, or shall be identified by distinctive white markings at terminals during the process of installation;
3. When, on a four-wire, delta-connected secondary, the midpoint of one phase is grounded to supply lighting and similar loads, that phase conductor having the higher voltage to ground (sometimes called "power leg" or "wildcat phase") shall be indicated by painting or other effective means at any point where a connection is to be made if the neutral (grounded) conductor is present;
4. Grounding conductors shall have a continuous identifying marker readily distinguishing it from other conductors. This marker shall show a green color.

METER SEQUENCE

In the early days of electric distribution it was the practice to install meters and service equipment in the sequence: switch-fuse-meter. In this sequence the meter was protected by the customer's fuses. Also, it was possible to open the circuit before working on the meter. With early meters this sequence was highly desirable. Meter coils and terminal chambers were of low dielectric strength requiring fuse protection. Meter terminals were such that meter changes with live lines often were hazardous. Although there are certain disadvantages, this meter sequence is still common.

As meter test blocks were developed and meter insulation was improved, and particularly when socket meters were introduced, it became feasible to install meters in the sequence: meter-switch-fuse. With this sequence, it became possible to establish a sharp dividing line between company and customer equipment. Connection of new loads to the customer's service equipment could not result in unmetered loads. This freed the company from any inspection requirement of the customer's service equipment.

Figure 13-3 gives schematic diagrams of these sequences.

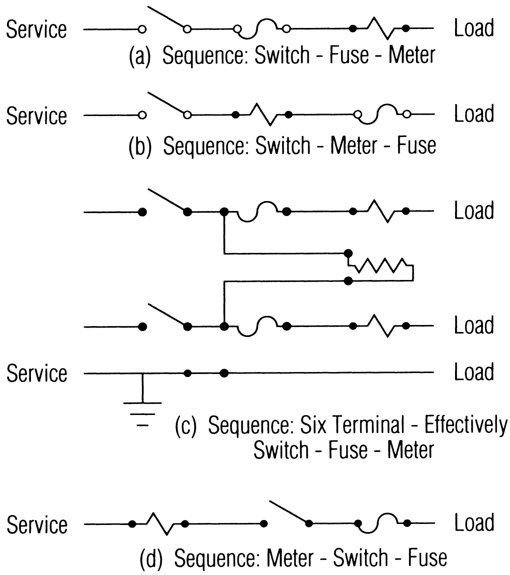


Figure 13-3. Meter and Service Equipment Sequence.

METER CONNECTIONS

Chapter 12, "Meter Wiring Diagrams," gives diagrams of correct meter wiring.

In all meter operations, it must be remembered that the most careful meter test and the most conscientious meter handling in shop and field, can all be made worthless by connection errors.

Employees involved in metering are advised to look for the following common connection errors.

Connection Errors

With the current coil connected in the grounded service conductor the meter may be partially or completely by-passed.

To correctly measure the power in a two-wire circuit, the current coil in the watthour meter must carry all the load current of the circuit. To accomplish this, the current coil must be connected in series with the ungrounded line.

It is worthwhile to elaborate on the importance of having the current coil in the ungrounded leg. Suppose the watthour meter has been installed incorrectly as shown in Figure 13-4 and a ground occurred on the load side of the meter. There are now two paths for current flow as shown by the arrows. The meter current coil is effectively shunted by the ground path. The meter is bypassed and the energy used is, to a considerable degree, unmetered and unbilled.

Figure 13-5 shows another condition which might result with the current coil connected to the ground wire and the fuses not blown. The arrows show that the meter is registering forward without a load being used because the meter and the load wires provide another path to the transformer forloads not properly on this

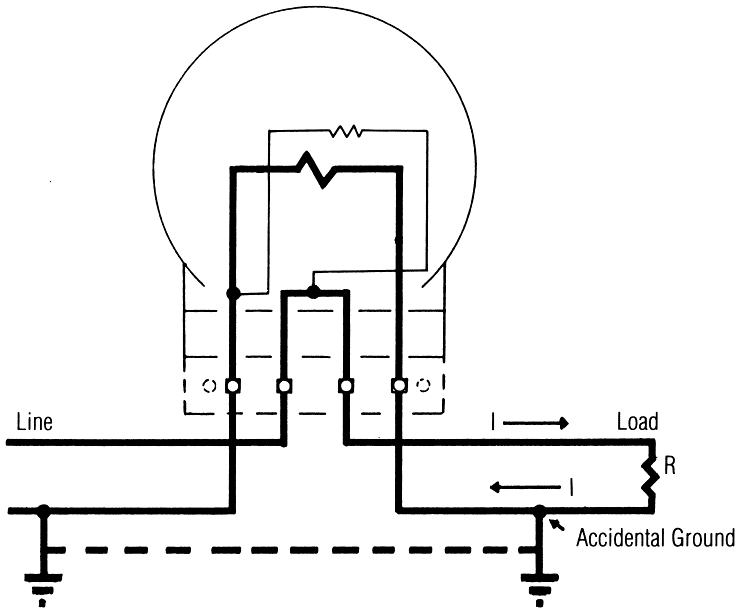


Figure 13-4. Wrong Connection of Two-Wire, Single-Phase Watthour Meter.

meter. The amount of current thus shunted will depend on the resistance of the neutral conductor. Due to numerous splices, the resistance may be quite high. This will cause even more current to take the path through the meter.

Note that the direction of rotation of this incorrectly wired meter will depend on the direction of current in the neutral. Furthermore if a three-wire load is taken, from the same service as is shown in Figure 13-5 for Customer C, any imbalance in the three-wire load will tend to produce rotation in the incorrectly wired meter.

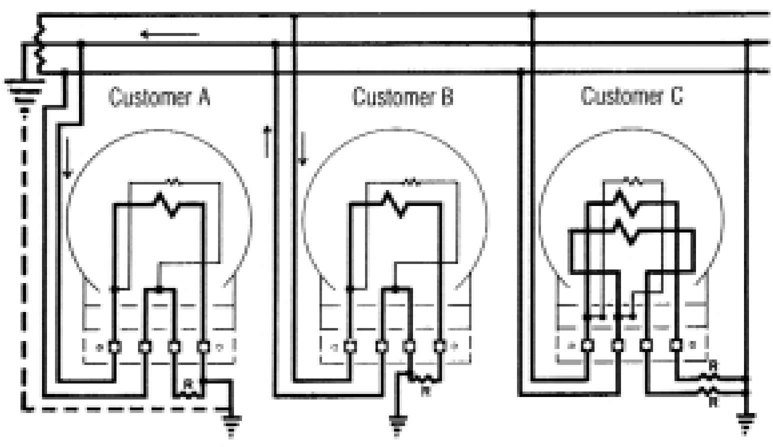


Figure 13-5. Wrong Connection of Two-Wire Meter on Customer A with Load on Meter of Customer B. Arrows Show Possible Direction of Current from Meter B.

If all the meters were properly wired with the current coil in the ungrounded conductor such conditions would not be possible.

Similar precautions must be taken when connecting a three-wire meter. If the neutral instead of an ungrounded line is connected to one of the meter coils, there is a variable error in the current components and a constant error of 50% in the voltage, since 120 volts instead of 240 volts is applied to the voltage coil.

A three-wire, single-phase meter installed on a two-wire circuit without alteration to fit the conditions, may have one current coil by-passed by the customer's ground. Correct metering of a two-wire circuit with a three-wire, single-phase meter is described under the subheading "Metering Two-Wire Service with Three-Wire Meters."

A three-wire, three-phase service is properly metered with a two stator meter. However, if one of the transformers has a center tap grounded, it is possible for energy to be consumed on this service that would not pass through the current coils of the meter. See Figure 13-6.

Other types of errors are possible. Careless or dishonest people may connect circuits at some point on the source side of the meter. In multi-family buildings, careless connection of customer's service conductors can result in the registration of one customer's use on both his and his neighbor's meter. It is also possible that meters measure loads other than those for which they are intended, such as a

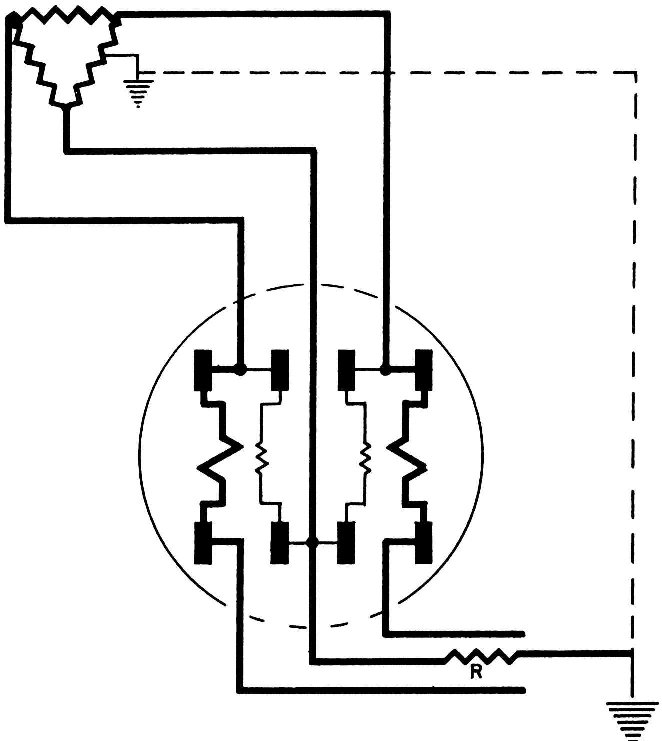


Figure 13-6. Wrong Connection for a Two Stator, Three-Wire Meter on a Delta Bank with Grounded Transformer Center Tap.

meter tagged Apartment A actually measuring the consumption of Apartment B. Sometimes an interruption of service is necessary to obtain assurance that these conditions do not exist.

In an apartment house, it must be recognized that both three-wire and two-wire services may exist. The customer's service equipment must be checked before the meter is installed.

The failure to meter the customer's load when one fuse on the supply side of the meter has been opened must be recognized. In this case, branch circuits from the live wire and the neutral are still energized but the meter will not register since its voltage coil is connected across the 240 volt circuit. Tying the outside wires together as in Figure 13-7 will make all 120 volt branch circuits alive with no meter registration. The 240 volt appliances will not be supplied.

Figure 13-8 illustrates a common error, the voltage link left open. Beware of making this mistake.

The misconnections described are examples of some of the errors to be avoided. Of course, there are many possibilities for wrong connections especially in polyphase metering with instrument transformers. Methods for checking the correctness of connections are outlined in the discussion of instrument transformer installations.

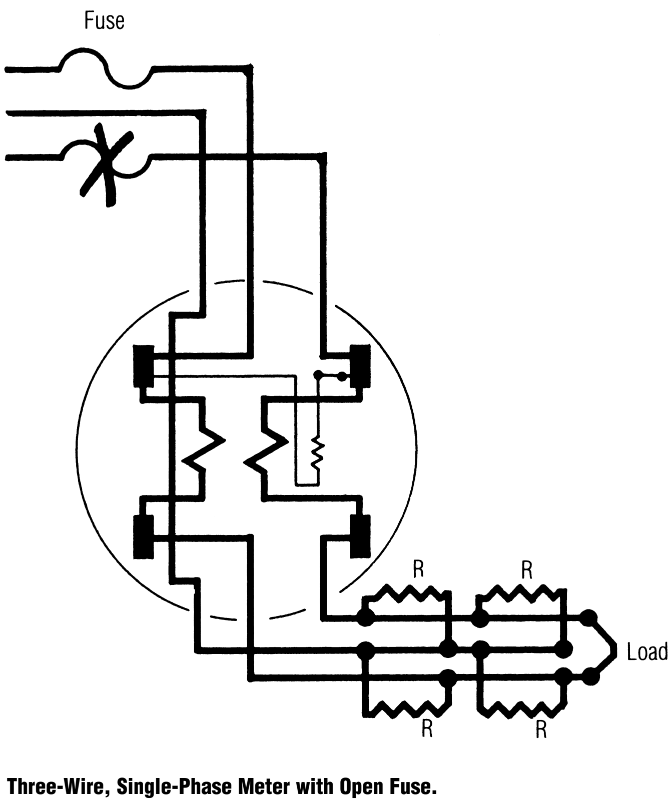


Figure 13-7. Three-Wire, Single-Phase Meter with Open Fuse.

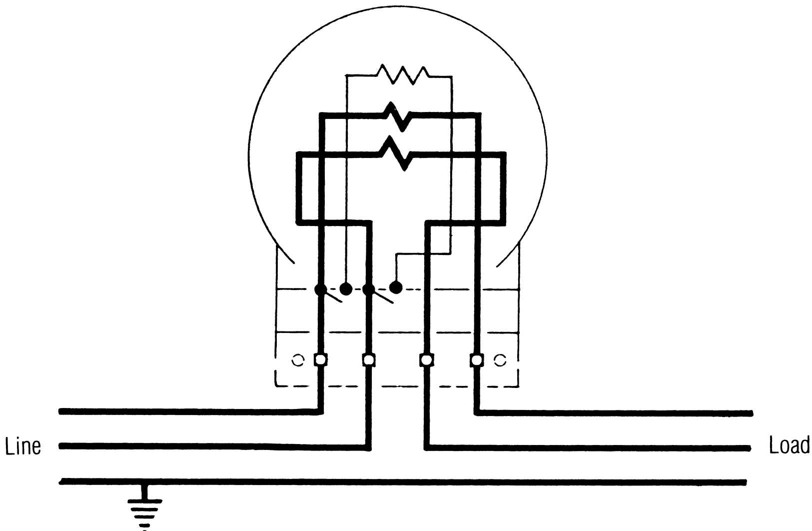


Figure 13-8. Voltage Link Left Open, a Common Error.

Metering Two-Wire Services with Three-Wire Meters

In those areas originally supplied by two-wire services but in which load growth and additions of 240 volt appliances necessitated a continuing changeover to three-wire, it is often considered advisable that new meter purchases be adaptable for either two- or three-wire use.

There are watthour meters available in which the internal wiring is easily converted from two- to three-wire and vice versa. Internal connections for such meters are shown in Figure 13-9. Note in the two-wire connection, the current in the grounded leg is not properly measured. By reconnection the meter constant is not changed but the full-load speed of the meter when connected for two-wire service is one-half that of the meter when connected for three-wire service.

It is often wise to calibrate the meter for the service on which it is to be installed, but the agreement in performance between the two connections is within commercial limits of accuracy.

In areas where there is a continuing changeover from two-wire to three-wire service, this type of meter may prove a practical answer to meter stocking problems and the rapid obsolescence of two-wire meters.

With the improvement of voltage coil characteristics in modern meters, it is feasible to use the standard three-wire meter with the current coils connected in series for two-wire services. In this connection, one current coil is reversed in order to provide forward torque from both coils. Compare directions of current in a three-wire meter. The voltage coil is not modified and is operated at half voltage.

In a meter socket as shown in Figure 13-10, the line wires are run to the top-left jaw and the ground tap. The load wires are taken from the top right jaw and ground tap. The meter voltage coil is connected from the top-left blade to the ground tap with the voltage clip open. The connection to the ground tap

Internal Connections for Self-Contained, Detachable, Two- or Three-Wire Single Stator Watthour Meters
Front Views

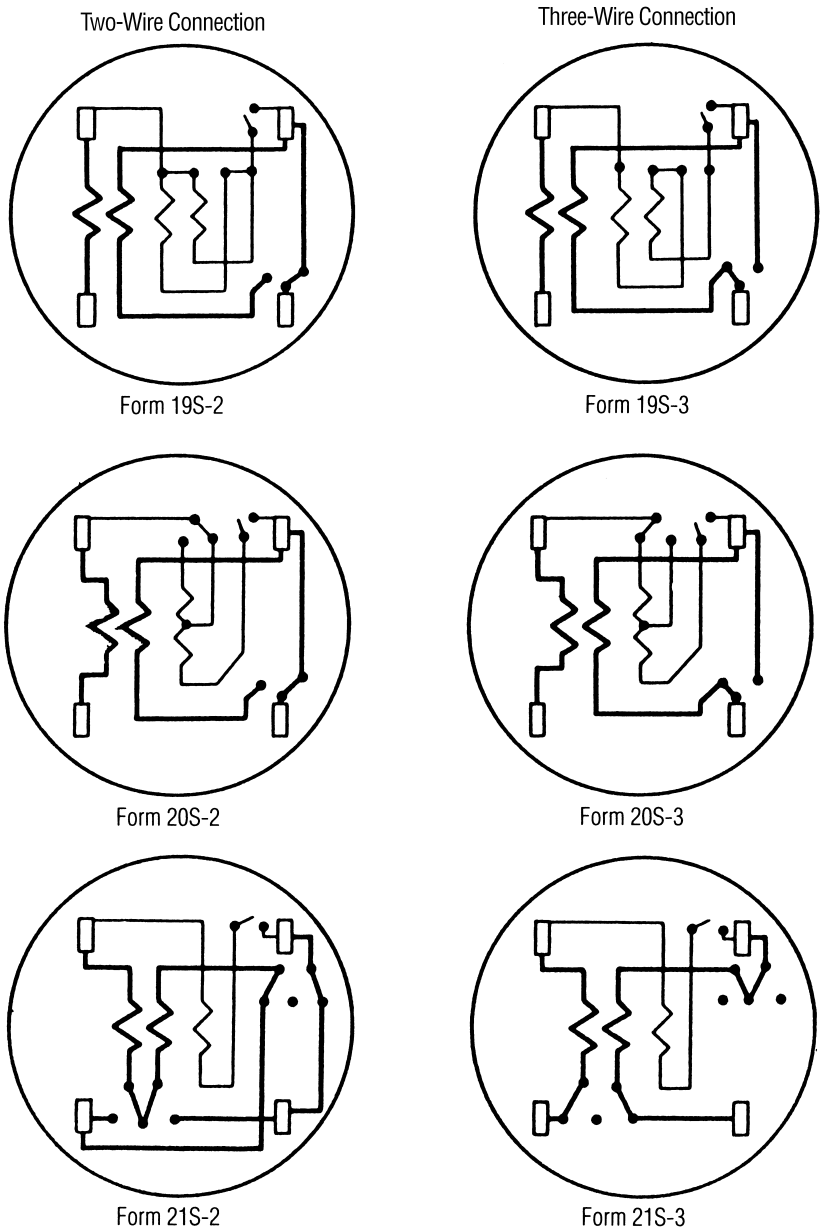


Figure 13-9. Convertable Watthour Meters (from ANSI C12.10).

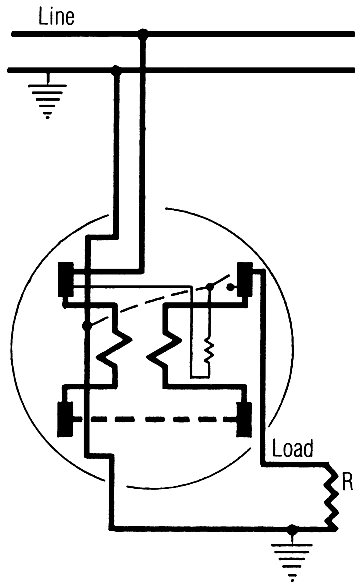


Figure 13-10. Three-Wire Socket Meter Converted for Two-Wire Service.

may be made by a flexible lead. The meter must be marked so that the tester or installer will know there is a flexible connection between meter and socket. *Note*: Reconnection of the current coils is necessary to put both coils in the ungrounded leg.

THE NEUTRAL WIRE

In a three-wire, single-phase circuit the current in the neutral is equal to the difference between the currents in the ungrounded conductors. This can readily be shown by applying Kirchhoff's Law of current. With a perfectly balanced load, the neutral in this type of circuit carries zero current.

What Happens if the Neutral Is Broken?

In a three-wire meter there is no connection to the neutral, so the meter will continue to correctly register the energy taken. The effect on the customer's load will depend on the location of the break. Normally, where grounds do not provide a return path for the current, two-wire branch circuits may be dead. If, to a three-wire appliance such as an electric range, the neutral is opened, the 240 volt units will continue to operate at normal heat, but on any 120 volt units it is possible to get excessive voltage on some units and deficient voltage on others, depending on the load balance among the units. That is, if loads on both sides of the neutral are connected, these loads will be in series across 240 volts and the lower-rated unit will draw too much current while the higher-rated unit will have too little current to reach expected heat.

Under these conditions, the customer loses the protection of the grounding conductor, the importance of which has already been discussed.

The neutral conductor is not fused because:

1. This conductor provides the connection to ground;
2. An open neutral presents more hazards to equipment than any protection a fuse could provide;
3. Load current in the neutral of a single-phase circuit is never greater than the larger of the currents carried by the fused, ungrounded conductors and therefore the neutral is protected by the circuit fuses.

Network Neutral

In the three-wire network circuit (two phase wires and neutral from wye-connected transformers), the condition is somewhat different. Under balanced load conditions and with only phase-to-neutral loads, the neutral wire carries the same magnitude of current as the phase wires.

If the neutral is broken in a network circuit, the customer loses the protection of his ground. Appliances operating at 208 volts will not be affected. Branch circuits operating at 120 volts will normally be dead, but currents may find a path to the other phase wire, thus putting 120 volt lamps in series across 208 volts.

What happens if the only ground that is lost is at the meter in a three phase meter?

The meter is connected properly and the required metered loads are grounded. Refer to Chapter 12 for proper phase wiring and ground connections at the meter. There may be times when the ground connection at the meter are accidentally or purposefully cut.

If the meter does not see ground then metering errors in the three-phase meter could range from 0 to 50% depending on how much of the loads are phase to ground versus phase to phase.

Check the ground connection at the meter with a voltmeter to a phase and then check the system neutral to the same phase. The voltages should be the same unless the ground connection at the meter is broken. Calculating the percent of error would almost be impossible unless you can determine if the amount of usage is phase to phase versus phase to ground.

METER LOCATION

Indoor

When meters are installed indoors, they should be located near the point of service entrance to avoid long runs of unprotected or unmetered conductors. If the meter is to be in a partitioned basement, it should be installed in the same area that the service enters. It is good policy to locate meters so that the customer will have as little inconvenience as possible.

Since meters must be read and sometimes tested in place, they should be mounted at a convenient height. Between three and six feet from the floor is generally satisfactory. Space is important. Since meter accessory equipment may have to be changed because of changes in the customer's load, space sufficient to permit such changes must be provided.

The area in which meters are located should be free of corrosive fumes and excessive moisture. Meters should not be installed near furnaces or water heaters, nor should they be mounted under pipes which may drip because of poor joints or condensation. It is extremely important that the wall or panel on which the meter is mounted is free of vibration.

Outdoor

Outdoor meters should not be mounted overhanging driveways or walks. In the one case, they may be damaged by traffic; in the other, they may cause accidents to pedestrians.

Although meters are well temperature-compensated, it is good practice to install them out of direct sunlight. The north side of the house is generally a good location if the service permits.

As in indoor metering, the height at which the meter is mounted must be convenient. However, in northern areas where snow is a problem, it may be advisable to require a height at least four feet above the ground.

SELECTION OF METER CAPACITY

In determining the capacity of the metering equipment, the current which the customer will demand is the immediate factor. The amount of current a customer will use is usually a matter of calculations involving connected load and estimates of diversity and growth. The capacity of the customer's main line switch or service entrance conductors may be used in determining the equipment selected. This keeps the equipment from becoming the weak point in the circuit and from being damaged by overload.

There are self-contained meters available which, with the appropriate sockets and other associated devices, will carry and accurately meter up to 400 amperes. For loads above 400 amperes, current transformers are necessary.

In cases where the load to be metered is only a fraction of the installed service capacity, it is wise to make adequate provision for the future metering of the total installed service capacity. This is particularly important when increases in load may necessitate a change from self-contained to transformer-type metering, or the increase involves a change in rate schedules requiring a different metering method.

METER SOCKETS

The Type-S meter is designed so that its terminals appear as short, rigid, copper contact blades extending outward from the back of the meter. To connect this meter to line and load wires, an auxiliary mounting device is required. This device is the meter socket.

The socket comprises connectors for line and load conductors, contact jaws to receive the meter terminal blades (thus completing connections between conductors and meter coils), and an enclosure for the whole assembly.

Early sockets were round, cast or drawn shallow pans with diameters matching those of the meters. In this type socket, wiring space was limited. This limitation led to the development of the rectangular-shaped trough with a round opening the diameter of the meter. A sealing ring, which fitted around the meter rim and socket cover rim, secured the meter in place. More recently a ringless type of socket has been developed in which the socket cover opening fits over the meter after the meter has been installed. The socket cover is then sealed in place to provide protection. In both types the primary functions are to: (1) fix the meter firmly on the socket; (2) close the joint between the meter and socket rim against weather and tampering; and (3) provide means for sealing the meter against unauthorized removal of the meter or cover.

Meter sockets are available in continuous duty current ratings of 20, 80, 100, 120, 150, 160, 200, 320, and 400 amperes and for one, two, or three stator meters.

The requirements for indoor and outdoor service differ. Meter sockets installed on the outside of the house must not only be weatherproof but must be of a material that is highly resistant to corrosion.

Under some conditions, such as leakage of pipe joints or cable assemblies, sockets will accumulate varying quantities of water. To guard against water accumulation, sockets are provided with a means for drainage.

Obviously the dimensions of both meters and sockets must be standardized and closely controlled so that meters of any of the major American manufacturers will fit all sockets. The ANSI and NEMA standards have developed standards for meter and socket sizes. The Meter and Service Committees of EEI and AEIC have agreed upon certain basic requirements applicable to meters and the associated mounting devices.

The basic requirements are:

1. Interchangeability of all manufacturers' meter mounting devices;
2. Mounting devices to be designed for single-meter or multiple-meter mounting either indoor or outdoor;
3. One seal to serve for both meter and mounting device;
4. Terminals to be inaccessible after the meter is sealed in place;
5. Meter base not to be insulated from the mounting device;
6. Mounting device to have an uninsulated terminal for the service neutral.

The material of the socket jaws is important. A tight contact between the meter connection blade and the contact surfaces of the jaw is necessary. This requires the use of an especially high-quality resilient copper alloy, which may be bronze or beryllium. Even with the best-quality material, it must be remembered that spreading the jaws by pushing screwdriver blades into them may spring the metal beyond its elastic limit and destroy the tight contact with the meter blades.

It is also necessary that the connection between conductors and the line a nd load terminals be secure and of low resistance. The connectors in the lower-rated sockets may be required to accept conductors as small as No. 6 while the 200- and 400-ampere sockets may be required to accept single or multiple conductors that will carry 200 or 400 amperes. When aluminum conductors are used, the connectors must be designed for this material; that is, they must not cut the comparatively soft strands and they must not encourage cold flow when the wires are under pressure. If aluminum wire is used in the socket that has plating over the copper connectors, use an aluminum electrical joint compound (antioxidant) to prevent metallic reaction between the alumiun and copper connections.

With the growth of domestic loads and the development of self-contained Class 200 meters, the heavy-duty socket also rated at 200 amperes has been introduced. There are two types of such heavy-duty sockets. In one the jaws are made of massive material and sometimes have only one flexible member. This may be spring loaded but will still depend on jaw resiliency for good contact. In the other type, the jaws are made of a nonflexible heavy material and the jaws are wrench tightened or lever tightened after the meter is in place. Either type of jaw can carry 200 amperes continuously without excessive heating.

Circuit-Closing Devices and Bypasses

Certain types of sockets are provided with circuit-closing devices or bypasses. These may be automatic, closing the current circuit as the meter is withdrawn from the socket; or manual, requiring an operation other than meter removal to close the current circuit.

Two types of automatic circuit-closing devices are shown in Figure 13-11. In Figure 13-11a, the meter blade is inserted into the socket jaw, causing the bypass contact 4 to be pushed away from the jaw by the small insulating rod 2. Withdrawal of the terminals allows the bypass and jaw to spring together to positively short circuit the current transformers.

In Figure 13-11b, the dual bayonet terminals of the meter current coil spread the dual socket jaws (left), to complete the current transformer circuit. Withdrawal of terminals allows the jaws to spring together (right), to positively short circuit the current transformer.

Figure 13-11c is a representative picture of the socket with bypass arrangements as shown in Figure 13-11b.

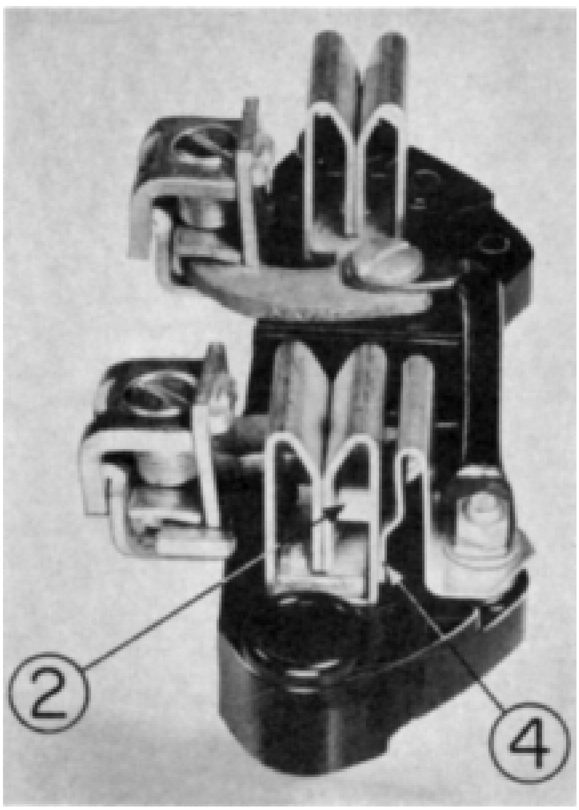


Figure 13-11a. One Type of Automatic Circuit-Closing Device. (No longer manufactured.) Circled numbers are Referred to in Text.

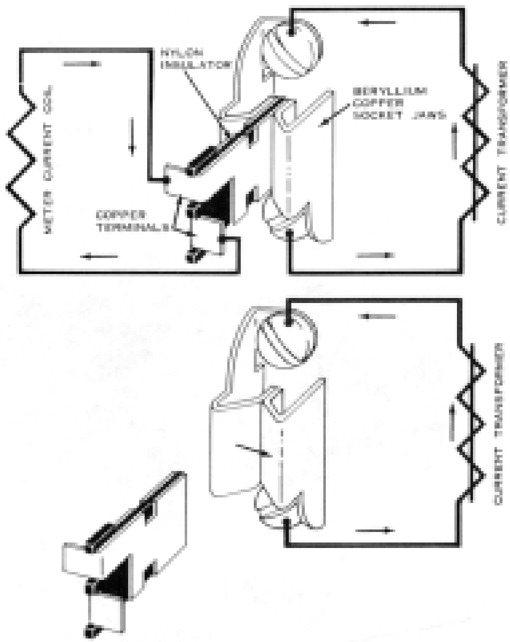


Figure 13-11b. Circuit-Closing Device for 20-Ampere Meter Socket.

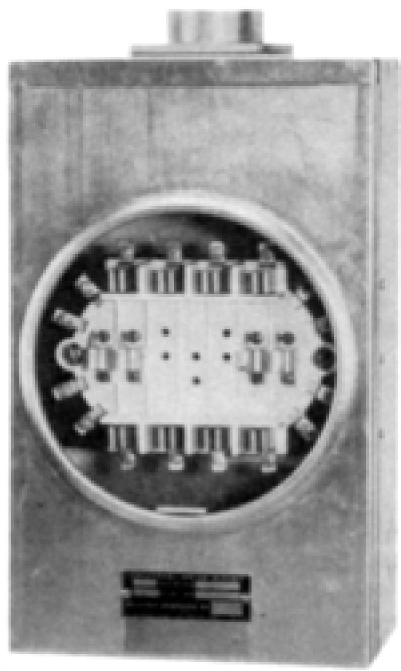


Figure 13-11c. Socket with Bypass Arrangement as Shown in Figure 13-11b.

When sockets with automatic closing devices are used, it must be recognized that removal of the meter does not de-energize the customer's service and that a socket with a blank cover instead of a meter may mean the customer is getting free electricity.

Manual bypasses are often provided in heavy-duty sockets when it is believed unwise to interrupt the customer's load or to pull the meter and break a circuit which may be carrying 200 or 300 amperes. Such bypasses may be integral with the socket, as in Figure 13-12, where, as the lever is pulled to release tension on the socket jaws, the bypass is closed; or the bypass may be similar to a meter test block and mounted in an extension of the meter trough.

Another type of socket has facilities for connecting flexible leads to bypass the meter before it is removed as shown in Figure 13-13.

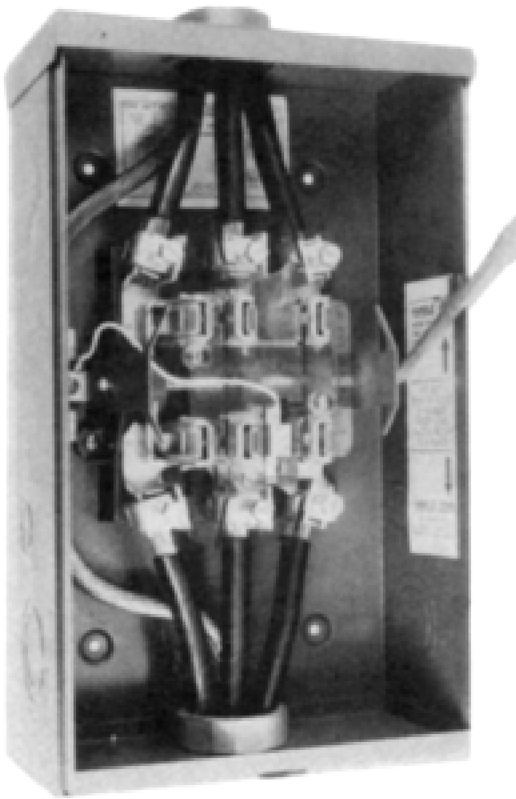


Figure 13-12. Heavy-Duty Socket with Bypass.

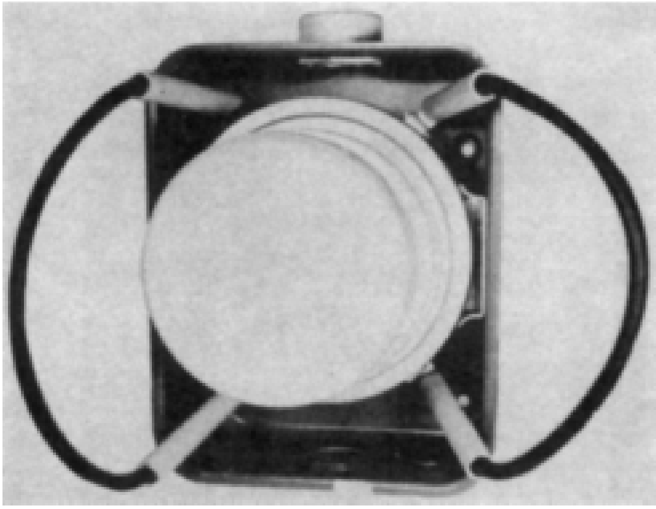


Figure 13-13. Socket and Meter with Flexible Bypasses in Place.

METER INSTALLATION AND REMOVAL

Socket Meter

Socket meters are commonly installed in meter-switch-fuse sequence. When this is the case, it must be remembered that the line terminals (top jaws) are alive. Do not attempt to correct major wiring defects on energized parts in the socket. Report such conditions to the supervisor. If it is necessary to make connections in a live meter socket, protective shields (Figure 13-14 shows a safety shield for live jaws) should be installed around the live parts.

Before installing the meter, check to see that voltage clips are closed.

Check correctness of the electrician's wiring. Is the grounded wire connected to the socket case?

If the socket is not level and plumb, report this condition to the supervisor.

When installing a socket meter, line up the load jaws and meter blades and press these home. Then, using the bottom jaws as a fulcrum, rock the meter into place.

Do not twist the meter in a manner to spring the jaws.

When closing into the line contacts, the action should be positive.

Do not pound the meter into place. Cuts from a broken cover can be serious.

Check the meter number against the number on the service order.

Check to see that the meter disk rotates in the proper direction.

If a solid-state meter is being installed, the meter normally displays which voltages are present. Compare display readings to the actual voltages that are present.

Solid-state meters have internal self-checking features called error codes, caution codes, diagnostic codes, etc., which will indicate if a problem is present. Correct the problem.

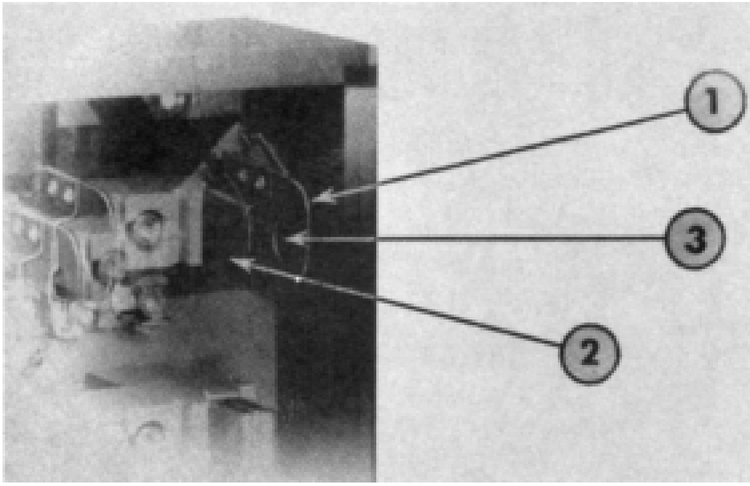


Figure 13-14. Safety Shield for Live Jaws. (1) Tough Phenolic Plate (Fabric Base) Fits Inside the Meter Jaw. Spring Tension of Jaw on Plate Holds Safety Shield in Position. (2) Vulcanized Fiber Shield Attached to Phenolic Plate Effectively Insulates the Meter Jaw from Accidental Contact. (3) Finger Hold for Easy Removal of Shield.

When removing socket meters, use the lower jaws as a fulcrum and pull the blades from the lineside jaws with a downward force on the meter before withdrawing the lower blades.

On removal of a socket meter without replacement, the trough or socket opening is closed with a blank cover plate and sealed. This is important because the top terminals are live and should not be left as a hazard to the curious.

When meter covers are broken due to accident or vandalism, great care must be taken to avoid cuts from the sharp glass. Heavy leather gloves should be worn for removing such meters or use a special meter removal tool.

When installing a meter, if it is found that the compression of the socket jaws is not sufficient to hold the meter in place, this should be corrected or reported to the supervisor. Poor contacts cause heating, and heating will further destroy the temper of the jaws.

Socket Adapters

When modernization of customers' services is taking place at the same time that a changeover from bottom-connected to socket-type meters is being made, adapters which permit the replacement by socket meters of bottom-connected meters may be considered. These adapters essentially give a socket meter a base which permits installation in a location designed for a bottom-connected meter. The adapter may be no more than a low-cost shell to hold the socket meter with facilities for bringing out flexible leads to the service switch, or it may be equipped with a standard terminal chamber similar to that of the bottom-connected meter.

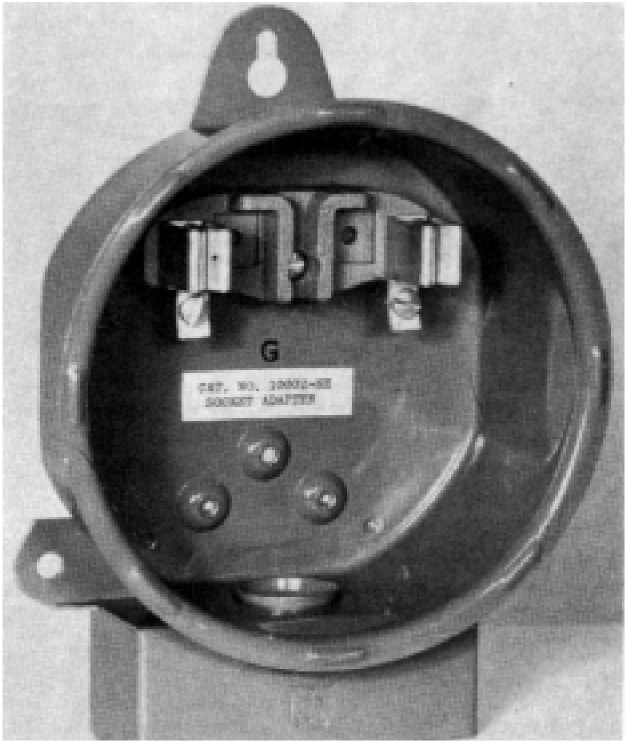


Figure 13-15a. Skeleton Socket Adapter.

Figures 13-15a and 13-15b illustrate this type of socket adapter. In Figure 13-15a only the top connections are shown. A bridge across the bottom blades of the meter completes the connections by putting the current coils in series.

Bottom-Connected Meters

The handling of A-type meters for installation or removal plainly involves operations not required with the S-type meters. All line and load wires must be removed from the several meter terminals before the meter can be lifted from its location. Unless the line wires can be killed by opening a service switch, removing the main fuse, or cutting the energized wires at the weatherhead, these wires must be handled carefully at all times.

Visually inspect the insulation of the wires before working on energized meters. Frayed wiring could cause a shorting condition.

Connection screws must be made up tightly and each wire tested by pulling and shaking it a bit to be sure that there is no looseness of contact. Keep in mind that smaller sized wires can be cut off in the terminal hole by forcing the terminal screws down.

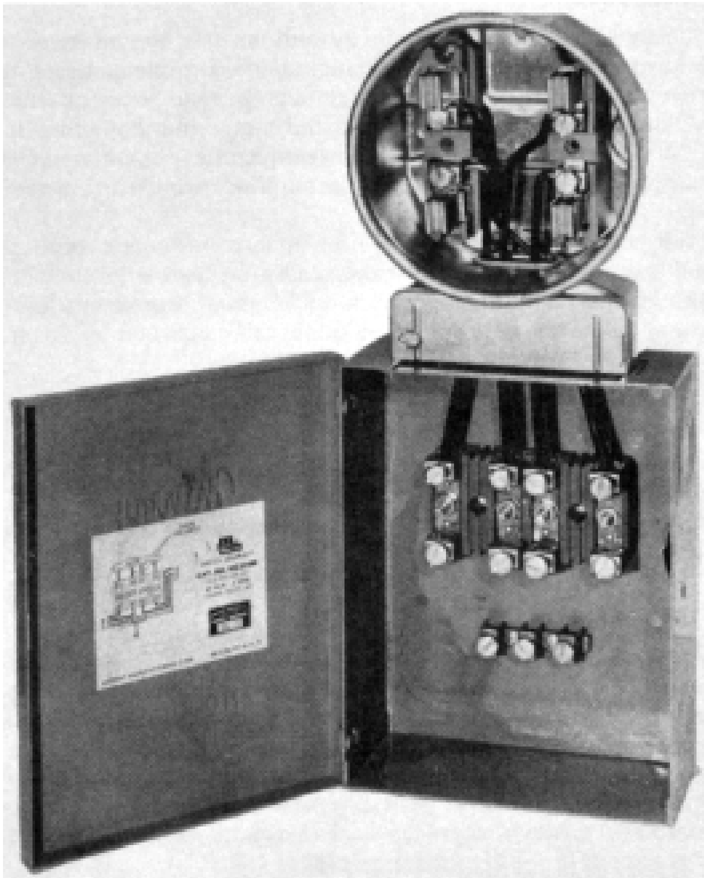


Figure 13-15b. Socket Adapter with Standard Terminal Chamber.

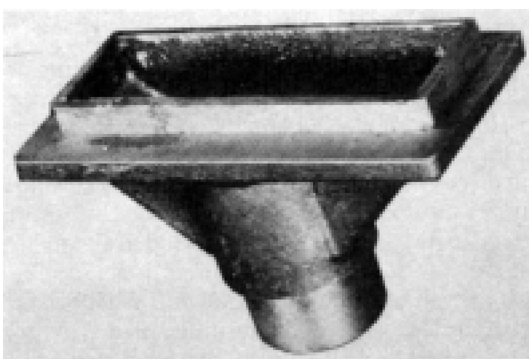


Figure 13-15c. Conduit Socket Adapter.

Where a service interruption cannot be tolerated for a period long enough to remove and replace a meter, the use of jumpers is necessary. When test facilities are provided or in certain types of service installations with line and load terminals available in the service equipment assembly, this is a simple procedure with test links or with leads equipped with spring-clip terminals. When the meter is located directly in the line, it will be necessary to remove insulation from the line and load wires ahead of and beyond the meter terminals. Jumpers are then attached to the bare spots.

Placing of such jumpers calls for careful work. If there is any doubt as to where jumpers should be connected, use a voltage tester. A jumper connected across a voltage difference is a short circuit and will result in a flash.

Any bare spots must be properly taped after the job is completed.

When the meter is mounted above a test block, a change of meter becomes a simple operation since the meter can be by-passed and isolated by test-block links and jumpers. There are two different test-block connections that must not be confused. In one, the test-block terminals are in the same sequence as the meter terminals and, to bypass the meter, flexible jumpers are used to connect each of the line wires to the corresponding load wires. The other arrangement is line-load in which the test block link can be used to short adjacent terminals. Generally, it is easy to distinguish one arrangement from the other. If there is any doubt, a voltage tester should be used.

Often a bottom-connected meter is mounted directly above the service switch which has test connections involved. Such test connections take many forms and here, particularly, the use of a voltage tester or voltmeter is advisable.

Outdoor Installations

To adapt the bottom-connected meter to outdoor use, several types of meter enclosures have been developed. These include the complete enclosure, generally with a window through which the meter can be read; the semi-enclosure in which the glass cover of the meter projects through a round opening in the box cover; the "banjo box" which provides a disconnect device and an enclosure for the meter terminals; and conduit pull boxes modified to enclose the meter terminal block.

A conduit pull box with a single cover to enclose both meter terminal chamber and pull box is often designed so that it also encloses a disconnect feature. This permits separation of the meter terminal chamber from a terminal block to which line and load wires are connected. With such construction, the meter can be tested or changed without service interruption.

Installation of Meters with Instrument Transformers

For the use of instrument transformers with meters, see Chapter 11, "Instrument Transformers."

For the economics of primary metering versus secondary metering with compensation, see Chapter 10, "Compensating Metering for Transformer Losses."

INACTIVE AND LOCKED-OUT METERS

It is usual practice to leave meters in place for a reasonable period, at least in certain classes of buildings such as residences, apartments, and offices where occupants are changing so frequently that the prospects of a new tenant at an early date are reasonably sure.

In commercial and industrial classes of business, the practice of leaving meters on vacant premises is not generally followed. The reason is that the new load is usually of a different character and alterations are probable, requiring a relocation or change in the metering equipment.

Inactive services may be left with the meter connected and energy available, with instructions for the incoming customer to notify the utility company of his occupancy of the premises, or the service may be disconnected at the meter switch or socket but with the meter left in place. The latter operation is often called a meter lockout. The disconnection is commonly protected by seals or locks to prevent unauthorized reconnection.

For A-meter installations, the practice may be to replace the main plug fuses with insulated dummy plugs which require a special tool for removal. In some installations, lockout can be accomplished only by sealing the main switch in the open position.

The service can be disconnected in the meter socket by several means:

1. Some sockets are provided with means for disconnecting the service. In some the meter can be removed and reinserted at an angle, in which case the meter does not make contact with the socket jaws;
2. Disconnection can be effected by use of thin plastic sleeves made for this purpose that can be slipped over the load terminal blades of the meter (do not sleeve the neutral jaw). The meter is then replaced in the socket with the plastic sleeve acting as an insulator between the meter terminals and socket jaws. These sleeves are not used on a current transformer-rated meter because of the hazard of an open secondary of the current transformer.

When meters are connected in the secondaries of current transformers, it must be remembered that the customer's service is disconnected only by opening the primary circuit. The current transformer secondary must not be opened because of the dangerously high voltage that may occur.

It is essential that all meters left on inactive service be visited periodically to guard against damage and unauthorized use of service. Some companies adopt the practice of continuing to read the meter so a monthly report is received on the existing conditions. Other companies obtain readings less frequently but often enough to assure that the metering equipment has not been disturbed or the service used without authority.

TEST SWITCHES

Test switches are generally used if meters are in the secondaries of instrument transformers. The functions of the test switch are to short-circuit the current transformer secondaries and to isolate the meter so that it may be tested or changed without hazard.

When the test switches are open, the current blades are grounded. The voltage blades, however, may be live and hence a hazard. When both voltage and current transformers are used, the low capacity of the voltage transformers limits the hazard to some degree, but when only current transformers are used and the voltage connections are made directly to the line, the entire capacity of the power transformer is behind this circuit and extreme care must be used. A screwdriver or even a connector clip falling across these blades can cause a severe flash. It is necessary to be particularly careful when changing connections on such a live test switch, as when inserting a test instrument. Because of this danger many companies install low-current, high interrupting-capacity fuses in the voltage circuits of meters used with current transformers. Another precaution that can be taken is to place insulating blocks over the open voltage blades of the test switch.

Removing or replacing test switch covers must be done carefully. Some nonmetallic covers have metal end walls that can cause a phase-to-ground short.

When paralleled current transformers are used, it is necessary to make sure that the test switch shorts the secondaries of *all* the connected current transformers before disturbing the meter leads.

INSTRUMENT TRANSFORMER METERING IN METALCLAD SWITCHGEAR

In 1958 the Meter and Service Committees of EEI and AEIC issued *Guide for Specifications for Revenue Metering Facilities Installed in Metalclad Switchgear.* This guide states the principal objectives to be attained:

1. That a separate sealable compartment be provided exclusively for revenue metering equipment when mounted within the switchgear;
2. That space be provided within the compartment sufficiently large to accommodate separately the installation of any standard current transformers and any standard voltage transformers required for metering;
3. That space be provided within the compartment for the installation of separate, isolated voltage transformer fuses, where required;
4. That, where required, adequate space and panel facilities be provided within the compartment to permit the installation of all necessary meters, instruments, auxiliary devices, or test facilities, of any type, whether they be front connected, back connected, surface mounted, or flush type;
5. That the arrangements be such that the secondary wiring may be installed in a manner to facilitate checking of connections.

By following these specifications, control of all metering transformers and conductors rests with the utility company.

When extremely high-capacity current transformers are used, it is essential that spacing of bus bars be adequate to avoid interference between individual transformers.

There are many advantages to be gained by mounting instrument transformers in the customer's switchgear. Protection, appearance, and, in many cases, economy, may be the result.

POLE-TOP METERING

Pole-top location of instrument transformers is often necessary. Poles with distribution equipment requiring maintenance mounted on them are generally avoided for metering, since the reduction of climbing space may present hazards to utility personnel.

Instrument transformers may be mounted on crossarms or may be put in place as pre-wired units on cluster mounting brackets. These brackets are generally designed to allow sufficient free climbing space. The transformers used are most often of a type that can be installed in any position. For low-voltage metering, window-type current transformers offer convenience and economy.

Meters may be located on the pole, or the instrument transformer secondary may be extended to a nearby building where a more suitable location may be found. In the latter case, sometimes an underground secondary run is involved. Such a conduit or cable run coming down the pole and extending up the building wall may form a U which will often collect water. When installing cable or conduit, care must be taken to prevent this condition. The comments in Chapter 11, "Instrument Transformers," referring to length of secondary run should be consulted.

Since pole-top metering is generally distant from any extensive water piping system, other forms of grounding must be employed. This is particularly true when meters are installed in an enclosure on the pole since the enclosure must be well grounded to protect the installer. To guard against high ground resistance, it is good practice to bury the ground wire connecting multiple electrodes in a circle around the pole so that the person working on the meter or enclosure is standing inside the grounding network. All grounding in the area should be bonded together.

Grounding of instrument transformer cases must be in accordance with general company practice. Whether secondary conductors are in metallic or non-metallic enclosures depends on the grounding practice.

GOOD PRACTICES FOR METERING PERSONNEL

Efficient metering personnel will make good installations. In doing so, they will observe certain practices that will be helpful to both their company and the customers. These good practices have many benefits. They insure good service by preventing unnecessary outages. They insure good customer relations by preventing damage to the customer's equipment. Also, the meter employee will not have to return to the customer's premises for things forgotten or left undone and thereby undermine the customer's confidence in electric metering. All these benefits, in turn, help the company and the employee.

Following are some of the good metering practices, not necessarily in order of importance.

Competent metering employees will:

Recognize their responsibilities while on the customer's premises.

- Take the nearest and safest route to accomplish the work.
- Take care not to damage any of the customer's property.

- Leave the area clean upon completion of the job.
- Report any hazards to the meter department supervisor.

Work in the safest possible manner.

- Keep in mind that no job is so important that it cannot be done safely.
- Inspect all meter wiring connections for correctness
- Check connections to prevent outages, damage to meter installation, damage to customer's property, and personal injury.

Inspect for loose connections.

- A loose connection can cause intermittent service or it can cause a complete outage. Loose connections generally arc, causing a fire hazard. Even if there is no fire damage, heating around the connection occurs.

Inspect for good grounding.

- Check for equipment ground at the installation. Realize that no ground at the installation is a potential hazard and report it to the supervisor.

Pay attention to details.

- Check meter voltage links.

Inspect connections between two dissimilar metals.

- Connection between two dissimilar metals often causes corrosion.
- Corrosion can be prevented by using the proper connector and by protecting the connector and conductors against oxidation.
- Wires corroded at a joint have the same effect as a loose connection since corrosion has a high resistance and causes heating, which, in turn, assists the corrosive action.

Check for proper voltages.

- Voltage should be checked before installing the meter.
- A reversal of the power and lighting leg on a four-wire delta system causes excess voltage on customer's equipment. Also, a reversal of the hot leg and ground has serious consequences.
- Grounded conductors and the power leg of four-wire delta services should be permanently identified.

Check phase rotation.

- Phase rotation on installations which have been disconnected temporarily for service work should be checked. If a reverse phase rotation is connected to the customer's motors, they will reverse, possibly causing extensive damage. This could also mean personal injury.

Check for single phasing.

- It is possible to prevent damage to the customer's property by disconnecting or warning the customer to disconnect the load on a three-phase service when one phase is out. A running three-phase motor may continue to run on single phase but will overheat. A stopped motor may attempt to start but cannot, which causes overheating.

Observe direction of disk rotation.

- Whenever possible, try to get a load applied to the meter in order to check for correct disk rotation.

Check for diversion.

- Always check for circuits tapped ahead of the meter or current transformers.

Check for correct installation information.

- Check for correct phase, amperes, volts, and frequency.
- Check for such details as multipliers, full scales, readings, and similar data.
- Check all written records against actual nameplate data.

Check to see if meter is level.

- An out-of-plumb meter may be inaccurate. Besides being inaccurate, it presents an unsightly appearance to the customer and may undermine his confidence in the electric metering.

Give the entire job a good once over before leaving it.

- Check the job in general for good workmanship and safety before leaving. Be sure the area surrounding the meter is left clean and neat.

Meter employees are the company in the eyes of many customers. They can make a good impression on the customer by being neat in dress, accurate in work, and courteous at all times. Having equipment and tools in good, clean condition will build the customer's confidence in the company and assure the customer of the employee's skill. Sloppy dress, actions, and equipment leave a poor impression.

There are probably many other practices which are followed on local levels throughout the country, but if employees observe those listed, they will turn out a good job. Failure to follow any one of these practices may result in extensive property damage, personal injury, outage of service, or a loss of revenue. And, last but by no means least, it may impair that valuable asset to a public utility—good customer relations.

GUIDE FOR INVESTIGATION OF CUSTOMERS' HIGH-BILL INQUIRIES ON THE CUSTOMERS' PREMISES

As a representative of the company, an employee who is assigned to investigate a customer's inquiry concerning his billing has a dual responsibility. First, make absolutely certain that all service used by the customer is being accurately registered on the meter. Attempt to explain some of the metering factors to a customer who does not understand them to assure the customer of the accuracy of the meter.

The following is a plan suggested for conducting metering investigations. Steps 1 and 2 are frequently performed by a representative of the commercial department of the company. In many companies, only Steps 3 and 4 are performed by meter department personnel.

Step 1

A. Upon arriving at the customer's home or place of business, the company representative should introduce himself, show his identification card or badge when requested, and explain the purpose of his visit. He should also advise the customer that, in the process of checking, the electric service might be momentarily interrupted.
B. The meter readings should be compared with those on the last bill. If an error is apparent, it should be explained to the customer and reported to the billing section.
C. If the customer's question concerning his bill cannot be explained from the aforementioned, the company representative should ask the customer if any appliances have been added recently. Inquiry about appliances that affect seasonal loads is particularly important. These may include air conditioners, dehumidifiers, space heaters, and heating cables. It should also be determined whether the customer has replaced any major appliances recently. The replacement of a refrigerator with a newer, frost-free model may result in an increase in operating cost, and this should be explained to the customer.
D. Ask the customer if there has been an increase in the number of persons living in the household.
E. Ask the customer if situations have occurred that were out of the ordinary routine of the household. These would include such things as more entertaining than usual, guests visiting in the home, an illness in the family, and other factors that would increase the customer's bill.
F. If the customer's inquiry can not be explained after carrying out the parts of Step 1, proceed to Step 2.

Step 2

A. Check for causes of abnormally high consumption.
   1. Dirt- or lint-clogged filters on furnace or air conditioning units.
   2. Leaky hot-water faucets where electric water heaters are used.
   3. Defective water pump.
   4. Use of electric range units for space heating.
   5. Heating water on range.
B. If the preceding investigation is sufficient, discuss these factors with the customer briefly, pointing out any reasons you have found for the increase in the customer's electric bill.
C. If further investigation is necessary, proceed to Step 3.

Step 3

A. If there is a load on the meter, ask the customer to shut off all appliances and lighting at the appliance or light switch. Recheck if the meter continues to indicate a load and determine absolutely whether rotation is due to a missed load or loss to ground. If there is a loss to ground, this should be checked with a stop watch and the rate of loss established.

B. If possible, it should then be determined which circuit is grounded and, if convenient to the customer, the circuit should be disconnected by removing the fuse or opening the circuit breaker. The condition should be explained to the customer and he should be advised to have the condition corrected by a wireman before using the circuit again. If the loss to ground is found to be a defective appliance, it should be disconnected and the customer advised to have repairs made before reconnecting the appliance.

Step 4

If no explanation for the bill has been reached, the meter should then be checked for accuracy, creep, proper constant, and correct register ratio. The results of each check should be noted on the investigation order.

METHODS USED IN CHECKING INSTALLATIONS FOR GROUNDS

In checking the customer's wiring for grounds, all the wiring and circuits should be connected; that is, any wall switches should be turned on, since there may be a ground between the switch and the load it controls. It is not necessary to turn on individual bulbs or floor lamps because these are always energized up to the socket and any trouble at that point would be a short circuit and not a ground. After finding a ground, the best practice is to turn off all other circuits and leave only a few lamps burning on the grounded circuit. This will make it easier to determine if it is a live-wire ground and to check the wattage.

The usual method of checking a small installation (see Figure 13-16a) is to connect the test lamp from the hot wire of the line side of the opened switch to the load side and determine from which switch blade the brighter light is obtained. That line will be the grounded wire. If the test lamp does not light on either wire, there are no grounds. After finding that a ground exists, it is usually necessary to disconnect the various circuits (removing both live and neutral fuses or wires) until the grounded circuit is found. Then turn off all but a few lights on this circuit so that the difference in brilliancy of the test lamp can be noted.

Perhaps the simplest method of testing a two-wire installation is to remove the load neutral wire, leaving voltage applied to the meter. With a load connected, note if the meter stops. If the meter runs, there is a ground; if the customer's lights burn, it is a neutral ground. If they do not burn, it may be a live-wire ground. If a neutral, the ground may be very weak so that the lights only burn dimly. In such a case, some lights can be turned off which will make the remainder burn brighter. See Figures 13-16b, 13-16c, and 13-16d.

Using this same principle, a large three-wire installation may be checked by leaving the voltage applied to the meter and disconnecting one live-load wire and the neutral, and then checking each side of the line separately, as in the case of the two-wire. If the meter stops, there are no grounds; if it runs, there is a ground. If the customer's lights burn on one side of the line, it is a neutral ground. If they do not, it may be a live-wire ground. In checking the wattage of a live-wire ground, the following method is an easy way. Leave only the grounded hot load wire in the meter and, with the neutral disconnected, check the load on the meter. If there is also a neutral ground, the customer's load will also register during the ground check. Therefore, as many circuits and lamps as possible should be turned off, so that the chances of this occurring will be lessened. Figures 13-16e and 13-16f illustrate the method of checking a three-wire installation.

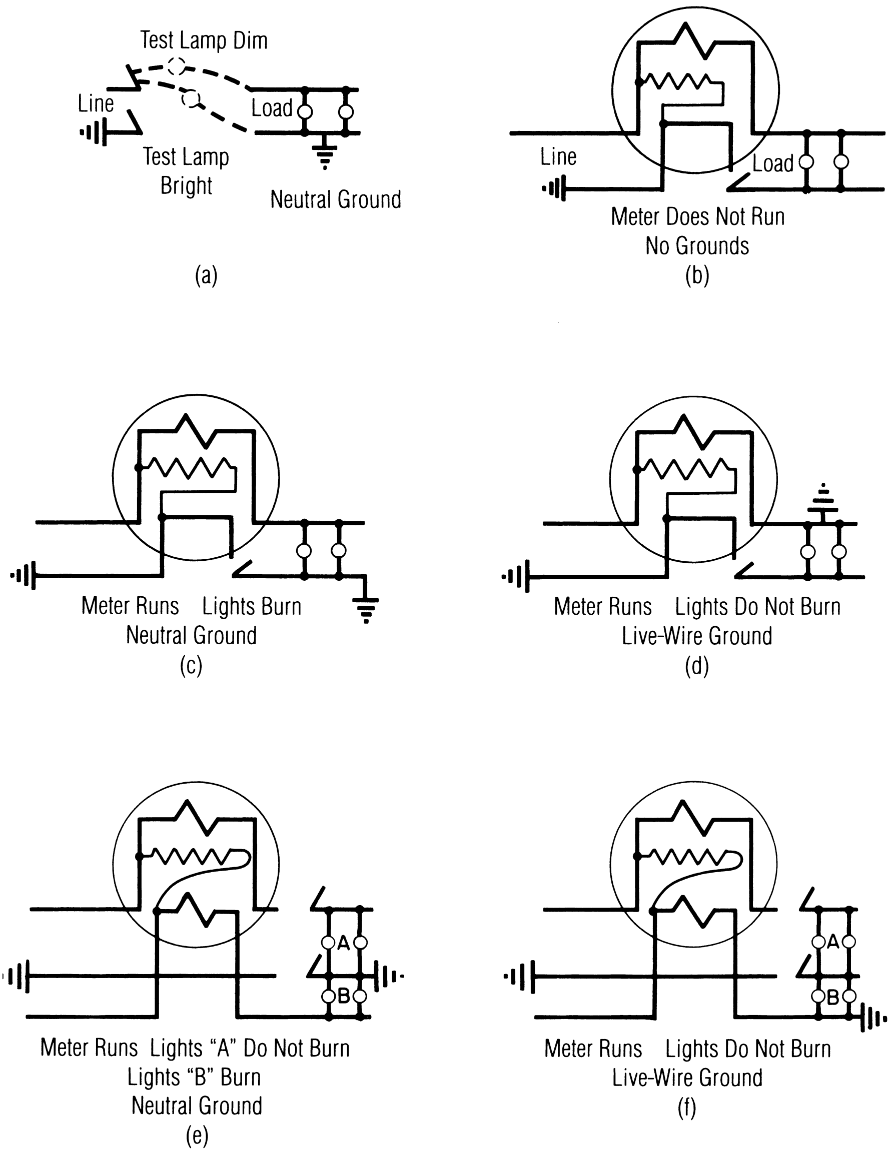


Figure 13-16. Methods Used in Checking Installations for Grounds.

CHAPTER 14

ELECTRICITY METER TESTING AND MAINTENANCE

BECAUSE ENERGY METERS are used for billing purposes it is important that their accuracy be validated and established. This validation requires that a true accuracy test be performed so this accuracy becomes a matter of record. It is also desirable to extend this accuracy by detecting and removing any variables that might tend to affect it. A test of an energy meter consists of determining whether the registration of the meter is correct for a given amount of energy as compared to the registration of a reference standard.

This test might be performed as an acceptance test at the receipt of new meters, as an in-service accuracy test to detect the wear-out of the population, or as verification that maintenance on the meter did not affect accuracy. The results of the accuracy tests are stored in a data collection system for comparison to future testing and to analyze trends in the performance of populations of meters. Many utilities receive the manufacturers' as-left test data with new shipments of meters and by analyzing the statistics of that test, have eliminated performing incoming accuracy testing. Other types of watthour testing are qualification tests when new products are first introduced to the utility and reliability tests to insure the product will perform its intended functions.

In this chapter, a test of a watthour meter will only determine the accuracy of the measuring element. Tests to determine the accuracy of the register functions will be discussed in the following chapter. For information on demand meter testing, see Chapter 15. For information on direct-current meter testing, see Chapters VI and VII in the 1923 edition of the *Handbook for Electrical Metermen*.

Meters may be tested on the customer's premises with a portable test kit, in a mobile test unit (such as a van or trailer) equipped with watthour meter test fixtures, or brought into a meter shop for testing. They may be tested in groups or as individual units, with manual or automated controls. Regardless of the test location and method, the principles are the same. These principles basically consist of applying the same voltage, current, and phase angle to the reference standard and to the meter under test for a defined period of time. After the test is completed the error is determined by making a comparison between the reference standard and the meter under test.

In this chapter, the various test instruments are described, then basic testing procedures and principles are covered.

To test the performance of an energy meter the following items are required:

1. A reference standard as a basis for comparison;
2. A current source to supply the test current;
3. A voltage source to supply the test voltage;
4. Sensors, counters and controls.

REFERENCE STANDARD

The reference standard is also known as a watthour standard, or an energy standard, or a standard meter. The standard is actually a very accurate energy meter of substantially greater accuracy than the revenue billing meter being tested (typically five times greater in accuracy). The standard is also extremely stable with a known calibration history and accuracy that is traceable to NIST or some other nationally recognized metrology laboratory.

There are different classifications of standards that relate to accuracy and application. Please refer to Chapter 16, "The Meter Laboratory," to learn about the classifications of standards.

There are four types of standards relating to the different generations of standards technology: Rotating Standards; Single Function Manual Ranging Standards; Single Function Autoranging Standards; and Simultaneous Multifunction Autoranging Standards. A description of each classification of standards follows starting with the latest technology.

SIMULTANEOUS MULTIFUNCTION AUTORANGING STANDARDS

These standards can be referred to as third generation electronic standards and they first appeared in 2000. The RD-20 and RD-21 from Radian Research are the most common standards in this category. The RD-20 and RD-21 utilize a Radian designed Integrating Analog to Digital Signal Converter as the heart of their measurement approach.

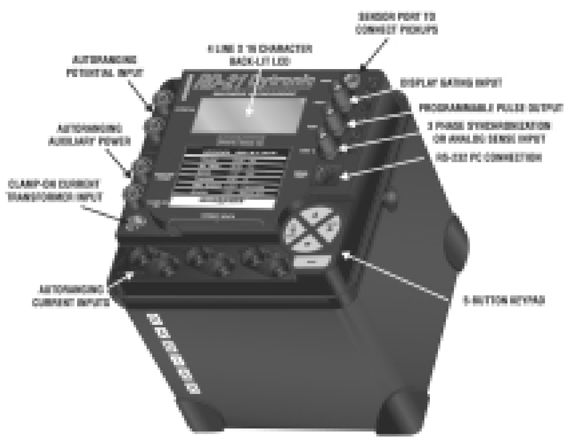


Figure 14-1. The Radian Research Model RD-21 Standard.

This advanced Analog to Digital (A/D) converter is combined with electronically compensated voltage, current autoranging input transformers, and an hermetically sealed reference set to provide a high degree of accuracy, stability, repeatability, and versatility.

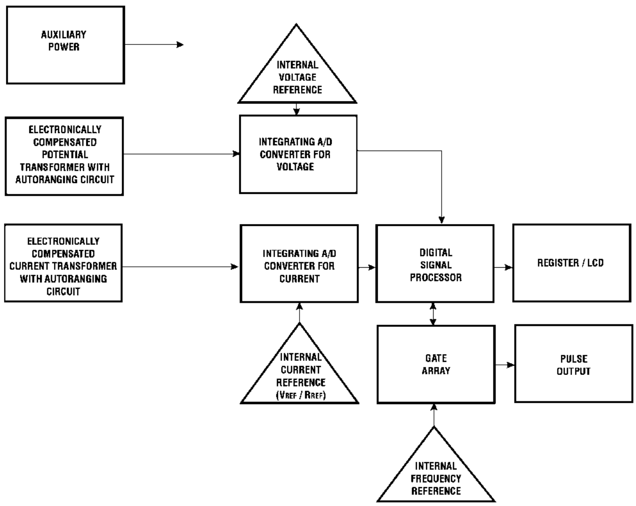


Figure 14-2. Block Diagram of the RD-21 Standard.

The RD-21 has a worst case accuracy of ±0.02% that applies to all measurement functions across the entire operating range of the product and includes the variables of stability, power-factor, traceability uncertainty, and test system errors. The custom A/D circuit greatly improves short-term repeatability over the Pulse Width Modulation measurement approach used in previous vintages of electronic standards. This allows for much shorter test times down to the minimal time allowed by the meter under test. The RD-21 provides four quadrant simultaneous measurements of: Watthours, VARhours, Q-hours, VAhours, Volts, Amps, Watts, VARs, VA, Phase Angle, Power-Factor, Volt-squared-hours, Amp-squared-hours, milli-Volt-hours, milli-Amp-hours, Frequency. Multiple function testing allows for a complete test of the energy meter for all billable measurement functions. The auto-ranging inputs for potential, current, and auxiliary power make it impossible to damage the unit by applying a signal to the wrong tap. The RD-21 can be used for laboratory applications as a reference standard or it can be used as a portable field standard whenever a higher level of accuracy is required. In the field, the RD-21 can be used with a controlled current load, or it can be used to perform customer load tests where it can analyze current and voltage waveforms through the 50th harmonic order. In addition, for improved efficiency, the RD-21 can automatically calculate and display the error of the meter under test. The RD-21 also provides a serial communication port for connection to a personal computer.

SINGLE-FUNCTION AUTORANGING STANDARDS

These standards can be referred to as second generation electronic standards that first appeared in 1985. The most common models are the RM-10 and RM-11 by Radian Research.

Figure 14-3. The Radian Research Model RM-10 Standard.

The RM-10 and RM-11 standards use a Pulse Width Modulation approach to measuring energy. These second-generation electronic standards introduced a multitude of new features to the metering industry.

Providing totally autoranging inputs for potential, current and auxiliary power eliminated the need for tap settings. A true watthour display with a Kh of one, allows for easier calculations. A high-resolution pulse output allows for shorter test times. A display-gating feature greatly improves safety by eliminating the need for potential gating while also improving accuracy. These standards also provide the accuracy and stability required to conduct a true test of an electronic meter. Although still widely used today, these standards do not provide all of the functions required to thoroughly test the new electronic revenue billing meters.

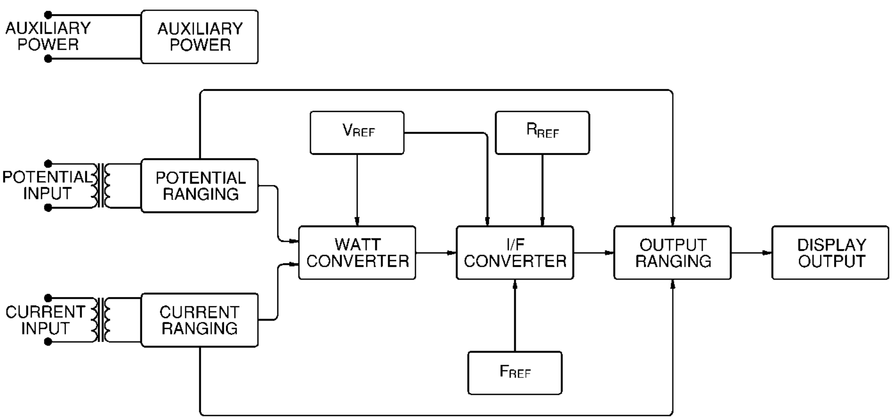


Figure 14-4. Block Diagram of the RM-10 and RM-11 Standards.

SINGLE-FUNCTION MANUAL RANGING STANDARDS

This can be referred to as first generation electronic standards with the first products appearing in the late 1970s. The most common model is the SC-10 by Scientific Columbus.

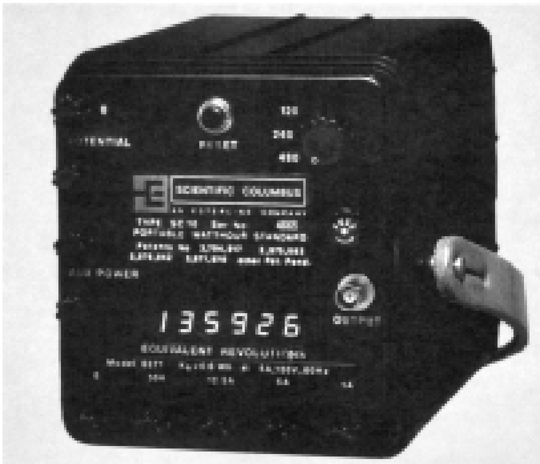


Figure 14-5. The Scientific Columbus SC-10 Standard.

The SC-10 standard utilizes Pulse Width Modulation to calculate energy thus eliminating the induction-measuring element of the Rotating Standard. The SC-10 is packaged to resemble Rotating Standards for interchangeability while providing improvements over the Rotating Standards. The lack of moving parts makes the need for leveling the standard unnecessary. The digital display reads in revolutions while providing better resolution. It maintains manual voltage taps and current taps that simulate the Rotating Standard. For testing operation, just as with the Rotating Standard, tests are started and stopped by closing and opening the voltage circuit with a snap switch. These standards are not widely used today due to advancements in electronic revenue billing meters. The revolution reading display is not easily compatible with testing an electronic meter and the accuracy and stability are similar to the electronic meter under test thus, not allowing for a true test of accuracy.

ROTATING STANDARDS

Rotating Standards have a rotating disk and are also referred to as induction standards or mechanical standards because the measurement principle is based upon the electromagnet. The most common model is the IB-10 by General Electric.

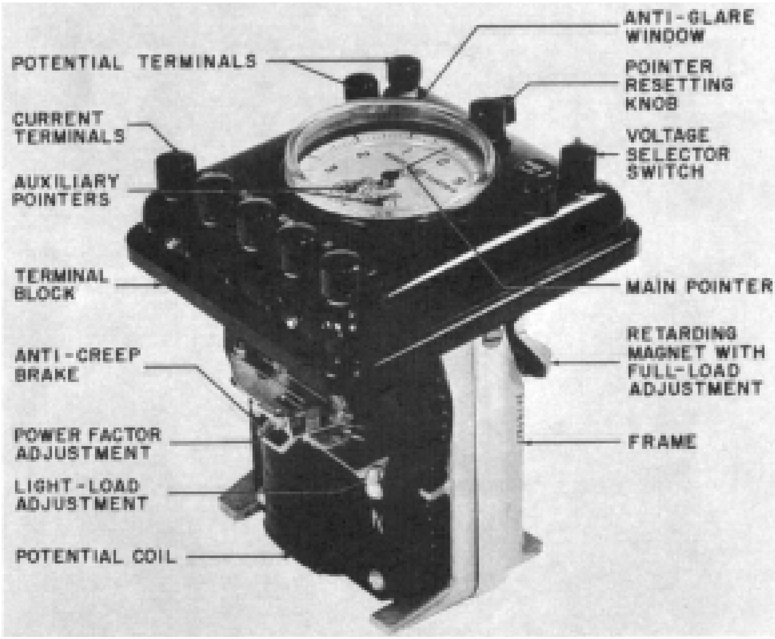


Figure 14-6. The General Electric IB-10 Standard.

Rotating Standards have voltage taps and current taps where the appropriate tap is used based upon the amplitude of the voltage and current test signals. Generally there are two voltage taps, rated at 120 and 240 volts. Generally there are four current taps with the most common rated at 1, 5, 15, and 50 amperes. Note that the watthour constant (Kh) varies depending upon which taps are used.

The normal procedure for using a Rotating Standard to test meters is to start and stop the standard by applying and removing the test voltage by means of a snap switch.

By the nature of its design, a Rotating Standard requires proper handling when transporting and in use to avoid damage. Although strong magnetic fields have little effect on Rotating Standards, they should be kept away from heavy current carrying conductors, motors, transformers, or other like apparatus. In addition, a Rotating Standard should be level if accuracy is to be maintained.

Rotating Standards are not widely used today due to their dated design relating to deficiencies in the areas of accuracy, stability, functionality, and maintenance costs combined with parts availability.

For further information on Induction-Type Watthour Standards, see Chapter 14 of the Ninth Edition of the *Handbook for Electricity Metering*.

TEST LOADING METHODS

An AC current signal is needed as a test current in order to test an energy meter. The various loading methods are discussed in this section. All concepts rely on the simple premise that the same test current should be used in series between the standard and the meter under test. Any one of the following methods may be considered.

Customer's Load

When testing meters in service, the customer's load itself may be used. Utilizing the customer's load while performing field meter tests eliminates the need for a loading device. This test procedure requires less time as only one test at the available load current is performed. In addition, artificial registration and or pulse counts do not have to be considered.

This type of testing has its limitations. The absence of load current will prohibit a test from being performed. In addition, most metering standard procedures and manufacturers' information recommend meter testing be performed using three controlled load test points; Full-Load, Light-Load, and Power-Factor Load. The Full-Load test point is identified as the meter's Test Amp (TA) rating or can be the associated current transformer secondary current rating. The Light-Load test point would then be 10% of the selected Full-Load current value. The customer's loading does not serve to satisfy these test points. Other disadvantages include the fact that stable test conditions cannot be controlled or duplicated. However, it can be a valuable type of test load under certain conditions. For example, a standard such as the Radian RD-20 or RD-21 can be used not only to test accuracy of the meter, but also to do harmonic analysis of the customer's load. This test also has the ability to test the accuracy of the meter under customer load conditions if a true reference standard is being used to conduct such a test. Additional information will be described later in this chapter under the subheading "Testing on the Customer's Premises".

Synthesized Loading

Synthesis is the latest technology applied to loading designs and is the most common and preferred source for a majority of applications. Synthesized loading is actually a type of phantom loading because it does not dissipate the full wattage of the test load. Synthesized loading is computer controlled and allows for very precise conditions of current amplitude, frequency, phase angle and harmonics to be created and maintained throughout the test period. Imperfections associated with the other loading approaches generally do not exist in a well-designed synthesized load.

Phantom Loading

Phantom loading reduces the power in the current circuit by reducing the voltage across the load connection. A phantom load is basically a small power transformer and an adjustable loading resistance. Test connections apply service voltage, 120 or 240 volts, to the voltage coils of the meter and the standard. The current circuits of the standard and meter, which are isolated from the voltage circuit by transformer action, are placed in the secondary of the low-voltage, phantom-load transformer whose primary is connected across the line. The regulating resistance of the phantom load is also in series with the meter and standard current coils.

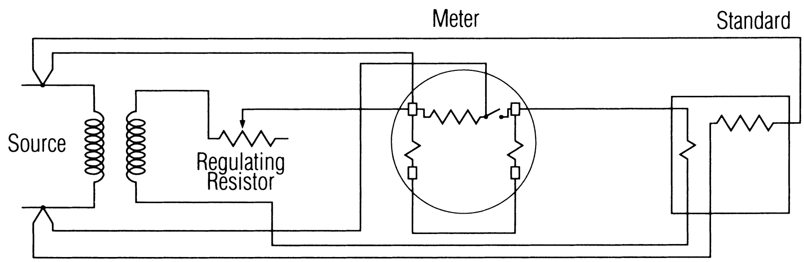


Figure 14-7a. Schematic Connections for Phantom Loading.

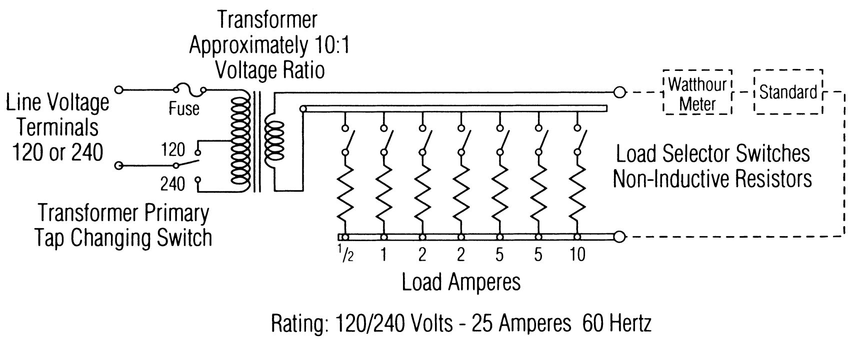


Figure 14-7b. Typical Wiring Diagram for Phantom Load.

Note that in this type of loading, although the current value is proper for the test being made, the voltage at which this current is supplied is low and, hence, the power has been reduced below that necessary for resistance testing. Assuming the phantom-load transformer is rated 240 to 12 volts and the regulating resistor is adjusted to provide 15 amperes to the test circuit, the power of the secondary circuit would be $15 \times 12 = 180$ watts. The current drawn from the secondary circuit is 15 amperes, but from the source is: $15 \times \frac{12}{240} = 0.75$ amperes. With the low power requirements, a phantom load can be constructed as a portable device.

The term "phantom load" is usually applied to the portable device that is used particularly for testing on customer's premises. The same principle of a loading transformer with low-voltage resistance units has been used in some test table designs. When the output voltage is lowered, the size of the current regulating resistors in the secondary circuit is also reduced while still maintaining the desired current magnitude.

When using phantom loads, the phase angle of the test circuit should not be ignored. Meter and standard current coils have inductive reactance as well as resistance. Normally, the regulating resistance is large enough to overcome any lagging effect caused by the reactance of the current coils and loading transformer. However, if the regulating resistance is small, the current through the current coils will lag the source voltage by some small angle. This change in phase angle may not be significant at unity power-factor tests, but may be of importance at 50% power-factor tests. This occurs because of the difference in values of cosines near zero and 60° angles. As an example, at 60° the cosine is 0.5 and at 61° it is 0.4848;

at zero degrees the cosine is 1 and at 1° the cosine is 0.9998. A small change in phase angle at unity power-factor causes a much smaller change in cosine than a similar phase angle change at 50% power factor. The phantom-load phase angle shift will increase rapidly with increasing secondary burden above rated burden capacity. Furthermore, when a phantom-load transformer is overloaded, the waveform of the output current may be seriously distorted. On the best modern test boards, the loading transformers are designed to avoid these shortcomings.

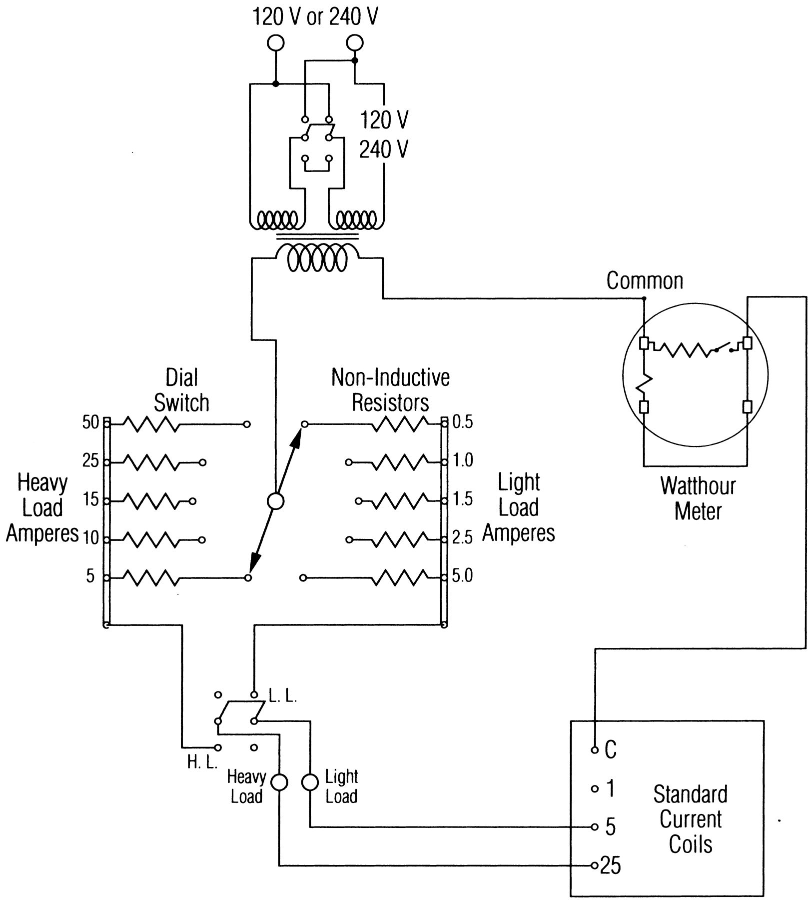


Figure 14-8. Dial Switch, Phantom-Load Circuits.

When using a phantom load for testing a three-wire, single stator meter, one end of the voltage coil must be disconnected from the incoming current lead by means of the voltage link due to the tying together of the current coils on the load side. If this is not done, the current test circuit will be connected across full voltage, with resulting damage to meter coils and phantom load. The disconnected end of the voltage coil is connected to the correct voltage source in order to energize the coil at full voltage.

Resistance Load

Resistance load is adjustable to provide the various test currents desired.

In the resistance-loading method, the current coils of the meter under test, the standard, and the loading resistance are connected in series. Thus, the current that is permitted to flow by the resistance passes through both the meter and the standard.

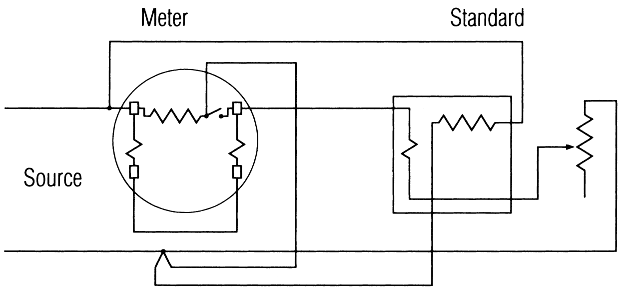


Figure 14-9. Schematic Connections for Resistance Loading.

The resistance type of loading device usually consists of a group of fixed resistances of various values which can be connected in any one of several series-parallel networks to give the total resistance which will allow the current flow required for the test. These loading devices are calibrated for specified voltages and the switches are generally marked to indicate the current each allows to flow so that currents can be obtained in steps from zero to the maximum rating of the device.

A real difficulty in this type of test load lies in the problem of dissipating the energy consumed by the I_2R loss at high currents. If the source is 240 volts and a 15-ampere meter is to be tested at the full-load point, a total of $15 \times 240 = 3{,}600$ watts must be dissipated in the loading resistance. The source also must be of sufficient capacity to furnish the full 3,600 watts. Furthermore, the weight and bulk of a resistance-loading bank may limit its usefulness as a portable device. Although resistive loading devices may have limitations as mentioned above, they are generally less expensive than phantom loading devices.

VOLTAGE SOURCE

A steady voltage source is required, particularly when indicating instruments are used as reference standards. When a standard is the reference, with the current circuits of the standard and of the meter being tested in series and their voltage coils in parallel, minor fluctuations in voltage or current have no significant affect on the test results. In this case minor changes in source or load affects both reference standard and meter in the same manner. This does not mean that wide and rapid changes in source voltage should be tolerated. Harmonics do not have the same effect on all meters and waveform distortion should be avoided.

Early meter test boards required a three-wire, three-phase voltage source. The three-phase feature provided a convenient way to obtain a 50% power-factor, single-phase test load. The connections are fundamental and in some form are used for all meter testing.

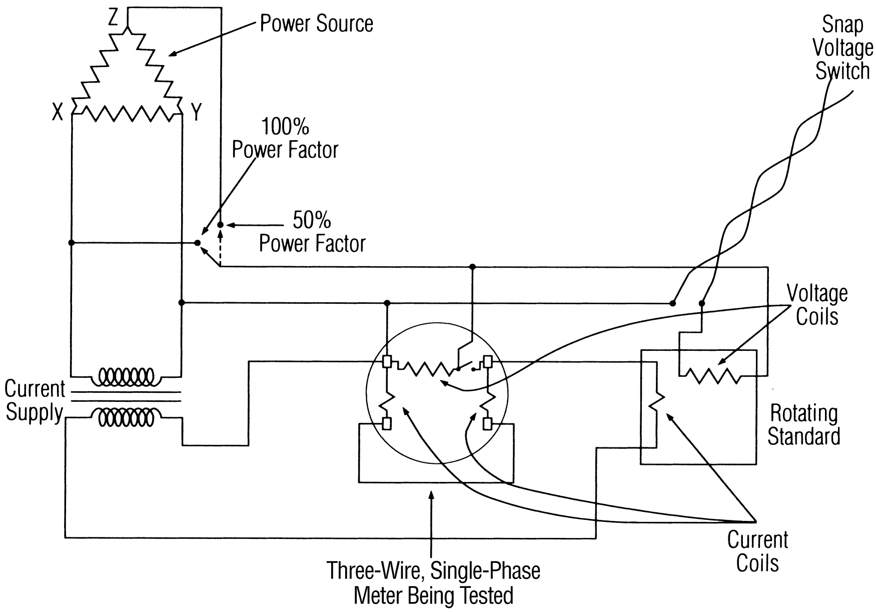


Figure 14-10. Fundamental Meter Test Circuit.

The preferred source connection is a closed-delta transformer bank. Both open-delta and wye connections may contain unduly large harmonics and will not provide a waveform as close to a pure sine wave as may be obtained from a closed-delta transformer bank. The closed-delta bank also provides better voltage regulation than the other two types of connections.

The source transformer bank and conductors must be of such size that the test load does not cause any material voltage drop from the source to the test equipment. Heavy loads, particularly motor loads such as elevators which cause excessive voltage fluctuations, should not be connected to the meter-test transformer bank.

Late-model electronic test boards usually are powered by 120-volt single-phase sources. Using electronic instruments, a variety of test waveforms are generated. These manufactured waveforms include harmonics, a variety of power-factors, as well as three-phase waveforms.

In field testing applications, the service voltage can be used as the test voltage signal. In this application, the true voltage as seen by the meter is used as the test signal. Or, a synthesized voltage signal can be used to provide a clean, consistent voltage test signal.

SENSORS, COUNTERS, AND CONTROLS

Sensors are used to sense disk rotation, infrared calibration pulses, visible calibration pulses, KYZ contact closures, or analog calibration signals. Generally, these sensors detect signals and send pulses to a counter. The counter actually controls the test.

With rotating disk meters, it is possible to conduct a manual test where the disk revolutions are manually counted and a switch is used to control the test by starting, stopping, and resetting the display of the standard. This switch is normally referred to as a snap switch or a reset switch.

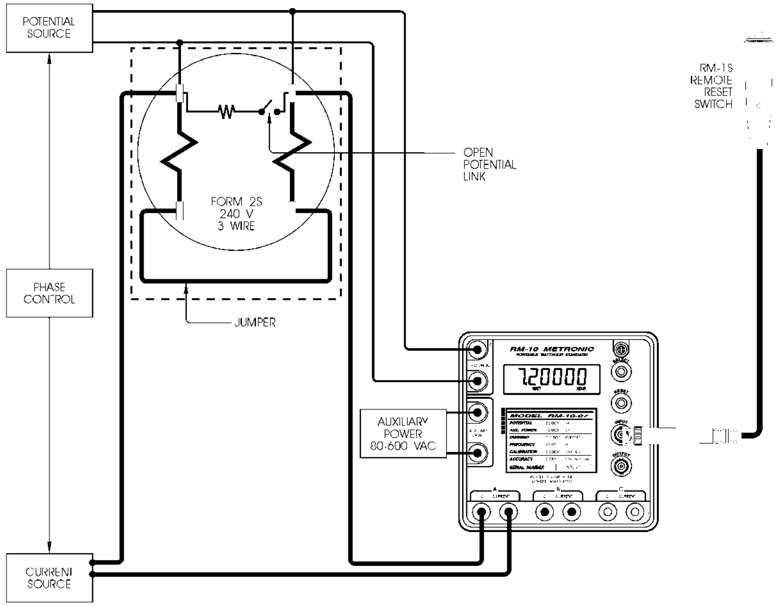


Figure 14-11. Open Link Manual Testing with a Reset Switch.

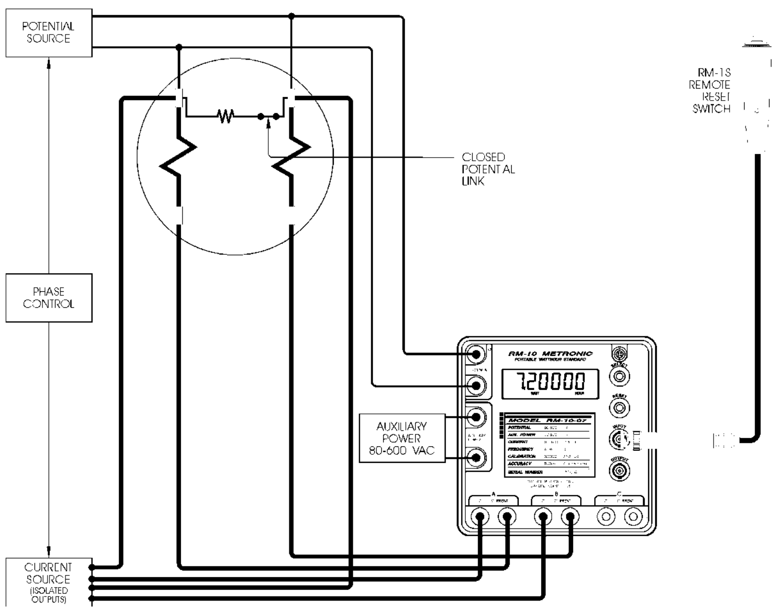


Figure 14-12. Closed Link Manual Testing with a Reset Switch.

As described earlier, this switch gates (starts and stops) the display of the standard while voltage and current circuits remain closed. Although the manual method is still used, often there are sensors, or pickups, along with counters that can be used to automate the testing of rotating disk meters. The Disk Sensor can perform an edge test where it senses the black flag as the disk rotates. As the Disk Sensor detects the black flag it sends a pulse to the counter. When the preset number of pulses has been counted then the test is automatically stopped. An error calculation can then be made based upon the reading on the display of the standard in association with other test variables. Some counters have the ability to automatically calculate and display the error of the meter under test.

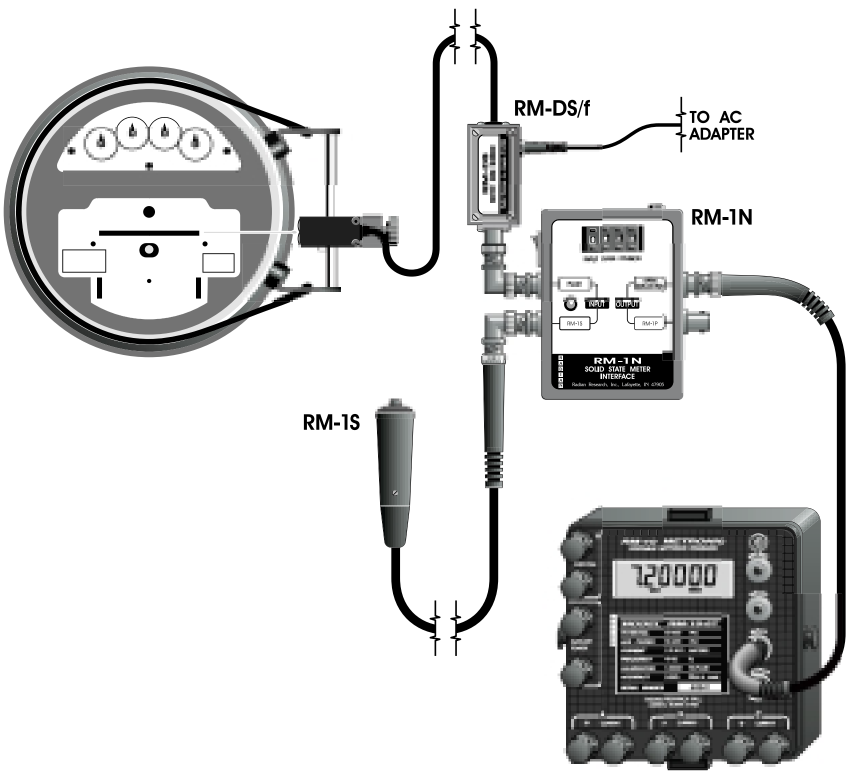


Figure 14-13. Automated Testing with a Disk Sensor and Counter.

When testing electronic meters it is necessary to have a sensor to detect the infrared (or visible) calibration pulse that emits from the meter. Generally, this calibration pulse sensor will send a pulse to a counter as it detects a calibration pulse from the meter under test. When the preset number of pulses has been counted then the test is automatically stopped. An error calculation can then be made based upon the reading on the display of the standard in association with other test variables. Some counters, such as the Radian Research RM-110, have the ability to automatically calculate and display the error of the meter under test.

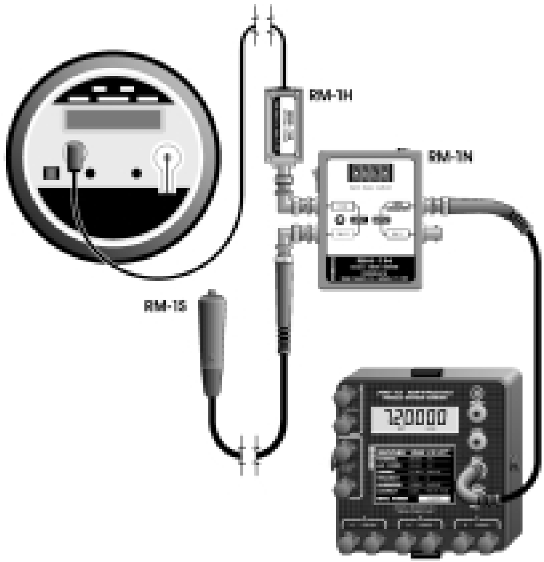


Figure 14-14. Automated Testing with an Optical Sensor and Counter.

Meters can also be tested from their KYZ output as described above. In addition, some meters emit an analog calibration signal. These meters can generally be tested using the Scientific Columbus MicroJoule Standard or the Radian Research RD-21 Standard.

BASIC INDUCTION-TYPE WATTHOUR METER TEST, SINGLE STATOR

Before suggesting procedures for the various classes of meter test and the several locations at which tests may be made, it is important to describe those practices common to all types of test. Some of these steps will be expanded later.

Step 1

Check meter number and meter rating. Record this data.

Step 2

Check for creep.

Creep may occur either backward or forward. When all load is removed, a meter disk may rotate for part of a revolution before coming to rest. This is not creep. All measurements of the amount of creep should be based upon at least one complete revolution for electromechanical meters and a change of more than ±1 least significant digit in 24 hours. Although only an unusually rapid rate of creeping will result in an appreciable registration, as a matter of principle, no meter in service should be allowed to remain creeping or with a tendency to creep.

In most induction meters, creeping is prevented by two holes or slots cut in the disk on opposite sides of the shaft. When either hole is near the pole of the voltage coil, forces set up by the alternating field tend to hold the disk in this position.

Step 3

Connect meter and take "as found" readings. The connections for testing are as follows: The current circuit of the standard is connected in series with the loading device and current coil of the meter under test, and the voltage circuit of the standard is connected in parallel with the voltage coil of the meter under test. When setting up a standard for making a test, the place selected should be reasonably free from vibration and magnetic influence. The meter should be plumb, without tilt, and the standard should be level during the test. The standard must always be reset to zero before starting a test. A reading of the standard is taken at the end of the test, which gives the number of revolutions of the standard pointer. If no correction is to be applied to the standard readings, the percent registration of the watthour meter under test is obtained as follows:

let r = revolutions of meter under test
R = reading registered by the standard
k_H = watthour constant of meter under test
K_H = watthour constant of standard

then, Percent Registration $= k_h \times \dfrac{r}{K_h} \times \mathrm{R} \times 100$

The method may be facilitated by introducing an additional symbol, values for which may be given to the tester in tabular form.

Let R_O = the reading the standard should register when the meter under test is correct.

The revolutions of two watthour meters on a given load vary inversely as their disk constants.

$$\frac{R_O}{r} = \frac{k_H}{K_h}$$

Substituting R_O in the equation for percent registration:

$$\text{Percent Registration} = \frac{R_O}{r} \times 100$$

In testing, the number of watthour meter disk revolutions should be sufficient to permit reading whole divisions of the standard register to the degree of accuracy required.

When the watthour meter under test and the standard have the following constants:

meter $k_H = 0.6$
standard $K_H = 0.12$

number of revolutions of the meter under test, $r = 2$

$$\text{then, } R_O = \frac{0.6 \times 2}{1.12} = 10$$

That is, for two revolutions of the meter under test, the standard registration should equal ten revolutions. Assume the standard actually registered 10.16 revolutions.

$$\text{then, Percent Registration} = \frac{10}{10.16} \times 100 = 98.4$$

When a correction is to be applied to the readings of the standard, the percent registration is determined as follows:

let A = percent registration of standard

$$\text{then Percent Registration} = \frac{k_h \times r \times A}{K_h \times R} = \frac{R_O}{R} \times A$$

Step 4

Examine the original condition of meter. The principal features are:

a. Is the disk centered in both permanent magnet gap and electromagnet gap?
b. Is the magnet gap clean?
c. Examine the mesh of the first register gear with the shaft worm or pinion. This mesh should be between one-third and one-half the depth of the teeth. A deeper mesh may cause binding. A slight amount of play is necessary. Where the pinion or worm is short, or where the worm is cut concave to match the curvature of the worm wheel, the vertical position of the moving element must be such that the center of the pinion or worm is level with the register wheel which it engages.

Step 5

Check the register ratio as marked on the register to determine if this ratio is correct for the type and capacity of the meter. For instructions on a complete register check see a subsequent discussion under the subheading "Register Testing and Checking".

Check watthour constant (k_H) for the meter type and rating with the correct constant from manufacturers' tables.

Check kilowatthour constant (register multiplier). Kilowatthour constant

$$= \frac{k_h \times R_r \times R_s}{10{,}000}$$

where: k_H = watthour constant of meter under test
R_R = register ratio
R_S = shaft reduction ratio

Step 6

Make adjustments. Since the full-load adjustment affects all loads equally, this adjustment should be made first. If, after adjustment at full-load, light-load performance is more than about one percent slow, a cause other than maladjustment of the light-load should be looked for. Such cause may be unusual friction or dirt. If the meter is clean and the register mesh is correct, the meter bearings should be suspected. See the bearing maintenance for suggestions.

Power-factor adjustment of single-stator meters is usually limited to shop testing. See the discussion following for descriptions of adjustments.

Step 7

Record final readings.

Step 8

Seal meter. Return meter to service or stock.

INDUCTION-TYPE METER ADJUSTMENTS, SINGLE STATOR

Full-Load Adjustment

This adjustment is made at nameplate rating of voltage and rated amperes or test amperes. The adjustment is made in most meters by varying the effect of the damping flux passing through the disk. This is done in older meters by changing the position of the damping magnets. Similar results are secured in newer meters by varying the amount of flux passing through the disk by means of a shunt, sometimes called a keeper. The change produced in the percent registration is practically the same on all loads; that is, if the registration is 98% at both full-load and light-load, shifting the full-load adjustment so as to increase the speed 2% will make the meter correct at both loads.

Moving the magnets toward the disk shaft causes the disk to cut the damping flux more slowly and the meter runs faster. Moving the shunt closer to the damping magnet poles causes more flux to pass through the shunt and less through the air gap in which the disk turns, thereby increasing the disk speed.

Light-Load Adjustment

This adjustment is normally made at the nameplate rating of voltage and 10% of rated amperes or test amperes. It is accomplished by varying the amount of light-load compensating torque.

This adjustment is changed by shifting a coil so that its position with respect to the voltage-coil is changed. No torque is produced on the disk as long as the light-load coil is symmetrical with the voltage-coil pole. When the light-load coil is shifted, a torque is produced in the disk that will tend to turn the disk in the direction of the shift. The coil is essentially a short-circuited turn of large cross section placed in the air gap above or below the disk so as to embrace part of the voltage-coil flux. Maladjustment of this coil may result in creep. See Chapter 7, "The Watthour Meter". The effect of this torque on meter percentage registration is inversely proportional to the test load, one-tenth as much effect is produced at heavy load as at 10% load.

When a meter, after adjustment at full-load, is found inaccurate at light-load, the cause may be some condition in the meter that should be removed rather than compensated for. In such cases the tester should locate the trouble, making no adjustments unless the meter is still inaccurate after going over all the parts and restoring them to proper condition.

Lag Adjustment

This adjustment is ordinarily made only in the shop. The flux established by the voltage coil of a meter should lag the flux of the current coil by exactly 90° with unity power-factor conditions for proper metering accuracy with any load power-factor. This flux relationship does not exist because of the inherent resistance of the voltage coil. Compensation to obtain the correct relationship is by means of a lag coil or plate on the voltage pole acting with another lag coil on the current poles. The explanation of how this compensation works is described in Chapter 7.

If the compensation is obtained by means of a coil, the adjustment is made by soldering the exposed pigtail ends of the coil so as to lengthen or shorten the overall length of the coil conductor to change the resistance of the coil. If a lag plate is used, the adjustment consists of shifting the position of the plate under the voltage pole radially with respect to the disk by means of an adjusting screw. On some types of modern meters the lag adjustment is made by punching a lag plate during the manufacturers' testing and cannot readily be changed in the field.

The test to determine the lag or phase adjustment is generally made at 50% lagging power factor with rated amperes and voltage applied. Fifty percent power-factor is used because it can be obtained readily from a polyphase circuit without auxiliary equipment.

MULTI-STATOR, INDUCTION-TYPE METER TESTS AND ADJUSTMENTS

Multi-stator meter tests follow a procedure similar to that used for single-stator meters. With the multi-stator meter voltage coils connected in parallel and all current coils in series, the procedure is identical to single-stator tests, but additional tests may be made with each individual stator energized. Each separate stator in a multi-stator meter must provide the same disk-driving torque with equal wattage applied to the individual stators for the meter to provide accurate registration when in service. Therefore, the individual stator torques must be balanced and this is the reason for the individual stator tests and the additional torque-balance adjustment on multi-stator meters. Individual stator tests are also useful in determining correct internal wiring of the voltage and current coils of each stator.

The torque-balance adjustment commonly consists of a magnetic shunt in the stator iron, the position of which may be changed to vary the effective stator air-gap flux and hence, the disk torque produced by the stator. This adjustment varies the driving torque produced by the individual stators, thereby allowing the torque of one stator to be made equal to that produced by a second stator. The usual practice is to make the adjustment at unity power-factor with rated meter voltage and test amperes. The adjustment may be provided on all stators of a multi-stator meter or, as on some modern meters, it may be omitted on one stator, in which case the torque of the other stator(s) would be adjusted to match the first.

All stators in a multi-stator meter must have a lagging power-factor adjustment to provide the proper flux relationships in each unit. The importance in meter testing of proper balancing of lag adjustments among meter stators is not generally recognized, for not only must the torque-balance adjustment be correct at unity power factor, but the lag adjustments of each individual stator must also agree to provide best meter accuracy under all service conditions.

An example of improper lag balance will illustrate the possible meter errors. Assume a two stator meter is found running 1.5% fast on a series-parallel, lagging-power-factor test caused by a faulty lag adjustment on stator 2. This error is equivalent to a 1° phase-angle error in the lag adjustment, as shown in Figure 14-15a. If instead of correcting the faulty lag adjustment on stator 2, the adjustment on stator 1 is changed, the end result at 100% meter accuracy with series-parallel connection will be a 1° lead error in the lag adjustment on stator 2 and a 1° lag error in the lag adjustment on stator 1, as shown in Figure 14-15b.

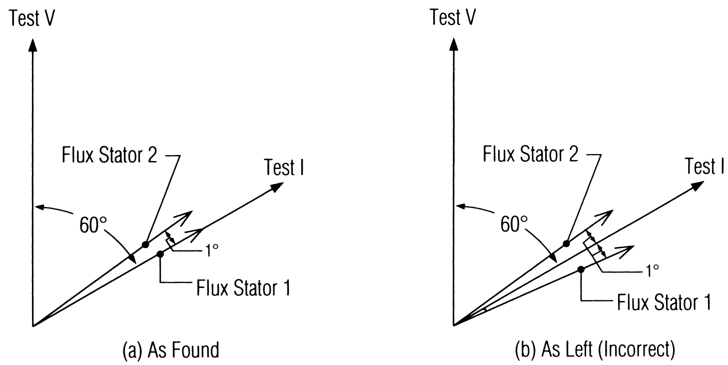
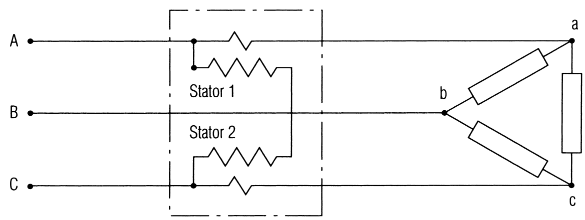


Figure 14-15. Incorrect Adjustment with Lagging Power Factor.

With the meter connected to a three-wire delta service, consider its operation on a balanced, unity-power-factor load. Figure 14-16 shows the circuit diagram and metering phasors. Note that in stator 1 the current lags the voltage by 30° and in stator 2 the current leads by 30°. With a maladjusted meter that has power-factor errors of 1° lead and lag, one possible circuit connection would, in effect, have both stators registering at a 29° angle instead of the proper 30°, or the other circuit connection would cause an effective angle of 31°. In either case, the meter performance error in this application would be approximately 1% even though the meter was adjusted to 100% performance in the usual series-parallel, single-phase test procedure.



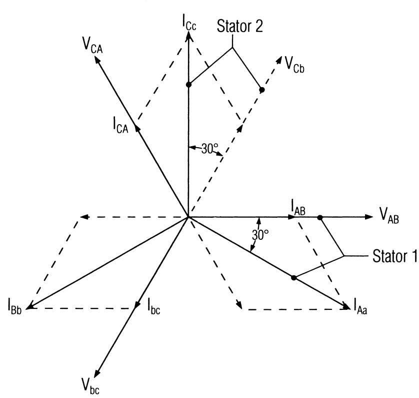


Figure 14-16. Three-Phase, Three-Wire Delta Circuit and Metering Phasors.

Light-load adjusters may be provided on all stators or only one stator in multi-stator meters. Since the light-load adjustment provides additional disk torque dependent on voltage, it is immaterial whether the torque comes from one stator only or all stators as long as all voltage coils are energized. In some meters, there is interdependence between the light-load and lagging-power-factor adjustments so that a change in light-load in one stator may affect the lagging power-factor performance of the same stator. If more than one light-load adjuster is provided, it is good test practice when light-load adjustment is required in a series-parallel test, particularly in field tests, to make equal changes with each light-load adjuster.

The full-load adjustment on multi-stator meters, operating on the braking magnets, has an identical effect on all stators. Hence, it cannot be used for torque balance. One or more full-load adjusters may be provided on multi-stator meters.

ELECTRONIC METER TESTING

Electronic or solid-state meters require testing to confirm their accuracy but do not normally have calibration adjustments. These meters are calibrated in the factory by running a succession of tests and finding an internal register constant that produces 100% registration. This constant is then burned into the meter to prevent it from accidentally being changed. This is a calibration process that is best left to the manufacturer.

METER TEST CIRCUITS

Over the years, many arrangements of test circuits have been devised and many forms of test fixtures are available. Modern test fixtures show major improvements over many of the older so-called “test benches or test tables”. Figures 14-7 and 14-10 show fundamental schematic diagrams for meter test circuits. Although the circuit arrangements, equipment, and methods of counting revolutions may differ in test fixtures, fundamentally all the circuits are based on that shown in Figure 14-10.

Meter Timing and Speed Measurement Methods

Before reviewing more complicated meter test fixtures, consideration should be given to the automatic timing methods used in various test fixtures. Two general methods are used, the photoelectric disk revolution counters and the stroboscopic comparison of meter disk speeds.

Photoelectric Counters

Modern test fixtures do not use a manual voltage switch for applying voltage to the standard meter. A photoelectric counter that contains photoelectric devices and associated equipment for automatically starting and stopping the standard watthour meter controls voltage. For this method of test, a light beam is directed through the anti-creep holes or reflected from the flag of the disk of the watthour meter under test and illuminates a photodiode or transistor. This illumination causes pulses to be transmitted to the control equipment where they are amplified and used to operate digital displays, which in turn operate relays controlling the voltage circuit of the standard watthour meter. This is done in accordance with a predetermined number of revolutions of the watthour meter disk.

It is important that the start/stop relays have exact or symmetrical reaction times. For this reason, some designs use two relays for the start and stop functions, arranged in such a way that they both pull-in to perform their function. Other designs use a single symmetrical reed relay controlled by zero crossing switching circuits to close the relay at zero voltage and open it at zero current. This method of zero crossing switching eliminates the need for arc suppression components used in standard designs that, with time, can cause testing errors.

This method of shop testing eliminates the necessity of manually counting the revolutions of the meter disk and, since the starting and stopping of the standard is automatic, human errors are eliminated.

ROTARY STEPPING SWITCHES

Many older photoelectric counters use rotary stepping switches for the counting, sequencing, and other functions in automatic test boards. For a detailed discussion of rotary stepping switches refer to the Seventh Edition of this *Handbook*, Chapter 15.

ELECTRICITY METER TEST FIXTURES

For further information on the construction of test fixtures for ganged-meter testing and in-house constructed test fixtures, see Chapter 14 of the Ninth Edition of the *Handbook for Electricity Metering*.

Today, meter manufacturers are building meters of superb quality and extensive functionality. In the United States, the polyphase meter market is dominated by electronic meters. However there continues to be an important market segment for new electro-mechanical polyphase meters. With technology ever increasing along with improvements in price and dependability, more and more electronic single-phase meters are being seen in the marketplace and from a variety of manufacturers. The capability and functionality of present solid-state meters create challenges for the meter tester and meter test equipment.

Electric meter test equipment has certainly changed over the years. Currently, all meter test equipment produced is totally solid-state. The technology that has propelled the solid-state meter development has done the same for meter test equipment. With the increased accuracy of the newer solid-state meters, it quickly became apparent that the conventional rotating type standards and associated phantom-loading designs were inadequate. The accuracy levels of the new solid-state meters were not only better than the conventional electromechanical meter but also better than the test equipment commonly used by most utilities.

Aside from this, there were other problems. Solid-state meters don't have a disk. They normally have an infrared LED on the meter which pulses at a rate corresponding to watthours of energy. This is similar to the K_h of a conventional electromechanical meter, but is normally termed K_e in the solid-state meter. Most of the earlier conventional meter test equipment had no means to trigger this new infrared LED.

In the 1980s, the utility industry began seeing changes in meter test equipment. Manufacturers of test equipment such as RFL, Knopp, Multi-Amp, and WECO began to make equipment available to address the utility's need to test these newer electronic meters.

Being able to test the watthour accuracy of the solid-state meter is not the only concern. Presently available solid-state meters have functionality that far exceeds simply watthours. A single solid-state meter can be purchased that can record forward and reverse power, forward and reverse reactive power, forward and reverse VAhours, voltage, current and more. A single meter can now take the place of many meters at certain customer locations. In addition to having better accuracy, this, of course, reduces the quantity of meters necessary to install and maintain. This translates into a savings of money.

With new electronic test equipment, quality and accurate testing was available. Also, the utility had greater flexibility and convenience. New electronic test equipment needs reasonably low power requirements. It is no longer necessary to have a three-phase source to run the test equipment. Since the test equipment is electronic, even true three phase testing can be easily accomplished. Simply plug the test equipment into a conventional 120VAC outlet and begin testing. This opens even further opportunities for the utility. With this low power requirement, the test equipment can be easily operated from a power inverter. Some utilities now make use of vans as mobile testing laboratories.

Figure 14-17. Mobile Meter Testing Facility.

Many utilities desire to conduct testing which is outside the normal ANSI testing requirements for the utility. There are now available standard production models of electronic meter test equipment that will allow testing from 10 milliamps to 225 amps and with true three-phase capability. The utility can run tests that previously were only able to be run by the meter manufacturer.

Figure 14-18. Dual Test Fixture.

Cost is obviously a big concern for most utilities. New electronic test equipment for shop, van, and field-testing must provide not only quality and flexibility but also features which relate to savings for the utility. Electronic test equipment is available that can have multiple test stations. One tester can operate, using one computer, more than one test station. The test stations are independent allowing the tester to test different meter "forms" at the same time. This easily increases throughput.

AVO Optima

WECO 2350

Figure 14-19. Watthour Meter Test Fixtures.

Present electronic test equipment, from manufacturers such as AVO and WECO, is becoming smaller and increasing further in convenience and functionality. The newest models of test equipment utilize laser optics for detecting the disk revolution for electromechanical meters. The test equipment has the convenience of a built in Opticom™ probe that can pick up the test LED and also be used for programming the meter.

Even total test time can be reduced with today's technology. On many solid-state meters, an accelerated test can be run. This unique testing method, called Turbo-Test™ by WECO, is different from the normal test using the test LED pulse output. Software allows the internal DSP of the meter under test to be read during the test. This allows *simultaneous* testing of, not only the series test, but separate elements as well. For polyphase electronic meters this can reduce the total test time by a factor of 5 or 6.

As technology advances further, no doubt there will be other demands for meter test equipment. Utilities may wish to test most or all of a meter's capability at one time, in one location, and with one piece of test equipment. Functions that have normally been outside the meter shop's area of responsibility are routinely tested. Electric meter test equipment manufacturers will certainly be challenged in the future. Such things as modem verification and AMR testing will most likely find their way into equipment that, not too many years ago, was the sole domain of a rotating watthour standard.

SHOP TEST PROCEDURE

Only general procedures are given for testing single-stator and multi-stator meters. Also included are variations in procedures that are dependent upon meter age. No attempt has been made to include details of meter repair, painting, handling, storing, and recordkeeping procedures. Such details vary greatly and are subjects for local consideration and decisionmaking.

Recently electronic meters have gained a substantial and increasing share of the meter market, as they can provide a great number of advanced functions at a modest cost. Unlike electromechanical meters, most electronic meters do not have user adjustments.

Procedure Variations

Variations in the following test procedures may be made based on the age and condition of the meters under test.

New meters may not be tested at all before being placed in service, may be sample tested, or may all be tested. However, tests of new meters seldom go beyond the step of taking the "As Found" test if they are found to be within the established accuracy limits.

Meters from service that are to be tested and returned to service are usually subjected to the entire test procedure. Under certain conditions, it may be deemed advisable to take no further tests if the "As Found" test shows that the meter is operating satisfactorily.

Meters from service which are to be retired may have an "As Found" test if such data are required.

Single Stator Meters

The following procedure for single stator meters is typical for a complete shop test. All companies may not use all of the steps listed, and the order given may be varied. For most solid-state meters, steps 3, 5, 6, 7, and 8 are not required. Steps 5 and 7 are not required for solid-state registers mounted on electromechanical meters.

Step 1

a. Check nameplate for wire, phase, volts, and amperes.
b. Connect standard on proper voltage and current coils.
c. Open meter voltage link, if necessary.
d. Connect meter.
e. Check for creep by applying voltage only.

Step 2

a. Start "As Found" test.
b. Record meter number, nameplate data, and reading.
c. Record "As Found" test results. "As Found" test load points are suggested as follows:
   – Full-load at 100% of the current rating or test amperes of the meter; 100% power-factor;
   – Light-load at 10% of the current rating or test amperes of the meter; 100% power-factor;
   – Lagging power-factor (if required) at 100% of the current rating or test amperes of the meter; 50% power-factor with lagging current.

Step 3

a. Remove and clean cover.
b. Clean meter with compressed air.
c. Check magnet gaps for iron filings or other dirt.
d. Check position of disk in air gap.

Step 4

Check insulation by high-voltage test. (This test may be made before the "As Found" test according to local company policy.)

Step 5

a. Remove and examine register.
b. Check register ratio. (See discussion under a later subheading, "Register Checking.")
c. Clean register with L. & R. or equivalent cleaning machine, or with brush and cleaning fluid.
d. Check register constant.

Step 6

a. Replace bearings, if necessary. Bearing replacement depends upon:
   – Light-load "As Found" performance slow, or inconsistent.
   – Meter on extended test schedule.
   – Open-type bearing in very dirty meter "As Found".
b. If bearing is changed, both jewels and ball or pivot should be replaced.
c. If meter is noisy, check top bearing.
d. Top guide pin should be replaced if pin is rusty or bent.
e. Check that bearing in the top of the disk shaft is not worn out of round.

Step 7

a. Remount register on meter.
b. Check register mesh with disk shaft.

Step 8

a. Make all necessary adjustments to bring meter accuracy within established company limits.
b. Check for creep after making adjustments.
c. Record "As Left" results.

Step 9

a. Close voltage link if necessary.
b. Replace cover and seal.

Multi-Stator Meters

All of the foregoing basic testing procedures apply to multi-stator meters. In addition there are several considerations made necessary by the multi-stator meter construction and its application. As in single stator solid-state meters, most multi-stator solid-state meters have no user adjustments. The following tests and checks, but not necessarily adjustments, are suitable for all multi-stator meters.

Multi-stator meters usually have two or three separate stators. It is very important that each individual stator exhibit accurate performance by itself as well as having good accuracy with all stators combined. This is evident with a three-wire, three-phase circuit metered with a two stator meter. Here, with a balanced-load power-factor of 86.6% lagging current, one meter stator is operating at unity power-factor and the other at 50% power-factor, lagging current. This leads to the additional test adjustment of polyphase meters, balancing the performance of the stators to provide the necessary separate stator accuracy.

The balance test is made by connecting all voltage coils in parallel and applying 100% of rated current or test amperes of the meter to each current circuit, first at unity power-factor and then at 50% power-factor, lagging current. Calibration of each stator is checked for both currents. In meters which have current circuits which are common to more than one stator, such as the Z-circuit in two stator, four-wire wye circuit meters, the common current circuit is not energized during the balance test.

Accuracy limitations for this test are established in accordance with local requirements. If the accuracies are not within the required limits, the following adjustments are made.

With unity power-factor, the torque balance adjusters on the individual stators are used. This additional adjuster allows adjustment of individual stator performance without changing the performance of any other stator. Thus, the individual stator performances may be adjusted to agree within the specified limits at unity power-factor. In meters where the torque-balance adjustment is omitted from one stator, the performance of the other stators is adjusted to match that of the first.

With 50% power-factor, the usual lag adjustment on each stator is used. If the lag adjustment is a fixed factory-made adjustment, the meter tester cannot easily change the lag balance. In meters where the light-load and lag adjustments are not entirely independent in their effects, the meter tester must remember that a change in light-load adjustment after establishing lag balance may have a detrimental effect on such balance.

After the balance adjustments are made, the "As Left" calibration is made by connecting all voltage coils in parallel and all current coils in series and making tests at the usual light, heavy, and lagging-power-factor loads. If adjustment is required on heavy load, the full-load braking magnet adjuster is used, resulting in an equal effect on the performance of all stators. If lagging-power-factor adjustment is required, equal changes are made with each lag adjuster to maintain as closely as possible proper lag balance. Similarly, required light-load adjustment would be accomplished by equal changes on each stator. However, on meters that have a light-load adjuster on only one stator, this procedure is not possible.

Multi-Function Meters

In addition to active energy (kWh) many solid-state meter types are capable of metering alternate electrical quantities. The most common alternate quantities are apparent energy (kVAh) and reactive energy (kVARh), also called quadergy. These meters, in addition to visual indicators, usually also have a test output signal that can be used to verify calibration. Because this test output signal can be used for both active energy and alternate energy, there is a method for the user to select which quantity will control the output signal. Common methods of control are a special command through the optical communication port of the meter, or manually scrolling to a specific display quantity.

Like active energy, metering test points for alternate quantities are usually taken at test amperes, light-load, and 50% power-factor. When setting up to test reactive energy, the user must remember that power-factor angles must be changed by 90°. For example, to obtain the nameplate test output rate for kVARh, the meter must be set for test amperes, test voltage, and a 90° angle between the voltage and current.

Calibrating Constants

In multi-coil meters the value of one revolution of the meter disk (or equivalent disk revolution for solid-state meters), the K_H, varies with the test connections. The test K_H is sometimes called the calibrating constant. When the same current passes through more than one full current coil (or current sensor for a solid-state meter), the calibrating constant can be found by dividing the normal K_H of the meter by the number of current coils in the meter connected in series. Table 14-1 may serve to check such calculations. Calibration constants for alternate energy quantities are usually the same as for active energy.

Table 14-1. Calibrating Constants.

Meter Type	Connection	Calibrating Constant
Single-phase, two-wire	All tests	K_H
Single-phase, three-wire	Current windings in series	K_H
Single-phase, three-wire	Individual current windings*	$2K_H$
Three-phase, three-wire	Individual current coil	K_H
Three-phase, three-wire	Current coils in series	$\frac{1}{2}K_H$
Three-phase, four-wire wye, two stator	Individual current coil	K_H
	Z coil alone (a double coil)	$\frac{1}{2}K_H$
	Two individual coils in series	$\frac{1}{2}K_H$
	Three-current coils in series	$\frac{1}{4}K_H$
Three-phase, four-wire delta, two stator	Two-wire coil alone	K_H
	Three-wire coil, windings in series	K_H
	Three-wire coil, individual windings	$2K_H$
	Three-current coils in series	$\frac{1}{2}K_H$
Three-phase, four-wire wye, three stator	Individual current coils	K_H
	Two coils in series	$\frac{1}{2}K_H$
	Three coils in series	$\frac{1}{3}K_H$
Three-phase, four-wire delta, three stator	Individual current coils	K_H
	Two 120-volt stator coils in series	$\frac{1}{2}K_H$

*In a single stator, three-wire meter the individual current windings are half coils.

TESTING ON CUSTOMERS' PREMISES

Meter testing on customer's premises will be referred to as "field testing" throughout this section.

Even when the normal routine testing practice is removing meters for test in the meter shop, field testing is still of importance in connection with complaint or witness testing and with the maintenance of instrument-transformer connected meters. Since there was little uniformity in the method of installation in the early days, and since very large numbers of such installations still exist, the meter tester must have a sound basic knowledge of test connections and methods on which to depend for meeting the unusual problems often encountered.

Customer Relations

On entering a customer's premises to perform a meter test, testers should make their presence and purpose known to someone on the premises. As employees of the utility company, the meter testers are perfectly within their rights in requesting access to the premises and the company meter. They must, however, recognize that the company that they represent is in the position of providing service to the customer and they must, therefore, avoid any action or statement that would be discourteous to, or inconsiderate of, the customer. The tester should be prepared and willing to establish his or her identity as a representative of the company. When the meter location is in a place accessible to the public and the entrance thereto is open, it should not be necessary to discuss the matter with anyone. It is important, however, that the tester does not interrupt the customer's service without notification. Every precaution should be taken to avoid damaging the property of the customer and consent should be obtained before making use of any furniture or equipment to assist in making the test. In case of an accident resulting in damage to the customer's property, a prompt report should be made to the customer and to the company.

Safety Precautions

It is important that the tester exercise all possible care to avoid accidents. In the interest of safety and the tester's well being, the prohibitions and suggestions that follow should be continually in mind.

- Beware of dogs. If you are bitten, go to a physician at once and then report the injury to your supervisor.
- Exercise care when entering customer's premises. Be on the lookout for nails, tripping hazards, low beams, or other overhead projections.
- Carefully examine ladders, boxes, and supports expected to carry your weight before making use of them.
- If the apparatus to be worked on is in a dangerous condition, or is so located as to be hazardous, a complete report should be made to your supervisor and the location should be passed without doing work.
- Do not attempt to make connections until proper light is arranged. A flashlight should be used until your portable lamp is connected.
- The use of matches or open flames on customer's premises is prohibited.
- Attention should be concentrated on the points where the tester is working; do not attempt to do two things at once.
- Only one jumper should be connected at a time. Before connecting a jumper or a test lead, be sure you know where the other end is. If necessary, tape it over or tie it in a safe location. Having connected one end of the jumper, be sure that the final connection of the free end does not create a short circuit. Always check with your voltage tester.
- All connections must be made securely to avoid possibility of their dropping or being pulled away from original location.
- All wires, jumpers, test leads, instruments, and other equipment should be so placed that they may not be run into or tripped over by passers-by.
- Use your voltage indicator to determine whether or not the meter, the meter box, or conduit are alive to ground as a result of insulation failure.
- Every tester should be familiar with his or her company's safety rules.

Procedure Preliminary to Test

Before making any connections or in any way disturbing the service meter, the following routine must be followed.

1. Check watthour meter number for agreement with the number given on the test slip.
2. Record the reading of the watthour meter.

3. Enter on the test slip the date, initials of the tester, and the number of the standard watthour meter being used. Make neat and legible records. The work is of little value if the office force cannot read the records.
4. Examine all meter and equipment seals and note conditions on test slip.
5. Clear the top of meter of all dust and dirt.
6. Examine the wiring and general condition of the installation for improper or unauthorized connections and possible hazards. When a connection is discovered which apparently was made by an unauthorized person and which might influence meter registration, a report should be made with a sketch of the connections as found. Do not alter such connections. Do not test meter. Report conditions to your supervisor at the earliest opportunity. If hazardous conditions are found, report them to your supervisor and defer test of this meter until the hazard has been removed.
7. Check voltage and record unusual readings.
8. Note particularly whether or not there is a grounding conductor.
9. Make sure that the grounded or neutral conductor of a two-wire service is properly connected to the voltage and not to the current terminals of the watthour meter.

The first purpose of all field tests is to determine the actual accuracy condition of the meter "As Found", the exact condition the meter is in at the time of test. To meet this requirement, the meter must not be disturbed in a manner that would alter the normal operating condition existing before start of test. The cover of the watthour meter is not removed until after completion of the "As Found" test.

Field Meter Test Equipment

Field meter test equipment has evolved over the past couple of years. Several manufacturers produce in-socket meter test equipment that enables a test utilizing the customer's load. Usually these test devices require removing the meter and inserting a socket adapter device in the meter socket and then placing the meter into the adapter. The adapter provides the connections from line voltage to the actual test equipment. It is no longer necessary to set up a rotating standard and phantom load to perform a meter accuracy test in the field or to be concerned with the safety precautions with using clip-on connectors. For a detailed description of a test setup using a rotating standard and a phantom load, refer to the section on Test Connections, Chapter 14 of the Ninth Edition of the *Handbook for Electricity Metering*.

Field Test Procedure, Single Stator

This section describes general test procedures regardless of the method of testing.

1. With test connections in place and the watthour meter voltage coil energized, but with no current in the current circuit, observe whether or not the meter disk creeps. A meter is not considered to creep unless the disk makes a full revolution in ten minutes or less. Intermittent creep due to excessive vibration may also occur. If the meter creeps, note the apparent cause and the time required for one revolution of meter disk. See later discussion of "Meter Maintenance" for causes of creep.
2. Before disturbing the meter in any way, take "As Found" tests at heavy load (between 60 and 150% of nameplate rating or test amperes) and at light-load,

which should be approximately 10% of test amperes. Both tests are made at 100% power factor. If the first set of runs shows evidence of excessive errors or improper operation, both tests should include as many runs as may be necessary to obtain a reasonable average of "As Found" conditions. The percent registration or percent error is calculated, where required standard corrections are applied, and corrected percent registrations noted.

3. Upon completion of "As Found" tests, the top of the meter is cleaned and the meter cover is removed. The register ratio and the marked register constant are checked and noted on the test slip. Next the entire meter assembly is inspected for presence of dust, dirt, paint chips, etc. All such foreign materials must be carefully removed. Particular attention should be given to the gap between the drag magnet and the disk. All particles of dirt in this area must be carefully and thoroughly removed with a non-magnetic cleaner. Check to assure that the mesh between the shaft worm or pinion and the first register gear is of correct depth and that it does not vary as the disk rotates.
4. Feel each dial pointer with the finger to assure that none of them are loose on their shafts and that the shafts are not loose in their pinions.
5. Check for disk clearances. The vertical play of the shaft should be approximately $^{3}/_{64}$ths of an inch. Reference should be made to manufacturers' instructions for this check, particularly for magnetic-bearing meters.
6. If light-load tests are variable or show the meter to be more than 1% slow, no adjustment should be made until a complete examination of the mechanical condition of the meter is made to determine possible causes for excessive friction. Sources of friction might be improper disk clearances, improper mesh between shaft worm and worm gear, or faulty upper or lower bearing, or a faulty register.
7. If light-load results are still in excess of 1% slow or show variability, the lower bearing unit should be removed and replaced. If it is found necessary to change the lower bearing, the top bearing should also be removed and, if possible, cleaned with pith and an orange stick. If it is not possible to secure a bright surface on the top bearing pin, it should be replaced.
8. Adjust meter if necessary. Refer to earlier discussion under the subheading, "Meter Adjustments".
9. After all inspections, adjustments, and tests have been completed, "As Left" results are noted on the meter test slip. As a final test, the meter must be checked for creep.
10. In the case of three-wire, single-phase meters, all tests are made with the current coils in series.
11. It is good practice to make "As Left" tests with the meter in place.

Having completed the "As Left" tests, the temporary connections must be removed in a careful manner. In removing connections, the leads that served to supply the phantom load and voltage circuits must be removed from the line service terminals first. Reconnect the meter line and load conductors in their normal positions and remove jumpers, being careful to reinsulate any section of wiring that has been bared for purpose of test. Finally, replace all seals, verify the fact that service has been returned to normal and that the watthour meter is functioning.

If service has been interrupted, the customer should be so advised, either verbally or by printed form, with a suggestion that their electric clocks be reset.

Before leaving the scene of the test, check your test paperwork to be sure that all data have been properly entered.

Field Test Procedure, Multi-Stator Meters

In general the single stator test procedure applies also to multi-stator meters. Before test connections are made a check with a voltage indicator is advisable for assurance that the meter case is not live to ground. With load wires disconnected a check for creep should be made.

To prepare for test, connect all voltage coils in parallel and all current coils in series. Note that this connection changes the test constant. See discussion of "Calibrating Constants" under the subheading, "Shop Test Procedure".

With this series-parallel connection a multi-stator meter is tested at 1.0 power-factor as though it were a single stator meter. An exception is the four-wire, three stator delta meter that is commonly tested by individual stators.

In addition to the unity-power-factor tests multi-stator meters may be tested with 100% test amperes at 50% lagging power-factor.

For lagging-power-factor field tests the portable test fixture used may have built-in switching and controls to obtain the desired power-factor. If not, the three-phase voltages at the meter installation may be used for this purpose.

When using the service supply to obtain lagging power-factor the phase sequence must be determined in order to make the proper connections. Phase sequence may be determined by means of a phase angle meter or with any of the phase sequence indicators described in Chapter 9.

After phase sequence has been determined, connections for a lag test at 50% power factor may be made as follows for the phasors shown in Figure 14-20:

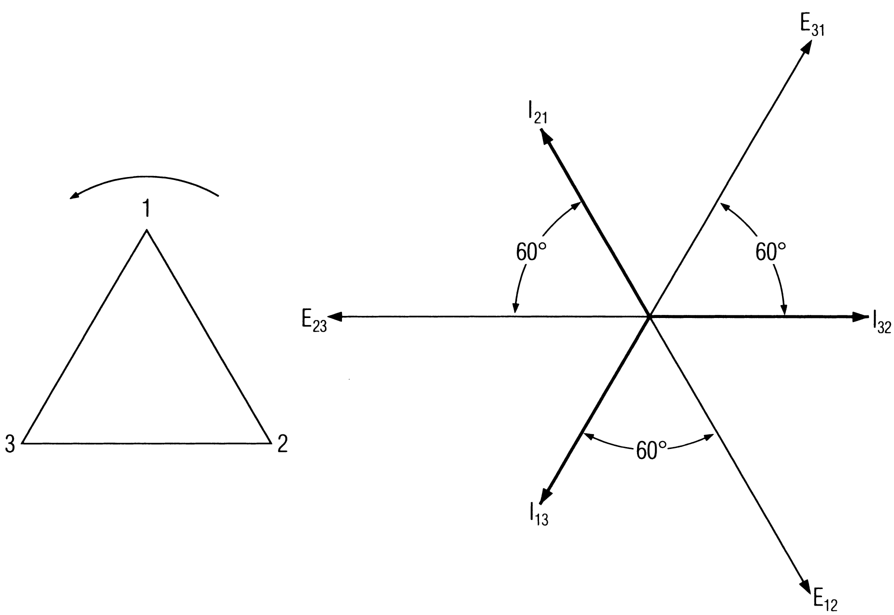


Figure 14-20. Phasor Relations of Voltage and Currents in Lag Test of Multi-Stator Watthour Meter.

When the sequence is 1-2-3:

Use voltage 1-2 with current 1-3, or voltage 2-3 with current 2-1.

When the sequence is 3-2-1:

Use voltage 2-1 with current 2-3, or voltage 1-3 with current 1-2, or voltage 3-2 with current 3-1.

Instrument Transformer Meters

Testers undertaking the test of instrument transformer-connected meters should be familiar with much of the material discussed in Chapter 11, "Instrument Transformers", where connections and correction factors are covered. The actual test of instrument transformer meters is similar to that of self-contained meters, since for test purposes meters are usually isolated from their associated transformers. Since the meters generally control more revenue than self-contained meters, additional tests may be required and test tolerances may be narrower.

Meter installations having current and voltage transformers require exceptional care and caution to safeguard personnel from injury through contact with high-voltage primaries or the high voltage developed across an accidentally opened current transformer secondary. If all safety rules are followed, these hazards will be avoided.

Normally, for instrument transformer meters, a test switch is installed between the transformers and the meter. It is the function of this test switch to short the current transformer secondaries before opening the connections to the meter, and to open the voltage secondary circuit. When a test switch is of an unfamiliar design it must be determined that such short-circuiting is effective before opening the switch.

When test switches were not installed, other means of short-circuiting the current transformer secondaries must be employed. In any case the short-circuiting connections must be made secure before opening the circuit to the meter. Clip-connection jumpers are not recommended. The use of temporary wire jumpers presents the possibility of leaving the jumpers in place after the test is completed, thus shunting the meter.

Test Procedure

With the meter disconnected from its instrument transformer proceed to test as a self-contained meter, with multi-stator meters connected with current coils in series and voltage coils in parallel. Additional individual stator tests may also be required for stator balancing. Three stator delta meters present special problems which are subsequently described.

When large loads are served from a delta power bank, power-factor tests may be required. When power-factor adjustments are necessary they should be made while testing individual stators rather than with the series-parallel connection. Lagging power-factor values should match the unity power-factor performance values in each individual stator so that proper balance is obtained under all conditions of loading. Since on delta circuits errors in power-factor balance affect meter performance on unity power-factor loads, the tolerance for power-factor balance should be narrow.

With unusual loads it is sometimes desirable to make a "running load test", that is, a test using the customer's three-phase load instead of the phantom load.

Such tests require two standards for three-wire, three-phase meters and three standards for four-wire meters, with a standard current coil in series with each meter current coil. The algebraic sum of the standard registrations is used to determine meter performance. Figure 14-21 shows test connections for a running load test on a two stator, three-wire meter.

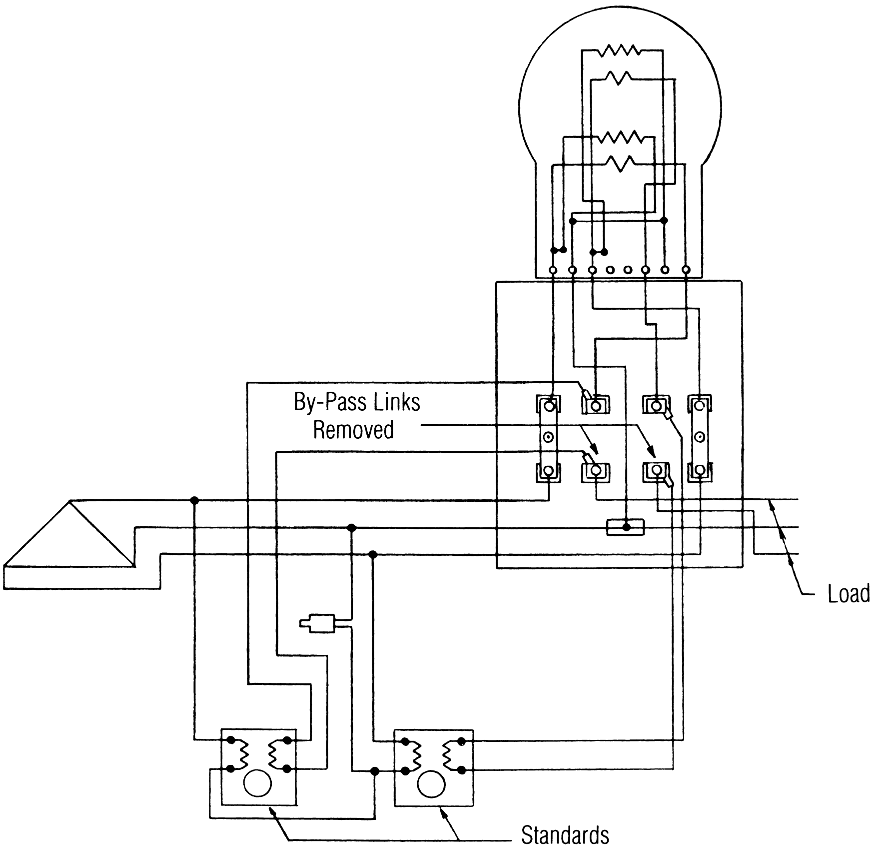


Figure 14-21. Test Connections for Two Stator, Three-Wire Meter Using Customer's Load and Two Standards.

When metering large power customers, register constants are particularly important. Primary register constant may be calculated by the standard formula:

$$\text{Primary Register Constant} = \frac{\text{Secondary } k_H \times R_R \times R_S \times C_T \text{ ratio} \times V_T \text{ ratio}}{10{,}000}$$

Register ratio and shaft reduction should be examined to make sure that the are correct for the application.

Network Meters

When meters are installed with current transformers but not with voltage transformers, which is often the case when customers are served from a 120/208 volt network, the test switch voltage blades may present a hazard which must be recognized. In this situation the voltage supply to the meter is taken from a high-capacity power transformer instead of from a low-capacity instrument transformer. Hence, any accidental short circuit of the voltage conductors can result in a severe arc. Unfortunately, in many test switches the voltage switch blades are live when open and protrude beyond the test switch barriers. When this is the case an insulated enclosure to cover the live switch blades will prevent accidents due to falling tools or contact with other metallic objects.

Three-Phase, Four-Wire Delta, Two Stator Meters

This meter comprises one three-wire current circuit at 240 volts and one two-wire current circuit at 208 volts. Except when extreme accuracy is required this meter may be tested with all current coils in series and voltage coils in parallel. The error introduced by operating the 208 volt coil at 240 volts is generally less than 0.2%.

Three-Phase, Four-Wire Delta, Three Stator Meters

This type of meter is unusual as compared with other meters, especially from a standpoint of testing. Since it consists of one stator with a voltage rating of twice either of the other two stators and a current rating of one-half of either of the other two stators, the usual method of series tests and balance test cannot be used. The common practice is to calibrate each stator independently, although the two like stators can be tested in series and also balanced against each other. Providing the correct ratio current transformer and voltage transformer so that the higher voltage stator can be connected essentially in series-parallel with the two lower voltage stators a series test can be made. This of course requires an accurate step-up voltage transformer and an accurate step-down current transformer. For more detailed discussions, see manufacturers' publications.

Three-Phase, Four-Wire Wye, Three Stator Meters

The necessity for making separate stator tests on three stator wye meters in the field and test loads to be used in such tests were investigated by an EEI Meter and Service Committee Task Force and the conclusions were covered in a report dated April 16, 1951.

The following recommendations were made in this report:

1. In calibrating separate stators, test loads should be based on percent rated current, rather than percent rated speed. This is based purely on economics in that fewer adjustments will be necessary under this procedure;
2. In the field the series test is sufficient except in cases of special investigation. Further details may be obtained by reference to the complete report.

MOBILE SHOP FIELD TESTING

In this system of testing, a large van-type truck or trailer is used to house a compact but very completely equipped meter shop. This mobile shop is moved to a convenient location near the scene of operations and a power supply tapped to it from adjacent company lines. Meter installers then proceed to remove meters from the services in the neighborhood, bypassing each service meter loop. The meters are immediately delivered to the mobile shop where the test crew makes "As Found" tests, high-voltage tests, thoroughly cleans the meter, makes adjustments, and "As Left" tests. The meter is then returned to service in its initial location, with the same reading that existed at the time of removal. This method of testing has many obvious advantages over the regular house-to-house testing system. Tests are made under nearly ideal conditions; high-voltage tests are possible; and a much more thorough job of cleaning the meter can be performed. The very considerable advantage of this system over shop testing methods is that no change of office or meter reading records are involved. See Figure 14-17.

METER TEST BY INDICATING WATTMETER

Load is applied to the meter and watthours are measured by means of indicating instruments and timing devices, such as stopwatches or chronographs. The time is usually that required for some convenient and predetermined number of revolutions of the meter under test. The procedure is as follows: The time required for an integral number of revolutions of the meter is measured by a stop watch and the power, in true watts, during the same period is measured by means of indicating instruments. The ratio between the indicated or meter watthours and the true watthours, as determined by the indicating instruments, multiplied by 100 is the percent registration of the meter under test.

Example:

Let P = true watts (average watts by indicating instruments)

k_H = watthour constant

r = number of revolutions of disk

s = time in seconds for r revolutions

then, meter watthours $= k_H \times r$

meter wattseconds $= k_H \times r \times 3{,}600$

true wattseconds $= P \times s$

Percent registration of the meter may then be determined from the following equation:

$$\text{Percent Registration} = \frac{k_H \times r \times 3{,}600 \times 100}{P \times S}$$

A wattmeter is required to measure A-C power. This method is generally limited to special meter tests.

When extensive tests to determine performance of meters under all conditions of voltage, current, frequency, and waveform are required, the latest edition of the *Code for Electricity Metering* should be consulted.

METER MAINTENANCE

Causes of Creeping

The causes of creeping may be classified as follows:

1. Incorrect light-load compensation;
2. Vibration;
3. Stray fields, either internal or external;
4. Too high voltage, which has the same effect as overcompensation of light load adjustment;
5. The voltage circuit being connected on the load side of the meter;
6. Short circuits in current coils;
7. Mechanical disarrangement of the electromagnetic circuit of the meter.

A high-resistance short or ground in the customer's circuit can cause a turning of the rotating element which may be mistaken for creeping. Therefore, residence wiring should be isolated from the meter when checking for creep.

If a short circuit is present in the current coils it will probably be difficult to stop creeping. Voltages being induced in the current coils by the voltage magnetic flux and resultant current low in the shorted current coil turns cause the creeping, due to current coil shorts.

Causes of Friction

Foreign matter, defective bearings, defective registers, or improper alignment of parts interfering with the operation of the rotating element may cause friction. A meter being out of level may also cause friction.

Particles of iron or other magnetic material cause friction by clinging to the magnet pole-pieces and trailing on the disk. To remove magnetic particles from the magnets, a thin brass or bronze magnet cleaner can be used, but a magnet brush with long bristles is preferable.

Bearings

Magnetic bearings should be inspected to determine if foreign material is present. Since the position of the disk in the air gap depends directly on the magnetic bearing, this characteristic should be checked. Detailed procedure for checking disk position is given in the various manufacturers' publications. The bearing magnets must support the disk and a simple check is to push the disk down gently with a finger to see that it is floating and not resting on the bottom guide pin. Inspection of the guide pin and ring bearings at both ends of the disk shaft may also be desirable. This could be done on a sample basis until experience has been obtained.

New and used meter jewel bearings are usually inspected in the shop. Old jewels are first thoroughly cleaned. After cleaning, the jewels, pivots, and balls are examined with a microscope and those considered unfit for further service are discarded. It is essential when inspecting jewels to provide adequate light in the jewel cups, free from shadows and reflections, to avoid false observations. The inspection of used meter bearing parts is an economic problem. In many cases, such inspection has been eliminated. This practice can be attributed to the use of improved bearing assemblies or the elimination of bearing systems.

Registers

The tester should inspect the register to detect any defects that may prevent its correct registration.

The worm or pinion on the shaft should be examined to see that it meshes properly with the register wheel that it drives. A slight amount of play is necessary to prevent excessive friction.

When the pinion or worm is short, or the worm is cut concave to match the curvature of the worm wheel, the height of the moving element should be such that the center of the pinion or worm is level with that of the register wheel which it engages.

For cleaning the pinion or worm, a small stiff brush or a sharpened piece of soft wood may be used.

In some meters the worm wheel is supported in a separate bracket attached to the meter frame, in which case it is customary to actuate the register by means of a dog on the register engaging with a star wheel or second dog on the worm-wheel shaft. It is important that these parts be in proper alignment.

All the gears on the register must be in mesh and all dial pointers secure. Misplaced pointers should be reset. The tester should record the position of the misplaced pointers. This condition may be an indication of an incorrect train ratio, i.e., one or more of the gears or pinions have the wrong number of teeth.

Register Testing and Checking

An important part of a watthour meter test consists of determining if the watthour constant, register ratio, gear ratio, and register constant are correct and also bear the correct relation to each other.

The correct watthour constant K_H for any particular size and type of meter can be found from the tables in the manufacturers' section. In order to check that a meter actually has the correct watthour constant, a test of the meter by any one of the methods previously described may be made.

The register ratio R_R may be determined by counting the number of revolutions of the first gear shaft of the register which is required for one revolution of the first dial pointer. It is generally checked, however, by comparison with a register of known ratio. In the first method it is not necessary to take a complete revolution of the first dial pointer, one-tenth of a revolution is generally sufficient. In the second method the register to be checked may be engaged with a shaft which is driving a register of known ratio, or the registration of the meter under test may be compared with the registration of a meter with known constants.

In order to calculate the gear ratio R_G it is first necessary to determine the ratio of reduction between the shaft of the rotating element of the meter and the first gear shaft of the register, this reduction being referred to as the shaft reduction R_S. If there is a worm drive on the rotating element of the meter, the shaft reduction is:

$$\text{Shaft reduction} = \frac{\text{Number of teeth in first register gear}}{\text{Pitch of worm on rotating element}}$$

If the driving means is a spur gear instead of a worm, the shaft reduction is:

$$\text{Shaft reduction} = \frac{\text{Number of teeth in first register gear}}{\text{Number of teeth in spur gear on rotor}}$$

The gear ratio R_G is equal to the product or the shaft reduction R_S and the register ratio R_R. One revolution of the rotating element of the meter is equal to K_H watthours. The number of revolutions of the rotating element for one revolution of the first dial pointer is equal to the gear ratio R_G and therefore one revolution of the dial pointer will represent:

$$K_H \times R_G \text{ watthours, or } \frac{K_H \times R_G}{1{,}000} \text{ kilowatthours}$$

The numerical value of the one revolution of the first dial pointer of a standard register is 10; therefore, the register constant K_R for kilowatthours is:

$$K_R = \frac{K_H \times R_G}{10 \times 1{,}000}$$

$$\text{and } R_G = \frac{K_R \times 10{,}000}{K_H}$$

With these relations established the value of any one of the factors under consideration can now be expressed in terms of the others.

Let K_H = watthour constant*
R_R = register ratio
R_S = shaft reduction
R_G = gear ratio
K_R = register constant

*Primary watthour constant for meters with instrument transformers.

Then $R_G = R_R \times R_S$

$$K_H = \frac{K_R \times 10{,}000}{R_R \times R_S} = \frac{K_R \times 10{,}000}{R_G}$$

$$R_R = \frac{K_R \times 10{,}000}{K_H \times R_S}$$

$$R_S = \frac{K_R \times 10{,}000}{K_H \times R_R}$$

$$K_R = \frac{K_H \times R_R \times R_S}{10{,}000} = \frac{K_H \times R_G}{10{,}000}$$

For example, assume that the following data are given for a meter and it is desired to verify the correctness of the register constant:

$K_R = 1$

$R_R = 66\,2/3$

$K_H = 1.5$

$R_S = 100$

$$K_R = \frac{K_H \times R_R \times R_S}{10{,}000} = \frac{1.5 \times 66\,2/3 \times 100}{10{,}000} = 1$$

The register constant of 1, given in the data, proves to be correct.

In selecting a register of proper ratio for installation on a meter, the formula

$$R_R = \frac{K_R \times 10{,}000}{K_H \times R_S}$$

may be used, but it will be noted that the value for R_R thus obtained depends upon the value selected for the register constant K_R.

There are available mechanical register checking devices for comparison of registers against a master ratio indicator. Providing the required mounting facilities and correct gearing, any type and make may be checked. A small air turbine that permits flexible speed and reversible operation may operate the device. The master dial is set at zero and the register or registers to be checked mounted in position. The lowest ratio is checked first by operating the device until the first dial pointer of the register makes one complete revolution. The register ratio is then read directly from the master dial. The register of the next lowest ratio is then checked by continuing the run until its first dial pointer has made one complete revolution and the master dial read, etc.

An alternative method of register checking is the use of a time-run test in which meters are connected in series with standard meters having known constants and are operated for sufficient periods of time to verify their constants.

This method has some advantage over the use of register checking devices in that the complete performance of the meter is verified as well as verifying the correctness of constants. The disadvantages of this method are the increased time, equipment, and space required. A representative connection diagram of a time-run test board is illustrated in Figure 14-22.

Defective Current and Voltage Coils

A short-circuited turn in the current coil will reduce the effective turns and consequently, lower the torque of the watthour meter and its speed at or near full-load. Induction meters will generally creep when some of the turns are short-circuited and often will be fast on light-load and slow on full-load. Meters with this defect should be provided with new current coils. On three-wire meters check the meter registration on each current coil separately to make the test.

A short circuit in the voltage coil will change the torque of the watthour meter, hence its speed. A meter with this condition will be found out of lag and the voltage coil must be replaced.

WATTHOUR METER TEST DIAGRAMS

For diagrams showing the connections of meters to phatom loads, rotating standards, and test jack assemblies, refer to the Ninth Edition of the *Handbook for Electricity Metering,* Chapter 14.

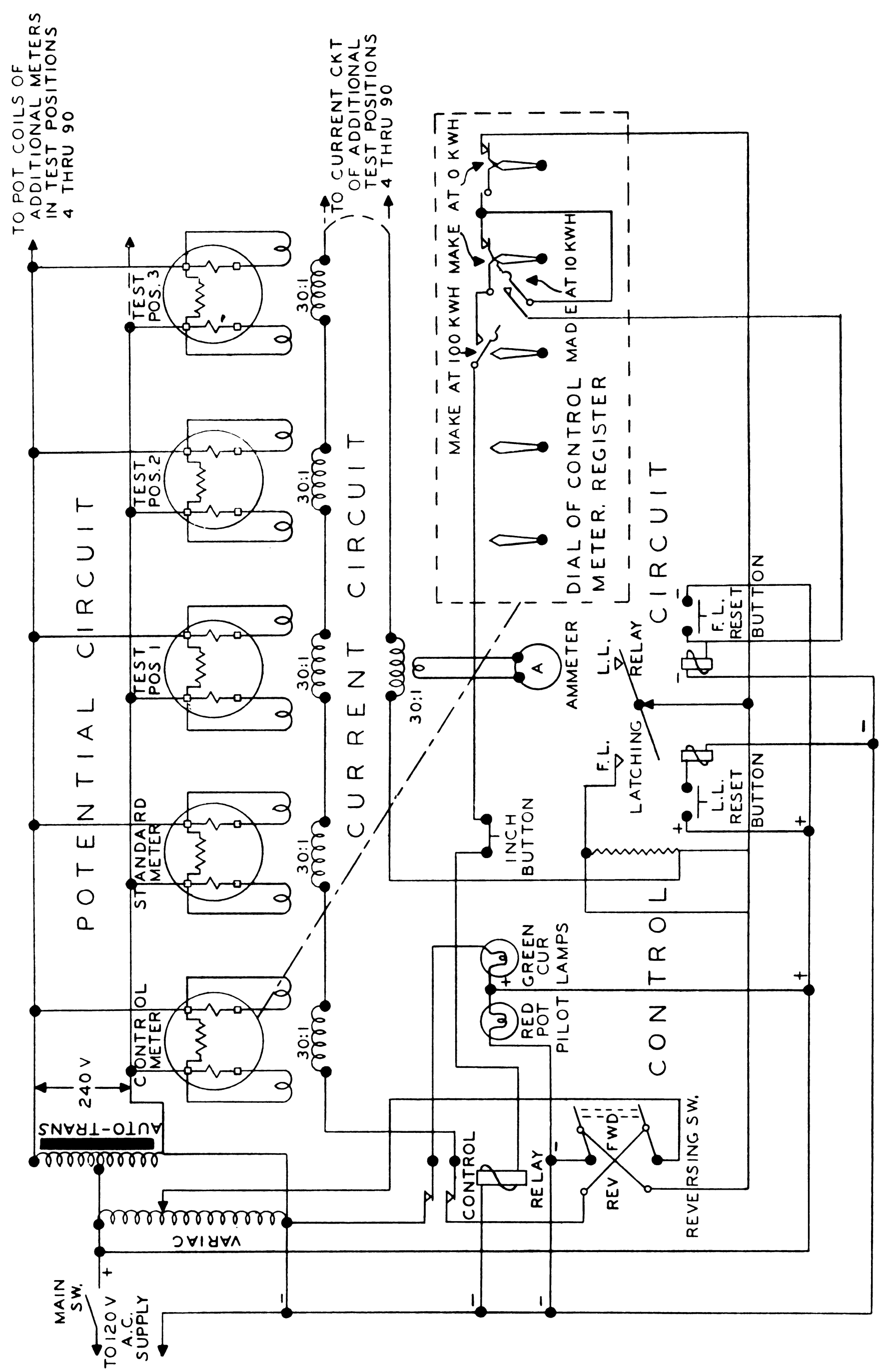


Figure 14-22. Gang Test Board Circuit for Testing with Closed Meter Voltage Gates.

CHAPTER 15

DEMAND METER TESTING AND MAINTENANCE

THE VARIOUS TYPES of demand meters are described in Chapter 8 and in sections of the Appendices. General test procedures and maintenance suggestions will be covered in this chapter, but no attempt is made to present all details of adjustments and maintenance. For such details reference should be made to the manufacturers' instruction books.

MECHANICAL DEMAND REGISTER

A mechanical demand register is designed primarily to replace the conventional register of a watthour meter for the dual purpose of recording kilowatthours and the maximum integrated kilowatt demand. In addition to the kilowatt gear train and dials, it includes a gear train driven from the first shaft to provide the demand indication and a synchronous motor driven gear train to provide the time interval. The maximum demand may be indicated by a sweep pointer operating over a semi-circular scale, or by dials similar to the kilowatthour dials.

Watthour meters equipped with demand registers are referred to as watthour-demand meters and, with the exception of the register and deeper covers, are identical to watthour meters of the corresponding type.

Principle of Operation

The demand gear train drives a pusher arm which advances the demand indicator in proportion to the speed of the meter disk, which is proportional to the demand.

At the end of a predetermined interval, usually 15, 30, or 60 minutes, the pusher arm is momentarily disengaged from its gearing and returned to zero, by the motor, a spring counter torque, or a gravity-driven mechanism. The time interval during which the pusher arm is advanced is controlled by a synchronous motor.

Therefore, a test of a mechanical demand register must satisfy these three questions:

1. Is the advance of the indicator correct?
2. Does the reset operate correctly?
3. Is the time interval correct?

To make clear the distinction between the space interval covered by the advance of the indicator and the demand interval controlled by the timing mechanism, the latter is, in this chapter, called "time interval."

Advancing Mechanism

Since the pusher arm which advances the demand pointer is geared to the watthour meter shaft, the accuracy of the demand indication is dependent upon the accuracy of the watthour meter. Therefore, the watthour meter must be calibrated correctly if the demand indication is to be right. The register ratio of the demand register must be correct for the application.

The register gearing must not impose a heavy or variable load on the meter. In other words, excessive register friction due to dirt or improper gear mesh must not exist. When demand meters are located in areas with unusual dust, dirt, or fumes, it is standard practice to clean the demand register thoroughly before reinstallation. If the period between tests is quite long, it is good practice to clean all demand registers as they come into the shop for routine tests.

Cleaning methods vary from the use of standard cleaning machines which have a cleaning solution, a rinsing solution, and a drier, to the use of ultrasonic cleaners. The cleaning solutions should be nontoxic and rinsing solutions should be acid free and not leave a film on the cleaned parts. Carbon tetrachloride should never be used for cleaning purposes because of the cumulative toxic effects that it may have.

After a register has been cleaned, a thorough examination should be made to detect faulty gears, worn bearing holes, and insufficient or excessive end shake of the various shafts. Particular attention should be given worm gear assemblies because malformation of the gear edges can cause a jerky advance of the succeeding gears.

Clutch

To permit reset of the pusher arm at the end of the demand interval, the reset of the maximum demand indicator to zero at time of test, there is a clutch in the demand gear train between the meter disk and the pusher arm.

The clutch usually consists of two flat disks with a felt washer in between, with some means of exerting the proper amount of friction which may be an adjustable spring. Some registers employ a cam-operated arm to disengage the clutch during the reset operation while others merely slip the clutch under full tension. While the adjustment of clutch tension is not critical, it should be checked to determine that it falls within the recommended limits, particularly if the register has been cleaned or disassembled for overhaul. Tension testing devices are available for this purpose.

The felt friction pads must be dry to insure proper operation and should never be subjected to cleaning fluids. If the register is to be put into a cleaning solution, the pads should be removed and then replaced after the register is dry. In many cases, the pads can be removed without dismantling the clutch assembly by slitting the pad radially with a very thin knife. New pads may be installed similarly, making sure that the pads, after insertion, lie flat on the disks.

Resetting Mechanism

At the end of the demand interval the pusher arm must be returned to zero. This requires that a counter-torque be applied to the pusher-arm side of the clutch.

In various types of registers, the counter-torque is supplied by one of three methods; a spring, direct drive from the timing motor, or gravity. In the spring-return type, the timing motor, in addition to driving the interval gearing, winds up the return spring during the interval. At the end of the interval, a tripping mechanism releases the spring energy to return the pusher arm to zero. In certain types of spring-return mechanisms, the clutch is simultaneously disengaged, while in others the clutch is allowed to slip but remain engaged. In the latter type, particular attention should be given to correct clutch tension.

On direct-motor-drive reset registers, the timing motor disengages the clutch at the end of the interval. Then, through cam and sector gear mechanisms, the pusher arm is returned to zero by the motor.

The gravity type of return mechanism requires that either a clutch or the demand gearing be disengaged at the end of the demand interval.

There are two main points to be observed concerning the operation of the reset mechanism. First, does the pusher arm return exactly to zero? Second, is the return to zero smooth and within specified time limits for the device?

An error in the zero setting will be reflected at all points on the scale. Most registers have an adjustable zero stop for the maximum pointer which should be checked to see that the pointer is exactly on zero. The pusher arm is provided with a micrometer screw adjustment for coordinating the zero of the pusher arm with the maximum pointer zero position.

A sluggish return to zero may be the result of excessive friction or a decrease in the amount of return power. For various types of registers, the return time, sometimes referred to as the "out-time," varies from a fraction of a second to four seconds for 15 minute interval registers and generally increases proportionally with the length of the time interval. On most registers, no adjustment is provided to change the reset time; some do have an adjustment in the cam mechanism.

Sluggishness is more pronounced and can be detected more readily in the spring-return and gravity-return type of registers. In the spring-return type, a change in torque is possible; a change sufficient to effect malfunction is uncommon. In the gravity-return type, since the weight is constant, there can be no change in return force. Therefore, sluggishness can usually be attributed to excessive friction due to dirt or gummy oil, maladjustment of the clutch, or a defective governor mechanism in types where used. Examination of the register should indicate the maintenance required—either cleaning, adjustment of the clutch, or replacement of defective parts.

Timing Motor

Failure of the timing motor is perhaps the most common fault in demand register performance. Under normal conditions, the synchronous motors are as reliable as the system frequency at which they operate. However, excessive friction may impose loads in excess of the motor capability causing the motor to stop or operate intermittently. This means that the demand interval is extended creating a high demand or an off-scale reading. If the condition is due to excess friction in the interval or reset gearing, correction must include removal of the friction through cleaning, adjustments, or replacement of parts as indicated by inspection.

The two most common causes of complete motor failure are the motor running out of oil and burned-out motor coils. Burned-out coils require replacement of the motor field coils or complete replacement of the motor.

If the motor fails due to loss of lubrication, it must either be reoiled or replaced. If the manufacturer has an exchange program, it is usually more economical to replace the motor.

Certain types of General Electric Company telechron rotor assemblies were provided with removable oil caps for flushing with a cleaning solution and reoiling. The modern rotors are grease-filled for longer life and have no provisions for regreasing. The motor operating unit for the General Electric Type M-60 register is an hermetically sealed unit.

The motors on Westinghouse Type RW and Duncan Type FW and HW registers are identical and oil can be added through the breather hole. For complete cleaning and reoiling, it is recommended that the gear case be dismantled by removing the top of the case. After complete cleaning and resealing, the gear case is refilled with the proper amount of oil. The Westinghouse Mark series register motor is provided with a separate oiling hole for convenient maintenance.

The Type A and A-7 motors used in certain Sangamo demand registers can be cleaned and reoiled by completely dismantling the motor. Bearings should be carefully inspected for excessive wear. The Type H motor is much easier to maintain by removing the rotor and cleaning and oiling the bearings using an hypodermic needle.

It is recommended that any demand motor that is reoiled or replaced be dated. Although there is no definite period of time that motors will operate correctly without attention, most of them will go 5 years or longer. Excessively noisy motors or motors that will not operate at 75% rated voltage should be cleaned and reoiled or replaced.

Maximum Demand Pointer

In order to leave an indication of the maximum demand for a billing period, a friction-type pointer is retained in a position representing the maximum advance of the pusher arm that occurred during a demand interval in the period. The friction may be obtained from a friction pad of felt or cork or by use of a silicone grease cup. When a friction pad is used, there is usually an adjustment by which the compression of the pad may be controlled which is not required with the silicone grease cup. The friction should be sufficient to prevent moderate vibration from changing the reading but well below the amount required to slip the driving clutch. Tension testing devices are available for checking and setting the correct pointer friction for the register.

Cumulative Demand Register

Cumulative demand registers usually have all of the operating principles described for indicating demand registers with an additional feature of retaining the maximum demand reading by adding the kilowatts for the current demand reading period to the accumulated demands of previous reading periods. This is accomplished by adding a gear train to advance dials which is manually engaged at the time of reading. Usually a small sweep hand is provided to indicate the current maximum demand. The recorded maximum demand for the period is the result of subtracting the previous reading from the reading after reset as indicated on the kilowatt dials.

Test Procedure

Most demand register tests are made to determine the mechanical accuracy of the register only or to determine that, for a marked register ratio and time interval, the demand pointer will give a correct indication for a definite number of revolutions of the first driven gear. The watthour meter on which the register is to be used must be calibrated accurately to give a true indication of demand when in service. Furthermore, the watthour meter should be tested with its demand register energized to insure the best accuracy.

Since there is a definite correlation between the time interval gearing and the demand gear train for any particular register, self-checking devices are available for most types. The register self-checking consists of gearing mounted in a framework, so that the gear trains of the register are locked together through the checker gearing. With the register energized, it will perform its normal function of resetting the register and driving the demand gear train a definite number of revolutions per interval.

Most self-checking devices can be manually operated to run the register more quickly through a demand interval. When operated manually, the checker should be run slowly during the reset cycle to be sure the pusher arm is allowed to return to zero. The true reading may be calculated by counting the number of revolutions of the first gear of the register for the demand interval:

$$\text{kW} = \frac{(\text{Revolution of first gear per time interval}) \times 10}{(\text{Register Ratio}) \times (\text{Marked time interval, in hours})}$$

Usually the self-checking devices are provided with two gear ratios to check two points on the scale. This type of test verifies the gear train ratios only, and it is necessary to check the timing motor to insure the correct time interval.

Some timing motors can be checked for correct speed by use of a stroboscope light, others by timing one of the slow-speed gears with an accurate stop watch. The time interval may be checked by timing with an accurate device, the interval between two successive resets. It is recommended that motors be checked at a voltage expected in service.

An overall test of a demand register can best be accomplished by a register-checking device that simulates a watthour meter on a constant load. This consists of a synchronous motor driving a shaft similar to a meter shaft for which the demand register was designed, and studs for mounting the register. With the register motor and checker motor energized from the same source, the register is allowed to operate through one or more complete intervals. Ignoring the demand multiplier, the demand that should be indicated may be calculated as follows:

$$\text{kW} = \frac{(\text{Revolution of first gear per time interval}) \times 10}{(\text{Register Ratio}) \times (\text{Marked time interval, in hours})}$$

Revolutions of the first gear can be calculated for the time interval from the checker shaft speed and the ratio of the first gear reduction. This type of checker is particularly adaptable to shop testing when several such devices may be mounted on a test board. They are usually equipped with two or more speed changes for checking different points on the demand scale. A correct indication verifies that the time interval and the gear ratios are correct.

A manual test may be made on the gear train and zero setting by resetting the interval reset to zero, then advancing the first gear a definite number of revolutions. The kilowatt indication is calculated by the same formula as for mechanical test devices. It is necessary to determine that the time interval is correct as just outlined.

Field tests on watthour demand meters may be made by connecting a field standard in series with the watthour meter as for a regular watthour meter test. With a load applied to produce approximately the desired demand indication, the field standard should be started at the instant of a demand interval reset and stopped at the succeeding reset. The true kilowatts that should be indicated by the demand register can be calculated as follows:

$$\text{True kW} = \frac{(\text{Watthours recorded by standard}) \times N \times 60}{1{,}000 \times (\text{Time interval, in minutes})}$$

ELECTRONIC DEMAND REGISTER

An electronic demand register is designed to perform the same function as the mechanical demand register, replace the conventional register of a watthour meter for the dual purpose of recording kilowatthours and the maximum integrated kilowatt demand. Use of electronics may provide some added benefits not available with the mechanical register. The electronic demand register displays the total kilowatthour consumption and the maximum integrated kilowatt demand via a digital display. The programming of this type of register varies and may include an EPROM with a program written by the manufacturer and software supplied on diskette.

Principle of Operation

For mechanical meters, the electronic demand register uses the principle of optical pickup directly from the rotating disk or a small shutter device attached to the shaft of the disk apparatus. The optical pickup feeds pulses to the register which allows the register to advance the demand display value in proportion to the speed of the meter disk which is proportional to the demand.

The microprocessor in the electronic register analyzes the pulses fed to it through the optical pickup. At the end of a predetermined interval, usually 15, 30, or 60 minutes, the register calculates the average or integrated maximum kilowatt demand, compares the result with the previous interval, and, if larger, replaces that value. If the resulting demand value is smaller than that of the previous interval, the previous interval value is retained and the new value is discarded. The register then begins analyzing the next predetermined interval and repeats the aforementioned process.

Therefore, a test of an electronic demand register must also satisfy three questions:

1. Does the register display the correct values upon completion of each interval?
2. Does the reset operate correctly?
3. Is the time interval correct?

Advancing Mechanism

Since the optical pickup which advances the electronic register relies directly on the motion of the watthour meter disk and shaft, the accuracy of the demand indication can only be as accurate as the watthour meter. The watthour meter must be calibrated correctly if the demand indication is to be right. Visual inspection of the shutter mechanism on the disk shaft for those meters using that method of pickup, as well as inspection of the holes in the disk for the other method of pickup, should be performed to check the integrity of the mechanical portion of the meter. Refer to the manufacturers' instructions for more information.

Resetting Mechanism

At the end of the demand interval, the microprocessor contained within the electronic demand register is programmed to return to zero and begin the measurements for the next interval. Many of the electronic demand registers provide visual indication that the interval has come to an end and the next is beginning. This indication consists of an End-of-Interval message displayed on the digital display. The loss of AC power at any time during a demand interval will cause the meter to store the current information into an EPROM where it is held until the meter is again energized. For example: A meter 25 minutes into a 30 minute interval experiences a power outage. All information is written to the EPROM memory. The meter, when reenergized, will begin its demand interval measurement at the same point within the interval maintaining the value of demand that had been measured up to the point of the power outage.

Careful attention should be given to the manual demand resets performed for billing. Each of the electronic registers has a demand reset indication that appears on the digital display when a correct billing reset has occurred. The manufacturers' information booklet for each of their registers will give the specific reaction which determines if a correct reset has occurred.

Test Procedure

The watthour meter on which the register is to be used must be calibrated accurately to give a true indication of demand when in service. Although the electronic demand register does not have any gearing or moving parts, it is very important that the register be mounted on the meter before the meter itself is tested. The energy required to power the electronic circuitry may be enough to affect the calibration of the meter.

The electronic demand meter to be tested must be programmed to display the maximum demand value. Many of the electronic demand registers have a special test mode which allows a complete test of the meter without affecting the billing values of the customer. The length of the interval within the test mode may vary from manufacturer to manufacturer and is often programmable as set up by the programmer. In addition, many solid-state demand registers will time out of the test mode after a programmed time in case the tester fails to manually take the register out of test mode.

A test voltage only is applied to the meter under test. If the register contains a test mode, it is good practice to enter that mode before any external currents are applied. Visual inspection of the display sequence is necessary to confirm that all segments of the display are functioning properly. If one segment of any of the digits is not functioning, erroneous readings could occur.

The actual test on the meter may be performed by connecting a field standard in series with the watthour meter similar to a regular watthour meter test. Realizing the length of the test mode interval, a desired demand value is established to be "run up" on the meter. With the load applied to produce approximately the desired demand indication, the field standard should be started at the instant of a demand interval reset and stopped at the succeeding reset. The true kilowatts that should be indicated by the demand register can be calculated as follows:

$$\text{True kW} = \frac{(\text{Watthours recorded by standard}) \times N \times 60}{1{,}000 \times (\text{Time interval, in minutes})}$$

N = Number of full-current coils in series in the watthour meter

ELECTRONIC TIME-OF-USE REGISTER

An electronic time-of-use (TOU) register (also referred to as a time-of-day register) is designed to produce time-differentiated billing. The register designates predetermined time periods as being peak and others as off-peak. Some utilities have established a shoulder-peak which may not be as critical as the peak periods, but more so than the off-peak periods.

Time-of-use is typically set up to reward the customer for consumption during the off-peak periods and to discourage consumption during the "shoulder" or peak periods. The reward, or discouraging factor, is the use of different billing rates for each time period.

Principle of Operation

The electronic TOU register uses the principle of optical pickup to establish pulse information. The pulse information is analyzed by an on-board microprocessor. The pickup generates pulses directly from the disk rotation and is only as accurate as the base meter.

Electronic TOU registers contain a microprocessor-based module with a program that is specific to a particular billing rate schedule as established by the utility. Electronic TOU registers are capable of measuring time-differentiated kilowatthours, and time-differentiated integrated kilowatt demand. The demand may take the form of the following; block interval demand, cumulative demand, continuous cumulative demand, and rolling demand.

The means of programming this type of register may include: an EPROM programmed by the manufacturer, or software. Each method of programming provides the register with information pertaining to: the peak, shoulder-peak, and off-peak times; season change dates; daylight saving dates; off-peak holidays; etc. Refer to the manufacturers' instructions or appendices for more information.

Time is the key word in "time-of-use." Each electronic TOU register maintains an ongoing date and time keeping function. During AC power outages, the registers rely on battery backup. Currently two types of batteries are used for this function: the non-rechargeable lithium cell and the lead-acid rechargeable cell. The register monitors the battery condition and produces an error code on its digital display if the cell is not adequate. Testing of these cells on a routine basis is advised to maintain proper operation of the register during power outages. Manufacturers' information provides insight as to when the register may require a new cell.

Test Procedure

Periodic testing of the register switch times and special dates is recommended to ensure the correct setup of the programming information. Many of the electronic registers have visual indications of the present rate (peak, shoulder, off-peak). The manufacturers' information on their product may offer additional insight of features that should be tested. Updates to any of the programs to be used with the electronic registers should be verified completely before use in a billing situation.

Careful attention should be given to the manual demand resets performed for billing. Each of the electronic registers has a demand reset indication that appears on the digital display when a correct billing reset has occurred. The manufacturers' information booklet for each of their registers will give the specific reaction which determines if a correct reset has occurred.

Many of the electronic TOU registers may be tested utilizing the test mode function maintained within the register. This feature disallows any load applied during a test to be applied to the customer's bill.

A test voltage is only applied to the meter under test. If the register being tested is one of the types that contain a test mode, that mode should be enabled. Visual inspection of the digital display is very important to ensure all segments of the display are functioning properly.

The actual test of the demand portion of the register is performed by attaching a field standard in series with the watthour meter as for a regular watthour meter test. Some TOU registers offer smaller demand intervals for test conditions. The test interval length is used to establish a demand level that is attainable during that time span. With the load applied to produce the calculated demand indication, the field standard should be started at the instant of a demand interval reset and stopped at the succeeding reset. The true kilowatts that should be indicated by the register can be calculated as follows:

$$\text{True kW} = \frac{(\text{Watthours recorded by standard}) \times N \times 60}{1{,}000 \times (\text{Time interval, in minutes})}$$

N = Number of full-current coils in series in the watthour meter

RECORDING WATTHOUR DEMAND METER

These meters combine a watthour meter and a recording demand meter. A pen or other recording device is geared directly to the watthour meter shaft causing it to travel over a properly scaled strip chart. At the end of the time interval, the pen is returned to zero. The length of line produced on the chart is proportional to the kilowatthours during the specified time interval and is proportional to the average kilowatt load for the interval, or the average kilowatt demand. For further discussion of this type of device see the Seventh Edition of this *Handbook*.

PULSE-OPERATED DEMAND METER

This type of demand meter is essentially a counting device operated by pulses obtained from a pulse initiator found on either a mechanical type meter or one of the electronic type registers. Since each pulse represents a definite number of watthours, the accumulation of pulses for a definite time interval represents the average watts or demand for the time interval. The demand meter may be of either the maximum indicating type or recording type. Depending upon the design, the record may be on a round chart, strip chart, printed or punched into a paper tape, or in the form of pulses on a magnetic tape. More recent technology has found devices where the record may be in the form of pulses collected on an electronic pulse accumulator or solid-state pulse recorder.

Most indicating and chart-type recorders have an internal synchronous motor for establishing the time interval and advancing the chart or tape. The printing type may use an internal timing motor or an external contact-making clock for determining the time interval. Since some advance the indicating or recording mechanism on each pulse received and others on alternate pulses, the multiplying demand constant must be calculated on the basis of watthours per advancing pulse.

$$K = (\text{Watthours per advancing pulse}) \times (\text{Time interval per hour})$$

TESTS

Shop tests on pulse-operated demand meters are performed by connecting the meters to a controlled pulse source operated by a synchronous motor. The pulse source is so designed that the number of pulses per interval may be varied from a very low value to about two-thirds full-scale value of the meters to be tested. With the interval timing mechanism connected, the meter should be operated through several intervals at varying pulse rates. On indicating types, it is necessary to take readings for each change of pulse rate, while on the recorders, each interval is recorded. If, at the end of the test, readings do not agree with the predetermined pulse rates, the trouble must be located.

Some sources of trouble are:

1. Incorrect time interval. The interval should be checked with an accurate stop watch from reset to reset;
2. Not returning to zero on reset. On recording types, this should be indicated on the chart. However, on indicating and printing types the reset operation must be observed. Most recording types have a register for accumulating the incoming pulses. Over the test period, the accumulation of pulses should check with the sum of the pulses indicated for each interval except that

a pulse may be received while the instrument is resetting. If the meter is returning to zero, low readings usually indicate mechanical fault in the advancing mechanism.

In any test, the legibility of the record should be observed closely and corrected if necessary. This may require a new stylus point on a G-9, cleaning or replacing a pen or, replacement or realignment of the printing platen for a printing type. Realignment of the printing wheels may be required.

Any search for trouble on a solenoid-operated, printing-type meter must include inspection for worn or defective parts and proper adjustments.

With electronic pulse accumulators or solid-state pulse recorders, care should be taken to assure the proper configuration program is in place. An improper program will result in incorrect pulse data.

Field testing usually involves more than just a test of the demand instrument since the main purpose is to determine that the demand of a particular installation is being recorded correctly. The following questions must be answered for a field test.

1. Is the watthour meter calibrated correctly?
2. How many meter revolutions produce one pulse?
3. How many watthours produce one pulse?
4. Is the demand meter receiving all pulses sent out?
5. Is the time interval correct?
6. Is the proper amount of pulses recorded on the chart or tape?
7. Are pulses properly recorded on the cumulative counter, where applicable?
8. Is the demand multiplier correct?
9. Is the demand record legible?

The demand meter test is usually performed at the time of periodic test on the watthour meter.

Since the pulse initiator is mounted in the watthour meter and its correct performance is one of the prime requisites for correct operation of a demand installation, it is generally the first component to be inspected in a field test. This is particularly true if the pulse initiator is a cam-operated contact device. Contact devices, if pitted, should never be filed but should be dressed with crocus cloth and then cleaned with paper. Slight pitting of the contacts is not serious but they should be clean and close flatly against each other.

Blade tension should be sufficient to prevent chattering due to vibration, but not so great as to cause excessive friction on the watthour meter. The spacing of cams should be such that the time intervals between successive contacts on a constant meter load are as nearly equal as possible.

After determination that the contact device is satisfactorily adjusted, the watthour meter should be tested and adjusted if necessary.

With the test load connected to the watthour meter, the demand meter should be checked to determine that it is receiving and correctly registering the pulses. One method of doing this is to open the load to the watthour meter, reset the demand meter to zero, and then restart the meter and run it for a definite number of revolutions. The demand meter should then read the correct number of pulses as determined from revolutions per advancing pulse.

The time interval can be checked by timing with an accurate stop watch the interval between successive resets.

SOLID-STATE PULSE RECORDERS

Solid-state recorders receive pulses from the pulse initiator in a watthour meter, or the pulse recorder can be "under glass" within the watthour meter.

Pulse data is stored in electronic memory and cannot be visually inspected. Instead, the stored pulse data is retrieved by a portable computer with an optical probe, or by a remote computer with dial-up capabilities. Once sent to a computer, the data may be formatted, printed, and viewed on a monitor. The software which retrieves the data may be supplied by the manufacturer of the solid-state recorder or by a vendor of general-purpose software supporting several recorders. For a complete description of solid-state pulse recorders, see Chapter 8.

One critical function of an electronic recorder is its clock, which must be accurate and stable. To test the clock in the recorder, methods described under "Test" earlier in this chapter can be used. If the recorder has an End-of-Interval output pulse, that pulse can be used to test the clock. The length of time between output pulses should exactly match the interval length programmed into the recorder. Another test method which also tests the interval data recorder, requires pulses from a precision source which are inserted at a known rate. The number of pulses-per-interval can be calculated, and if the End-of-Interval pulse is produced by more or fewer pulses than expected, the timing may be inaccurate.

Other parameters that should be verified during testing are pulse-multiplier factors, calendar settings to change between daylight saving and standard time, and settings for seasonal peak periods.

MAINTENANCE

Solid-state pulse recorders require very little maintenance. Most of these recorders are designed so that the circuit board assemblies in the recorder can be easily replaced. Some recorders use rechargeable batteries which should be checked periodically. Some recorders perform a self-check of the battery and send a low-battery alarm to the device interrogating them. All batteries should be changed at intervals less than the expected shelf life.

Planned replacements of solid-state pulse recorders as part of a maintenance program should be made based on the estimated product-life of solid-state electronics, which is usually 10 to 15 years.

CHAPTER 16

THE STANDARDS LABORATORY

SCOPE AND RESPONSIBILITY

THE STANDARDS LABORATORY is generally a part of the Meter Department, but is a separate division from the meter shop. The scope of the standards laboratory may include only the certification of portable watthour standards and other portable instruments, or it may be extensive and include such functions as new product approval testing, acceptance testing of materials and apparatus, special investigations, and research work. Regardless of the scope, the fundamental responsibility of the laboratory is to obtain accurate measurements while maintaining accuracy traceability.

The basic functions of the Standards Laboratory are as follows.

1. Accuracy calibration and certification of Working Standards by comparison with Secondary Reference Standards.
2. Accuracy calibration and certification of Secondary Reference Standards by comparison with Primary Transfer Standards.
3. Accuracy calibration and certification of Primary Transfer Standards with Fundamental Primary Standards. If the Primary Standards are maintained within the Standards Laboratory, the comparison is an internal function. For those electric utility companies that do not maintain Primary Standards, the calibration of Transfer Standards may be performed in other approved laboratories.
4. Certification of Transfer Standards directly with the National Institute of Standards and Technology (NIST) or with an approved laboratory that maintains direct traceability to NIST.
5. Intercomparison of Primary Standards. The DC volt references, standard resistors, time base, and associated equipment employed to calibrate the Primary Transfer Standard are the laboratory's highest internal authority on the value of electric measuring units and should be intercompared regularly to ensure the integrity of their measurement accuracies.

6. Regular certification of Primary Standards. Primary Standards should be sent periodically for certification to NIST or to an approved laboratory that has its own Primary Standards regularly certified by NIST.
7. Acceptance tests and determination of the characteristics of new types or designs of watthour meters, watthour standards, portable instruments, instrument transformers, and other electric measuring devices to determine their suitability for use by the electric utility company.
8. Special investigations relating to metering or measurement problems. Such investigations may require extensive tests both in the laboratory and in the field under actual operating conditions.
9. In addition to these basic functions, the Standards Laboratory may include in its scope of operations the repair of electric instruments and related devices. Assistance may be given to other sections of the electric utility company with electric measurements and tests.

Following are the key instruments used in the Standards Laboratory to carry out the above listed functions:

1. Primary Standards for DC Voltage, Resistance and Time
2. DC to AC Primary Transfer Standards
3. Secondary Reference Standards
4. Portable Working Standards
5. 8 ½ digit multi-meter
6. Computer controlled voltage and current sources

STANDARDIZATION AND NATIONAL METROLOGY LABORATORIES

The basic electric units of the volt, ohm, ampere, and the second have been established by international agreement in conferences attended by scientists from many of the leading industrial nations of the world. Countries such as the United States, Canada, England, France, Germany, and Japan maintain bureaus of standardization in which duplicates of these units, or the means for producing the units, are kept under conditions which ensure their permanence. As a further check upon the constancy of the units, intercomparison is made periodically.

In the United States, the source of ultimate authority in electric measurements, and the U.S. representative in the international system of standardization, is NIST located in Gaithersburg, Maryland. Here, basic units are preserved, together with secondary units and high-grade instruments by means of which commercial measuring devices may be compared with these basic units.

Starting with NIST, a comprehensive system of standardization has been developed. Facilities are available whereby each electric utility company may be assured of the accuracy of its measurements, and may have its standards compared with the basic units at NIST. It is important to note that in recognition of NIST's services and metrology capabilities, many electric utility companies in various countries utilize NIST as their traceable pinnacle for the watthour and other key measurement functions.

STANDARD TYPES

An electricity reference standard is an instrument that measures electrical parameters and is accepted as a basis for comparison. This acceptance is based upon its traceable accuracy and the criteria used to define its accuracy. The standard is used as a comparison to measurement instruments of lesser accuracy and therefore plays a key role in the Standards Laboratory.

Electric utility companies use reference standards to ensure the integrity of their revenue billing system. Because consumers are charged a fee for the energy they use, it is important that the accuracy of the revenue billing meters be maintained, documented, properly stored, and easily proven. The various types of reference standards are the foundation of that responsibility. In addition, reference standards are used to evaluate the performance of new metering products and to do approval testing of those new products.

There are different types of standards designed for different applications. Following is a description of each.

Primary Standards

Primary Standards are the basis for all measurements and consist of a DC Voltage Standard, a Standard Resistor and a Time Standard.

Zener References (such as the Fluke Zener Reference model 732B), and the Josephson Junction (such as the HYPRES model 2000), have effectively replaced the dated saturated and unsaturated standard cells which are no longer manufactured. When using the Zener Reference it is common to maintain a four cell array of Zener References. The Josephson Junction is used by some National Metrology Laboratories, such as NIST, but to this date is not commonly used by electric utility laboratories.

Resistance Standards (such as the Guildline model 9330/10k) are used as the primary reference for the ohm. If the Laboratory maintains temperature control, then the Standard Resister can be used at room temperature. For more precise ambient temperature control the Standard Resister can be maintained in a temperature-controlled oil bath for maximum stability.

Time Standards commonly used today consist of crystal based Universal Counters (such as the Hewlett Packard model 5334B), or Global Positioning Systems (such as the Arbiter Systems Satellite Controlled Frequency Standard model 1083B). These two modern Time Standards have effectively replaced the pendulum clock.

Primary Standards are normally used to calibrate the Primary Transfer Standard. The three fundamental calibrations performed on the Primary Transfer Standard are DC Voltage, DC Current (using the Standard DC Volt Reference and the Standard Resister), and Time. These three Primary Standards and their subsequent measurements, or values, determine the watthour calculation of the Primary Transfer Standard. See Figure 16-1 illustrating the balance of the DC to AC accuracy transfer.

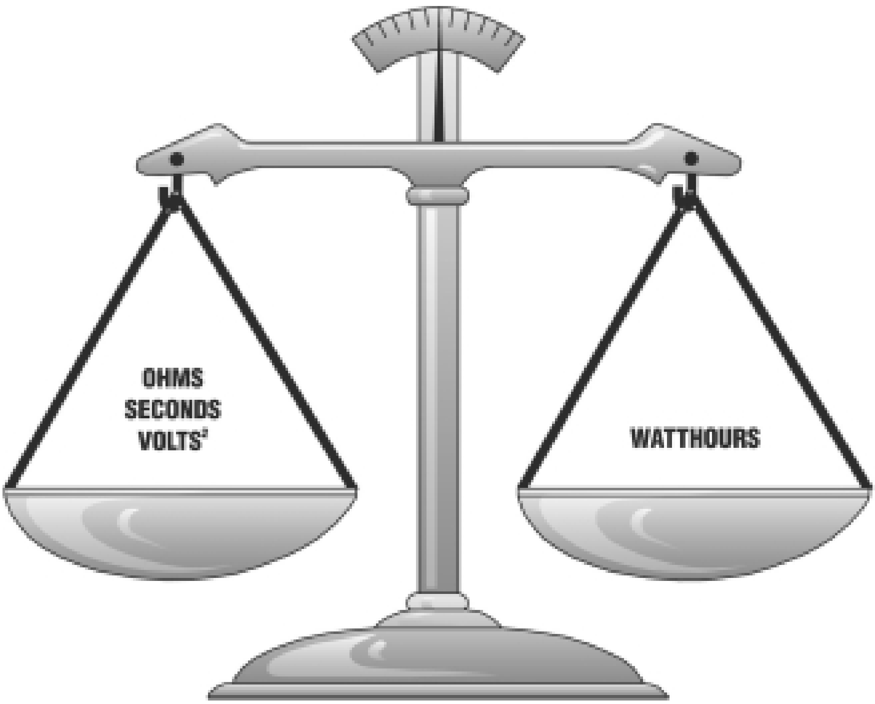


Figure 16-1. Balance of the DC to AC Accuracy Transfer.

Primary Transfer Standard

This standard has the ability to do a DC to AC accuracy transfer whereby Primary Standards can be compared to the Transfer Standard. The Transfer Standard can then be used to test Secondary Standards and/or Portable Working Standards. If the electric utility company does not maintain Primary Standards, then the Transfer Standard can be tested directly by NIST or another approved laboratory that maintains direct traceability to NIST. The Primary Transfer Standard is the most accurate and precise energy reference standard in a given laboratory because its accuracy is transferred directly from Primary Standards or a higher level metrology laboratory such as NIST. The accuracy of the Primary Transfer Standard is then transferred to all other AC measuring instruments. Normally a quantity of three of these standards would be used together as a Standard Bank. The use of three can improve repeatability of results and better ensure measurement integrity.

The Radian Research model RD-22 is an example of a Primary Transfer Standard. See Figure 16-2. The RD-22 has a maximum worst case DC to AC transfer accuracy of ±0.005%. The RD-22 provides simultaneous measurements of multiple functions including Watthours, VARhours, VAhours, Q-hours, volts, amps, watts, VAR, VA, millivolt-hours, milliamp-hours, volt-squared-hours, amp-squared-hours, phase angle, power factor, and frequency. The multifunction capability of the RD-22 has eliminated the need for separate standards for the Watt, AC Volt, and AC Current. The RD-22 has a wide autoranging voltage input of 60 to 600 volts AC and wide autoranging concentric core current comparator input of 0.2 to 200 amps therefore eliminating the need for external transformers historically used to isolate the Reference Standard from the standard being tested. The RD-22 can also analyze distorted waveforms up to the 50th harmonic order allowing for traceability with harmonics. See Figure 16-3.

Secondary Standard

The Secondary Standard is also referred to as the Working Reference Standard. The Secondary Standard is tested against the Primary Transfer Standard to assure its accuracy status. The role of the Secondary Standard is to test Portable Working Standards. Some electric utility laboratories may not use a Secondary Standard. Instead, they may use the Primary Transfer Standard in this role.

The Scientific Columbus model SC-60 and the Radian Research model RM-11 were very popular Secondary Standards. The Radian Research model RD-21 is a modern Secondary Reference Standard with a worst case accuracy of ±0.02% that applies to all measurement functions across the entire operating range of the product, and includes the variables of stability, power factor, traceability uncertainty, and test system errors. The RD-21 provides simultaneous measurements of multiple functions including watthours, VARhours, VAhours,

Figure 16-2. The Radian Research Model RD-22 Primary Transfer Standard.

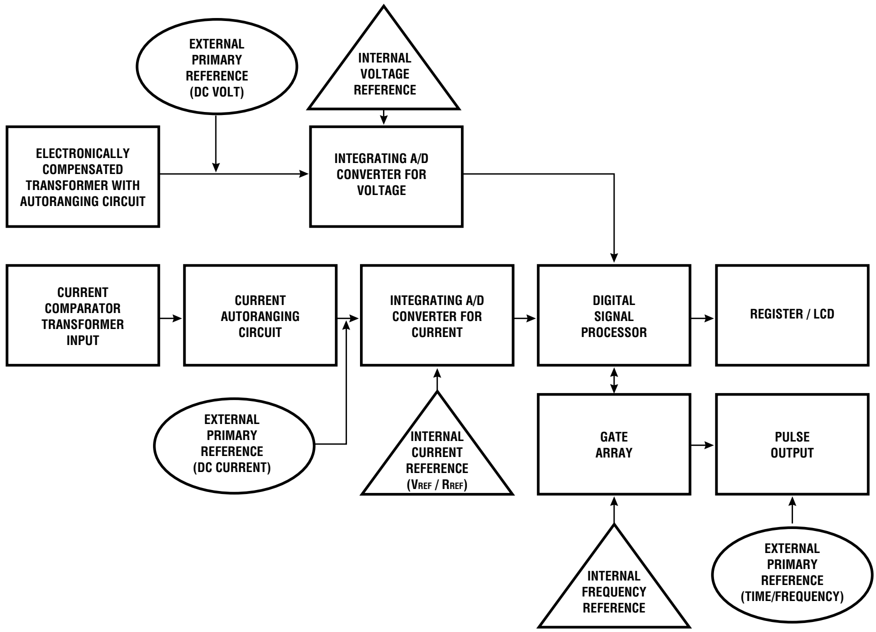


Figure 16-3. Block Diagram of the RD-22 Interfaced with Primary References for a DC to AC Accuracy Transfer.

Q-hours, volts, amps, watts, VAR, VA, millivolt-hours, milliamp-hours, volt-squared-hours, amp-squared-hours, phase angle, power factor, and frequency. The wide autoranging voltage input of 60 to 600 volts and wide autoranging current input of 0.2 to 67 amps (per input) have effectively eliminated the need for external transformers historically used to isolate the reference standard from the standard under test. These external transformers added unnecessary error to the test system. The RD-21 can accurately sense and measure the exact voltage and current test signals being applied to the standard under test. The RD-21 can also analyze distorted waveforms up to the 50th harmonic order allowing for testing of harmonic analyzing instruments. See Figure 16-4.

Normally a quantity of three of these standards would be used together as a Standard Bank. The use of three improves repeatability of measurements and assures measurement integrity.

It should be noted that there are sourcing standards available such as the Radian Research RS-703A. The RS-703A is used by many electric utility companies as a secondary working standard because it is a complete system capable of collecting data from multiple standards being tested simultaneously and then displaying and saving the test results. Further details of the RS-703A are provided in the “Voltage and Current Sources” section of this chapter.

Figure 16-4. Radian Research Model RD-21 Portable Reference Standard.

Primary Watthour Standard

This Standard is not used by all Standards Laboratories, but is used enough to justify a description of its application and purpose. Some electric utility companies do not maintain Primary Standards and therefore do not have traceability to NIST or another approved Metrology Laboratory for those Fundamental References. However, these same electric utilities companies may choose to maintain traceability for the watthour as well as other key measurements, such as the VARhour, AC volt, etc. The standard used in this application is sometimes referred to as the Primary Watthour Standard or Primary Multifunction Standard. This standard may be used to test Secondary Standards or it may be used to directly test Portable Working Standards. Normally a quantity of three of these standards would be used together as a Primary Standard Bank. The use of three improves repeatability of results and ensures measurement integrity. The Scientific Columbus model SC-60 and the Radian Research model RM-11 were used in this application. Modern standards that could be used in this application are the Radian Research models RD-22 and RD-21. Therefore, the Primary Watthour Standard can be either the Primary Transfer Standard or the Secondary Reference Standard as described in the previous two sections—but without the use of the Primary Standards.

Portable Working Standard

The Portable Working Standard may also be referred to as the Field Standard. The Portable Working Standard is the most common type of standard and is used to test revenue billing watthour meters. The Portable Working Standard generally has its accuracy tested against a Secondary Working Standard. Electric utility companies typically test their Portable Working Standards monthly, quarterly, or bi-annually. The Portable Working Standard may be found as the reference in meter shop test tables and field test kits. The Scientific Columbus model SC-10 and the Radian Research model RM-10 were very popular Portable Working Standards. The Radian Research model RD-20 is a modern Portable Working Standard with a worst case accuracy of ±0.05% that applies to all measurement functions across the entire operating range of the product and includes the variables of stability, power factor, traceability uncertainty, and test system errors. See Figure 16-5.

The RD-20 provides simultaneous measurements of multiple functions including watthours, VARhours, VAhours, Q-hours, volts, amps, watts, VAR, VA, millivolt-hours, milliamp-hours, volt-squared-hours, amp-squared-hours, phase angle, power factor, and frequency. The wide autoranging voltage input of 60 to 600 volts and wide autoranging current input of 0.2 to 67 amps (per input) allow for simple operation in the field. The RD-20 can also analyze distorted waveforms up to the 50th harmonic order allowing for customer load analysis in the field.

Figure 16-5. Radian Research Model RD-20 Portable Working Standard.

VOLTAGE AND CURRENT SOURCES

The voltage and current sources provide the needed test signals to carry out accuracy certifications. The voltage signal is connected in parallel between the reference standard and the standard under test. The current signal is connected in series from the reference standard to the standard under test. Modern computer controlled synthesized sources allow for very precise control over signal amplitude, phase angle, and frequency. Systems such as the Radian Research model RS-703A also provide the ability to create operator defined harmonic waveforms. The RS-703A Automated Calibration System provides computer controlled sources along with data collection capabilities to automatically calculate and save test results. See Figure 16-6.

In fact, the RS-703A can be used seamlessly with the Radian Research RD-22 Primary Transfer Standard. In this arrangement, the RD-22 is communicating with the RS-703A using the serial port while the standards under test have their pulses counted by the RS-703A Data Collection Module. At the conclusion of the test, results are saved and displayed showing the error of the standard under test against that of the RD-22 as well as against the results calculated by the RS-703A. In this arrangement, the RD-22 is a sensing standard while the RS-703A is a sourcing standard providing an effective check and balance system. See Figure 16-7.

Therefore, as a stand alone calibration system, the RS-703A can be used as a Secondary Standard. Or, with a Primary Transfer Standard, such as the RD-22, the RS-703A provides accurate, stable test signals while also serving as a cross check for the test results.

Figure 16-6. Radian Research Model RS-703A Calibration System.

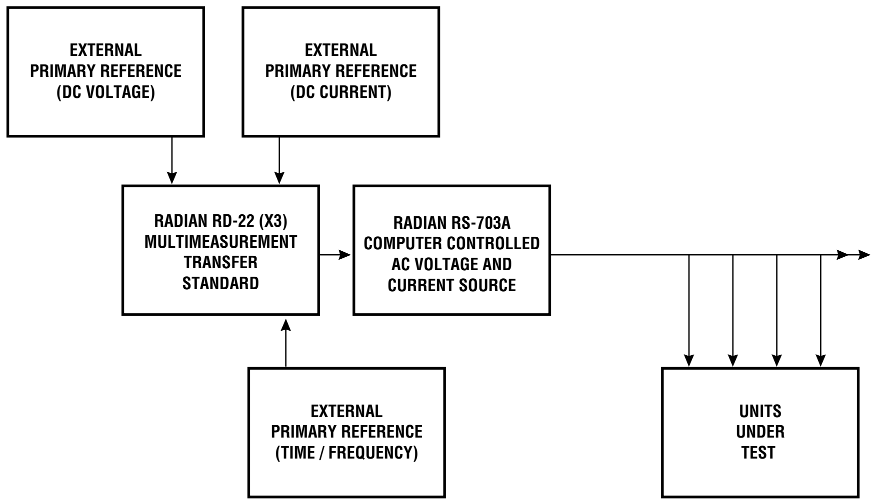


Figure 16-7. Block Diagram of the Radian Research RD-22 and RS-703A Test System.

DIGITAL MULTIMETER

The digital multimeter has effectively replaced the role of the potentiometer and resistance bridge methods in the Standards Laboratory. The 8 ½ digit multimeter is used as the key instrument for performing intercomparisons of Primary Standards. The Hewlett Packard model 3458A is a common laboratory multimeter.

THE CHAIN OF STANDARDIZATION

Every measurement performed in the Standards Laboratory must have accuracy which is traceable to a national metrology laboratory, such as NIST. The path of that traceability is often referred to as a Chain of Standardization. See Figure 16-8 for a typical chain of standardization from NIST to the Portable Working Standard.

This diagram illustrates the interrelations of the instruments and methods discussed. The three intrinsic references of NIST are the Josephson Junction for the volt, a Superconducting Hall Effect for the ohm, and a Hydrogen Maser for the second. Numerous variations of the basic procedures are possible. In some cases, electric utility companies will have a Standards Laboratory fully equipped with all of the instruments as described. However, Alternative A (as shown in Figure 16-8) illustrates that a laboratory could forego maintaining the Primary Standards and could use the Primary Transfer Standard for traceability to NIST. Or, Alternative B (as shown in Figure 16-8) illustrates that a laboratory could forego maintaining the Primary Standards as well as the Primary Transfer Standard and only use the Secondary Reference Standard for traceability to NIST. This would then be referred to as the Primary Watthour Standard as described earlier in this chapter. However, it is important to note that Alternative B will not provide the same degree of accuracy and certainty of measurements. Note 1 of Figure 16-8 points out that some manufacturers, such as Radian Research, have a complete metrology laboratory

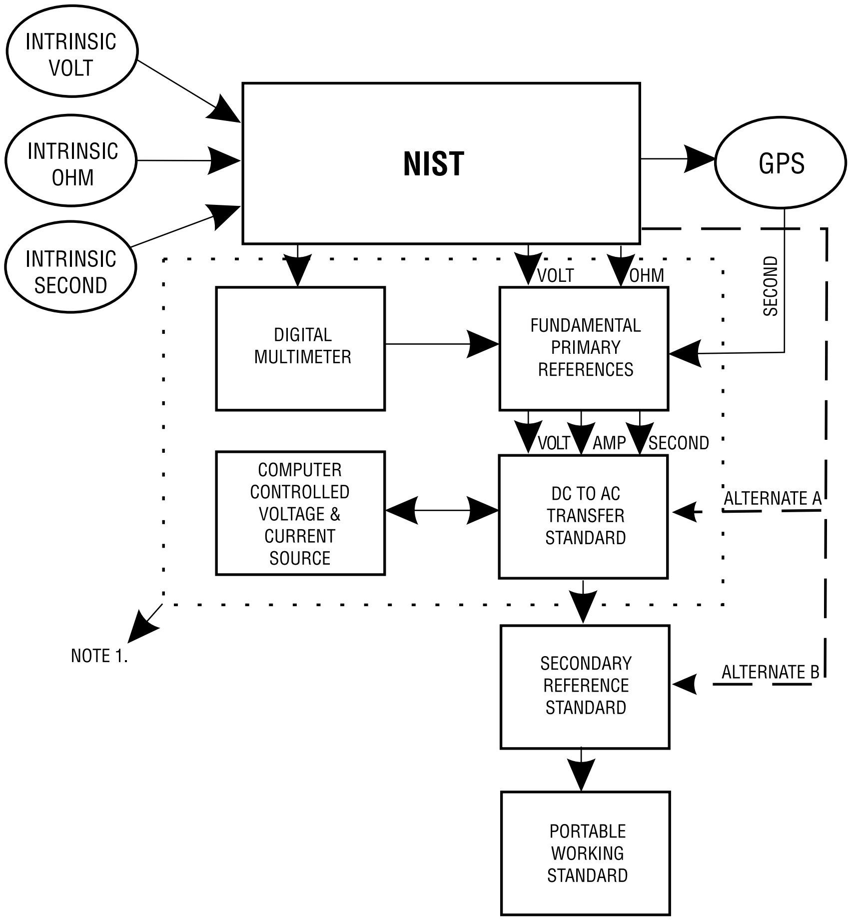


Figure 16-8. Typical Chain of Standardization from NIST.

and maintain all of the necessary instruments, including both DC and AC, for traceability to NIST. These laboratories provide certification and calibration services to the electric utility industry. Some electric utility companies choose Alternative B and utilize a metrology laboratory, such as Radian Research, for their traceability to NIST.

The particular Standards Laboratory approach used will vary among electric utility companies and may depend upon factors such as size of the utility and the accompanying description of its laboratory responsibilities.

Therefore, certification of instruments may be obtained from sources other than NIST, such as manufacturers or other laboratories having Primary Standards certified by NIST. In all cases, the calibration of the equipment used to establish the watthour should be traceable to NIST.

ACCURACY RATIOS

The accuracy in the chain of standardization is determined by the combined accuracy of calibration involved in all previous steps. Theoretically, the total error could equal the sum of all previous errors. In actual practice, there will generally be some cancellation of errors.

To reduce the effect of accumulated errors in a chain of standardization, each higher standard in the chain should also have greater accuracy. Ideally, each standard should be 10 times more accurate than the one it is to test. A 10:1 accuracy ratio in each step cannot be maintained because in a six-step chain, the overall accuracy ratio would be 106, or one million to one. The accuracy requirements of the higher steps would greatly exceed the capabilities of the best available standards.

In practice, accuracy ratios of 2:1 (at a minimum) to 5:1 are generally the best that can be realized for each step with the present state-of-the-art instruments. With these lower accuracy ratios, great care is required to eliminate, or correct for, errors in each step.

It is important to point out that verifying products have become very common for field applications. These verifying products should not be confused with true reference standards. Verifying products do not have the accuracy ratios required to perform an actual test of the revenue billing meter. Generally, verifying products do not list complete accuracy specifications which define all variables that can contribute to error. While these verifying products do have an application, this application does not encompass testing of the meter.

STANDARD ATTRIBUTES

A reference standard, regardless of its type or classification, has certain attributes by which it is classified. These attributes are generally listed in the manufacturer's specifications for a given model of standard. They are Accuracy, Repeatability, Stability, Uncertainty, Traceability, and Functionality.

Accuracy

Accuracy is a measure of the degree to which a measurement or calibration approaches the true value. In an accurate measurement, both random and all systematic errors have been reduced to small values. The terms precision and accuracy are often used interchangeably in general conversation, but in the standardization field they have distinct definitions which should be clearly understood by laboratory workers and all metering personnel. An accurate measurement is precise, but a precise measurement is not necessarily accurate, since unknown systematic errors may still be present. The laboratory employee must never forget that a measurement can be inaccurate even with a high degree of precision.

Repeatability

Repeatability is also referred to as precision. This variable relates to the degree of self-consistency an instrument has for the same given test parameters. Note that an instrument can have repeatability without being accurate. Repeatability or precision is a measure of the degree of consistency in a series of measurements. In a precise measurement, the random errors and the variable systematic errors have been reduced to small values.

Stability

Stability relates to an instrument's accuracy drift over a designated period of time. Therefore, it refers to how consistent the instrument's measurement accuracy is over time.

Uncertainty

This variable refers to the degree of certainty that a given measurement and/or accuracy specification is correct. This variable is applied so that those using the instrument (and therefore its accuracy capabilities) can assess the reliability or certainty of the results.

Traceability

This variable refers to the accuracy path of a given instrument back to a national measurement laboratory—in the United States it is NIST. It is important that the accuracy of a given instrument be traceable back to the highest available level with the shortest possible path.

Functionality

Functionality refers to the different types of measurements that the standard is capable of measuring and therefore is has traceability for these measurements. The more measurement functions, the more applications there are for the standard.

RANDOM AND SYSTEMATIC ERRORS

Small residual errors are always present in any measurement. These errors may be divided into two general types; random or systematic. Random errors occur without any apparent pattern in a series of repeat measurements with the same equipment. Random errors can be detected through statistical analysis. The standard deviation, sigma, of a series of measurements containing random errors is a good indication of the precision of the measurement. (The calculation and uses of the standard deviation are found in books on statistical analysis.)

Systematic errors are much more difficult to detect or analyze. These are errors that may be fixed or may vary in a recognizable pattern. If variable, they may be detected as a systematic change in the results of a series of repeated measurements. The pattern may be a trend in one direction with time, a periodic function of time, or a function of temperature or some other variable. Systematic errors which remain constant are the most troublesome of all, as they cannot be readily detected in a series of repeated measurements.

Fixed systematic errors are detected and eliminated by making cross checks using a different method, different equipment, or both. If the results agree, the probability of an undetected systematic error is small, since it is unlikely that each test involved identical systematic errors. If the results do not agree, systematic error is present in one or both measurements. Fixed systematic errors may be due to an unknown change in the calibration of any piece of equipment, unknown voltage drops in test circuits, unknown magnetic coupling between circuits, or innumerable other causes.

CROSS CHECKS AMONG LABORATORIES

To eliminate the possibility of systematic errors, and thereby establish confidence levels for accuracy at each level of standardization, suitable cross checks must be made. Much of this cross checking may be done within a single laboratory if some alternate equipment is available. However, complete duplication of all equipment is seldom economically feasible. To overcome equipment limitations, cross checks may be made with other laboratories. Two electric utility laboratories may easily make cross checks of their watthour standards by carefully packaging and shipping calibrated portable secondary reference standards from one laboratory to the other. The electric utility can also use the certification and calibration services of a metrology laboratory such as the one maintained by Radian Research in Lafayette, Indiana. Radian Research maintains all needed references traceable to NIST. The standards should be rechecked upon return to the home laboratory to be sure they have not changed due to transportation. Such cross checks or round robin checks, involving several laboratories, provide information of great value to all participating laboratories. Good agreement in such inter-laboratory cross checks provides assurance that accuracy is being maintained, while a lack of agreement will often uncover unsuspected systematic errors.

RESOLUTION

Resolution refers to the number of significant digits that can be read from the display of a given instrument. Resolution has no direct relationship to precision or accuracy. In good instruments, the resolution is usually slightly greater than the precision of the instrument, and the precision, in turn, usually exceeds the guaranteed accuracy. Instruments with a resolution which is in excess of their precision or accuracy are misleading because they imply a higher degree of precision than actually exists.

The resolution of a portable watthour standard can be increased almost without limit by increasing the time of the test run, but this does not increase the precision or the accuracy of the measurement after the point is passed where resolution is the limiting factor.

LABORATORY LOCATION AND CONDITIONS

The Standards Laboratory should be located in an area free from sources of noise, vibrations, dust, and dirt. Ideally, it should be located in a room separate from other meter department operations.

Air conditioning should be used to control room temperatures to 23° C ± 2° to keep relative humidity below 65%. For the most accurate work with Primary Standards, such control is a practical necessity. The accuracy of some standards is significantly affected by temperature and humidity. If humidity is to be controlled, 50% is considered ideal.

High-intensity lighting with a minimum amount of glare is necessary for the accurate testing and repairing of precision instruments. Diffused light sources provide ideal laboratory lighting conditions.

The basic 60 hertz power sources to the laboratory should be of ample capacity, well regulated, and free from sudden transients caused by motor starting. A separate transformer bank for laboratory test circuits is often a necessary or desirable solution. If laboratory motor-generator sets and phase-shifting generators are used, they should not be sourced from the test circuits.

In many cases, electronic voltage regulators may be needed in the laboratory to provide stable test sources. All AC sources should supply clean sine waves, as waveform distortion can cause measurement errors. Direct current sources can be obtained from batteries or rectifiers. If rectifiers are used, they must be well filtered to keep the AC ripple at a very low value. Dynamometer and D'Arsonval instruments will not agree on a DC source containing significant ripple. Rectifiers must be extremely well regulated if they are to be used for potentiometer work.

Regardless of the accuracy of the equipment used, accurate electric measurements cannot be made with unstable or distorted sources of power.

LABORATORY OPERATION

Successful operation of a standards laboratory requires the possession and maintenance of certified standards of suitable types, highly trained laboratory personnel who understand the art and science of accurate measurement, the availability of sufficient time and money for the regular program of periodic standardization and cross checking, and proper documentation. This documentation includes defined and controlled procedures for the key laboratory activities of calibrations, certifications, cross checks, and traceability. It is very important that records be appropriately maintained and accessible.

CHAPTER 17

METER READING

THE ACCURATE READING of meters is an operation of major importance for any electric utility company, not only from a revenue standpoint but also in the promotion of strong customer relationships. In gaining access to meters, the meter reader makes many personal contacts with customers and is often the only utility employee seen by the customer. With this in mind, most electrical utility companies choose, for their meter reading personnel, employees who are conscientious and have the natural attributes of friendliness, courtesy, and a neat appearance.

A meter reader's initial training course usually includes the fundamentals of good public relations, familiarization with the types of metering equipment likely to be encountered, and thorough explanations of the terms used in customer billing. It is important that meter readers be familiar enough with their company's organizational structure to be able to channel a customer's requests and questions to the proper departments.

Meter reading is carried out under a carefully planned program, and meter routes are arranged in proper reading order. Readings are taken on a pre-arranged schedule to make the billing cycle practicable and to provide an even flow of work for other operations, such as billing, auditing, and collecting. To prevent undue annoyance to customers and to expedite the work, meter-reading records usually contain notations showing the exact locations of meters, means of access, keys needed (if applicable), and notes of any unusual conditions, such as physical hazards and/or dangerous pets.

If it is necessary to enter a customer's premise, it is a good practice for readers to announce themselves courteously and produce proper identification when requested. Meter readers can be of considerable help to the company in reporting irregularities, such as changes in customers, meters without a reading record, vacant buildings, stopped meters, unsealed meters, unmetered service, and any other condition that might adversely affect customer billing, safety, or the quality of service rendered.

The principal duty of a meter reader is to obtain the meter readings and to make certain that these readings are entered on the correct reading records by verifying addresses and meter numbers. A good meter reader will enter the readings on mark sense cards or meter reading sheets in a clear, precise, and legible manner.

HOW TO READ A WATTHOUR METER

Electromechanical Meters

There are three styles of mechanical kilowatthour meter register types in general use. One has individual dial circles as shown in Figure 17-1, another has interlocking dial circles as shown in Figure 17-2, and a third style of register uses cyclometer-type dials.

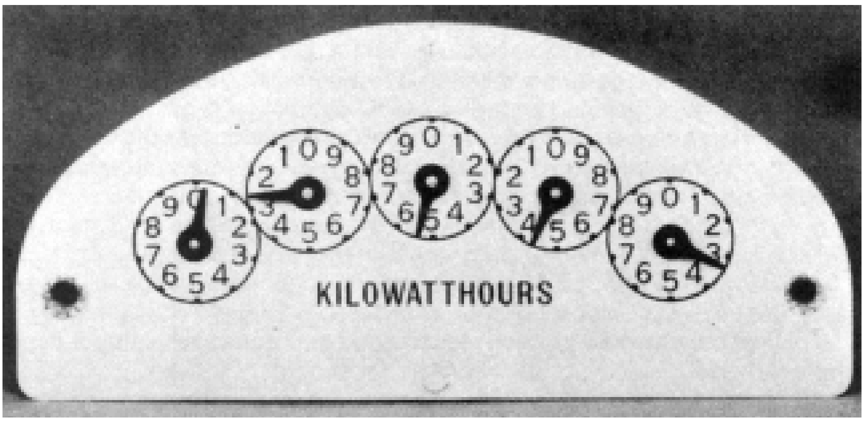


Figure 17-1. Conventional Five-Pointer Kilowatthour Dial.

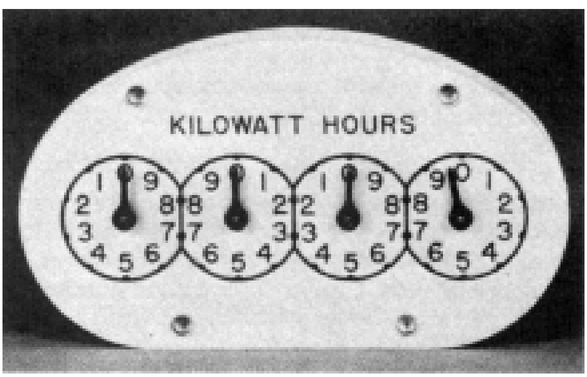


Figure 17-2. Conventional Four-Pointer Kilowatthour Dial with Overlapping Circles.

Registers with dial circles have either four or five dials; five dials being provided to avoid a dial multiplier of 10 and the possibility of a register "turn-over" during the normal billing period. Adjacent pointers rotate in opposite directions and are geared for travel so that the pointer on the right will make one complete revolution while the one next to it on the left makes one-tenth of a revolution. When a pointer is between two figures, the smaller figure is the one to use for the reading.

A watthour meter is read from right to left by reading all dials and recording the reading on a meter reading form in this same sequence. The reason for reading the dials from right to left is that the right-hand dial governs the one to its left in each instance. With all pointers at zero and a dial multiplier of one, one clockwise revolution of the unit's dial pointer will indicate a reading of 10 kilowatthours on the register. A complete counterclockwise revolution of the 10's dial pointer will indicate a reading of 100 kilowatthours on the register and so on. When reading the dials the procedure is analogous to reading 1s, 10s, 100s, and 1,000s.

Remember that each pointer must complete a revolution to advance the pointer located to its left by one division. Therefore, to correctly determine the reading of a pointer, the previous pointer (located to the right) must be consulted. Unless this pointer has completed a revolution by reaching or passing the 0, the pointer in question has not completed the division on which it may appear to rest. For this reason, reading the meter from right to left increases both accuracy and efficiency.

A simple analogy can be made to a wristwatch. When the hour hand is near 8 and the minute hand is at 11, it is not yet 8 o'clock, but it is 7:55 and, obviously, it will not be 8 o'clock until the minute hand has advanced to 12.

Figures 17-3 and 17-4 show examples of typical watthour meter readings.

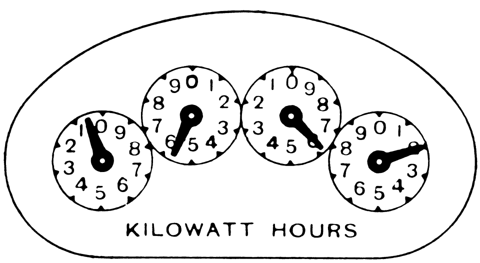


Figure 17-3. Kilowatthour Register Showing Reading of 0562.

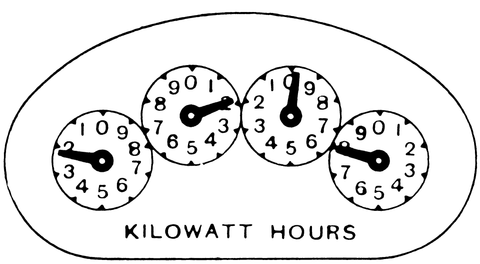


Figure 17-4. Kilowatthour Register Showing Reading of 2198.

To obtain the use in kilowatthours over a designated period of time, it is necessary to subtract the previous reading from the present reading. When the dial multiplier is one, the difference will be the number of kilowatthours consumed between the two readings. When the dial multiplier is a number other than one, the difference between the readings must be multiplied by the given dial multiplier to obtain the kilowatthours consumed. Dial multipliers of one generally are not shown, but those other than one are shown on the dial faces.

Double- or two-rate registers employ two sets of dials and two complete register mechanisms that are automatically switched into gear with the moving element shaft at predetermined times. These two-rate registers are generally used in conjunction with off-peak water-heating rates.

REGISTER CONSTANTS

The register constant is also known as the dial constant, dial multiplier, or reading multiplier. It represents the factor by which the register reading is multiplied to obtain the total registration.

Each disk revolution represents a definite value of the units being measured. The register gearing converts these disk revolutions into the units used for customer billing. For small capacity domestic meters, the register commonly reacts directly in the billing units.

Changing the gearing between the dial pointers and the disk shaft introduces a constant. If the value of this gearing is doubled, the speed of the register pointers is halved and the reading must be multiplied by two to obtain the true value.

On modern high-capacity meters, particularly with bi-monthly billing, a four-dial register may not have the capacity to indicate the customer's consumption during the billing period. That is, the register may turn over. This difficulty can usually be avoided by increasing the capacity of the register.

One way to increase register capacity is to add an extra dial at the left of the four dials commonly used. This means that the capacity of the register is increased ten-fold and, instead of a maximum reading of 9,999 kilowatthours, there is a maximum reading of 99,999 kilowatthours. Another solution is to change the register ratio or gearing and introduce a multiplying factor or constant of ten. In this way, the capacity of the register is changed from 9,999 kilowatthours to 99,999 kilowatthours.

Many factors enter into the decision as to which method is used. Among these factors are the procedures and billing machines used by the billing group and whether they require major modification to accept five-digit readings. On the other hand, constants other than one must be carefully controlled and checked if errors are to be avoided.

Register constants are also introduced when meters are supplied from instrument transformers. If the meters are supplied for use with instrument transformers of specified ratios, the register constant is a multiple of ten, i.e., 10, 100, 1,000, etc. If transformer-rated meters are not supplied for specified transformers, then the register will read directly for the meter alone (considered as self-contained), and the register constant will be the current-transformer ratio or the product of the ratios of the current and potential transformers when both are used.

Meter manufacturers have recently made available demand registers with a scale and gear shifting design that provides full-scale deflection at 50% and

100% of meter capacity. These registers provide flexibility for future load growth with better reading accuracy at smaller loads.

METERS WITH ELECTRONIC DISPLAYS

Electronic meters or electromechanical meters with electronic registers use digital displays to indicate power readings and other information. The display can show a series of readings, automatically stepping through each parameter at a programmed rate, five or ten seconds per step. This allows the meter reader to record each reading by writing it on a meter card or by keying it into a handheld terminal. In addition to measured values, the display can show time, date, and perform an "All-Segments" test to verify the proper operation of all display elements. Figure 17-5 shows an All-Segments test. Some electronic registers display prompts such as "01" or "02," which identify the parameters being displayed. Figure 17-6 shows an electronic display that incorporates prompts.

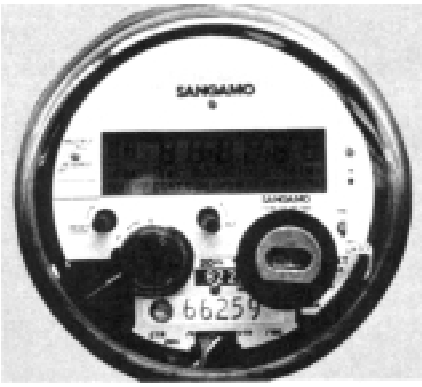


Figure 17-5. Electronic Display, All-Segments Tests.

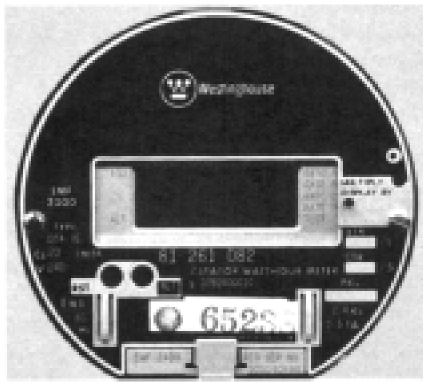


Figure 17-6. Electronic Display, with Prompts.

DEMAND METERS

Demand readings are usually measured in kilowatts, kilovoltamperes, or kiloVARs, with the quantity measured being indicated on the dial face, the nameplate of the instrument, or an icon/identifier on the electronic display. The demand device may be incorporated within a watthour meter or associated with an auxiliary demand device connected to the meter. Demand readings consist of two types—indicating or recording.

Indicating Demand Meters

Indicating demand meter mechanical registers consist of four basic types.

Sweephand Type of Pointer (Mechanical-Type Register)

How to Read—The position of the sweephand is read and the pointer reset to zero. A register of this type is shown in Figure 17-7. The maximum demand is determined by the position of the pointer on the scale in a manner similar to reading a voltmeter or a speedometer. The value of the smallest subdivision on the scale may be determined by dividing the first numeral by the number of divisions between this numeral and zero. When the number of subdivisions between the marked or numbered divisions is 10, the reading of the pointer is the value of the marked division, plus the value of the subdivisions, which are expressed in tenths of the major division. The demand value shown in Figure 17-7 is 1.45 kilowatts. Figure 17-8 shows four demand scales with different subdivision values.

How to Reset—This mechanical type of register has a clutch in the advancing mechanism and therefore both the indicating pointer and the pusher finger may be returned to zero by a counterclockwise movement of the reset knob. The wire reset should not override the pointer, as the resulting spring action may cause a false demand indication.

Sweephand Type of Pointer Showing Maximum Demand, Plus a Sweephand Pusher Pointer, Showing Current Demand (Thermal-Type Register)

How to Read—The maximum demand is read in the same manner as the mechanical-type register.

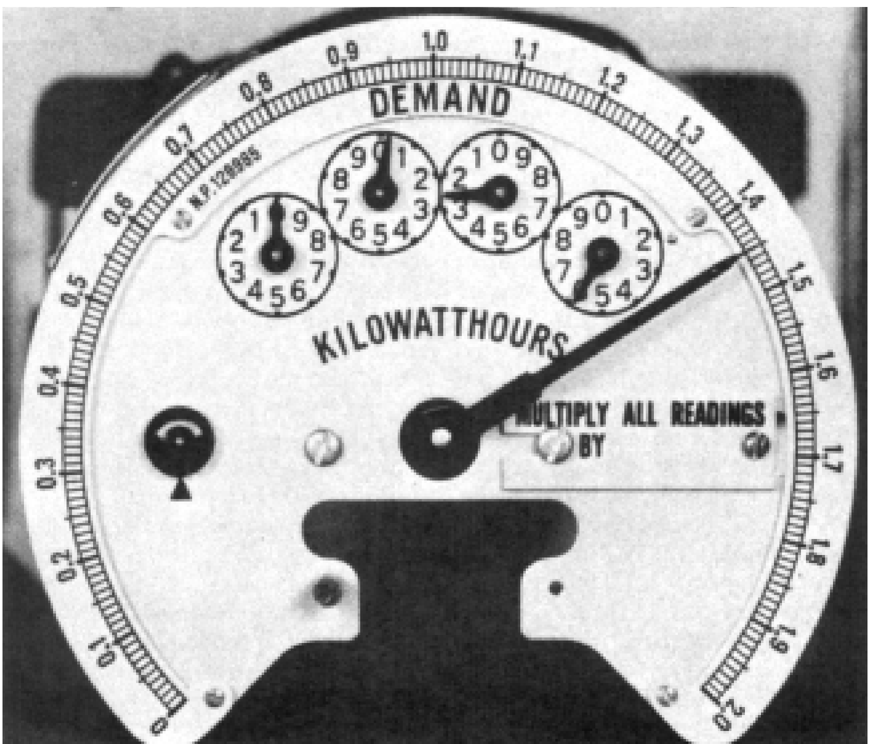
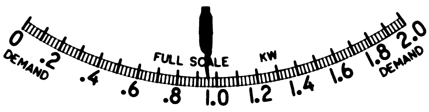
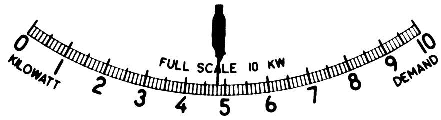


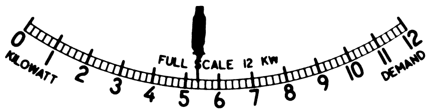
Figure 17-7. Watthour Demand Register, Indicating Type.



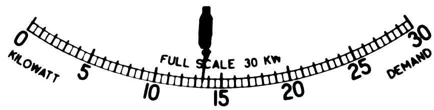
Subdivision Value: 0.5
Indicated Value: 13.5



Subdivision Value: 0.1
Indicated Value: 4.8



Subdivision Value: 0.2
Indicated Value: 5.4



Subdivision Value: 0.02
Indicated Value: 0.96

Figure 17-8. Watthour Demand Scales Showing Various Subdivision Values.

How to Reset—Unlike the mechanical register, the pusher pointer is not driven by a clutch in the thermal-type register, but is directly attached to the moving element and must not be forced back to zero. Therefore, it is customary to record the position of the maximum pointer, and then to reset the maximum pointer back to, or slightly depressed beyond, the indication of the pusher pointer.

Dial Type of Pointers (or Cyclometer) Showing Cumulative Readings

How to Read—In addition to four or five kilowatthour dials, this type of register features four similar dials at the bottom for registering maximum demand. These demand dials are read in the same manner as the kilowatthour dials. To obtain a maximum-demand reading from this device, it is necessary to operate a mechanism attached to the meter cover. The kilowatt demand for the billing period is then automatically added to these dials and a record is then made of the new readings. The dial pointers are stationary between reading periods. A solid black index line equal in height to the demand dials is used to denote the decimal point.

How to Reset—When resetting cumulative demand registers, which are motor operated, firmly push the reset plunger against the reset knob until the knob starts to rotate. Do not hold the plunger against the knob for the completion of the accumulation because this may jam the register. For a meter equipped with a reset lock device, insert the key, turn to the left one eighth of a turn and push the key forward causing the plunger on the lock to push against the reset knob. When the knob starts to rotate, release the pressure on the key and rotate it back one eighth of a turn to its normal position and remove the key.

Dial-Type Pointers (Non-Cumulative)

How to Read—This register has three demand dials similar in appearance to the kilowatthour dials (Figure 17-9). These dials are located at the bottom of the register and are read in the same manner as the kilowatthour dials. The pointers are reset to zero after each reading. A solid black index line equal in height to the demand dials is used to denote the decimal point.

How to Reset—The dial pointers are reset to zero by turning the reset lever approximately one fourth of a turn in a counterclockwise direction; then the lever is returned to its normal position.

Electronic Demand Register Meter

Electronic meters or electromechanical meters equipped with electronic registers are capable of displaying peak and present power demand. Information is presented on the electronic display in various formats and sequences. Reset of the peak demands is accomplished using a lever or pushbutton techniques depending on the device type.

Sealing

Following the operation of a reset device or operating mechanism, it is necessary that the device be sealed or locked and that it remains so until the next reading. Some companies require that old seals be returned for their salvage value and in the interest of cleanliness and safety on the customer's premise.

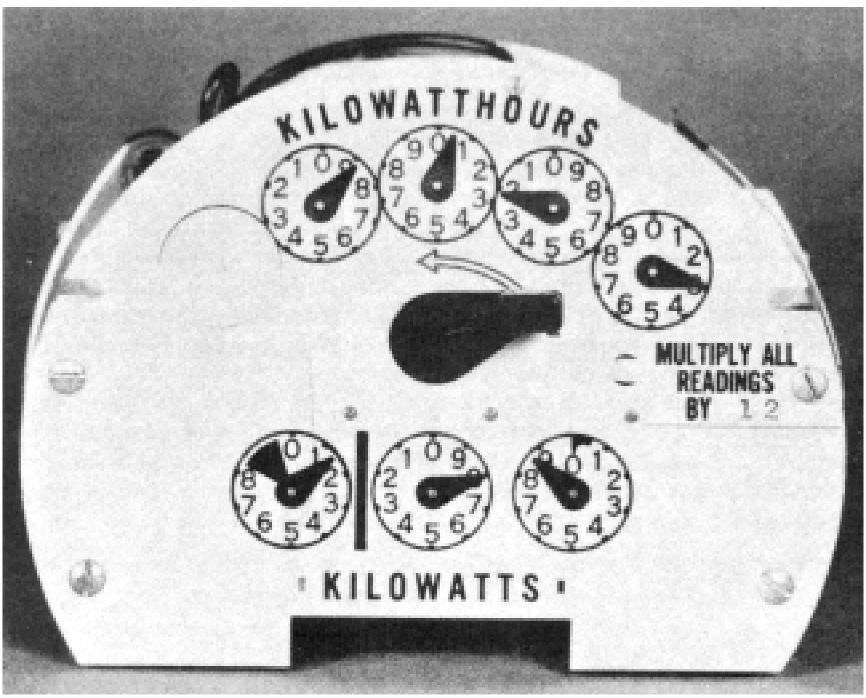


Figure 17-9. Watthour Demand Register, Non-Cumulative Dial Type.

Recording Demand Devices

Recording demand devices may consist of older mechanical chart recorders or newer microprocessor based solid-state memory devices. Instructions for reading and the operation of older mechanical chart recorders can be found in earlier editions of this *Handbook.* Today, recording chart and magnetic tape devices have been replaced by solid-state recorders in the electric utility industry. They can be integral to the meter or a separate auxiliary unit. An operational description of solid-state demand recorders is found in Chapter 8.

AUTOMATIC RETRIEVAL OF DATA FROM SOLID-STATE RECORDERS

New technology now makes it possible to retrieve information electronically from certain solid-state recorders using both wired and wireless communication networks. If the recorder has a modem and is connected to a communications network (RF, telephone, cellular, CDPD, ARDIS, etc.), the recorder can connect with the central office periodically and transmit the data it has stored. If the recorder does not have a modem or network connection, a portable computer can be taken to the site to collect the information in the field.

Some solid-state recorders have an optical port for transmitting readings through an optical probe to a portable computer or handheld device.

When this data is returned to the central office, it can be processed using software provided by the recorder manufacturer or by general meter reading software, which has been developed for processing data from a variety of recorders.

ELECTRONIC METER READING

The use of electronic devices within meters opens up new options for accurately retrieving larger volumes of data from meters. A wide variety of methods and technologies for automating the meter reading process have been developed, tested, and are being deployed by hundreds of utilities throughout the country.

New electronic meters also have the ability to record a wide variety of consumption information. As described in earlier chapters, electronic meters can measure consumption by time-of-use, record peak consumption values, and collect load survey data. New meter-reading technologies also make it easier for the utility to automatically collect all types of data in a much more accurate, efficient, and reliable manner.

Handheld Data Entry Terminals

Handheld computer terminals are carried to the field and meter readings are entered via a keyboard on the face of the terminal. The meter reader can verify the entry of each reading by checking the digital display on the terminal. Some terminals are programmed to guide the meter reader through the daily route, and to advise him of special conditions related to the reading of each meter. At the end of the route, data collected is downloaded to a computer and the billing department can use it immediately.

These handheld terminals, specially designed for reading utility meters, are available from several manufacturers. General purpose computers, such as laptop and palmtop computers, are also used by electric utilities.

Handheld terminals increase the productivity of the meter reader and reduce errors. Meter readings are entered in the field and downloaded into the central computer without further human involvement.

Handheld Terminals, Automatic Data Entry

Some meters and some handheld terminals have the ability to transfer readings from meters into terminals automatically. Instead of manually entering data via a keyboard, the meter reader uses an optical probe to collect the data. Meter data is sent through an optical port on the meter directly to the handheld terminal. This technique virtually eliminates human reading errors.

AUTOMATIC METER READING

To eliminate meter access problems and data entry errors while improving overall meter reading efficiency, many utilities are implementing Automatic Meter Reading (AMR) technology. The AMR technology enables utilities to collect meter data without having to visit the meter. Nationwide, an increasing number of electric, gas, and water utilities are installing these remote data collection technologies.

Electric utilities are also beginning to deploy AMR technology for reasons that go beyond metering and customer billing. As the energy marketplace deregulates and becomes more competitive, utilities are seeking ways to use advanced metering data throughout their distribution operations to achieve a variety of other objectives. These are; improved demand forecasting accuracy, increased energy distribution system efficiency, delivery of new rates and services, and successful management of customer choice and retail competition in their service territories.

Utilities have a wide choice of AMR technologies and companies from which to choose. These technologies include wired and wireless data collection systems that use both public and private communication networks, including broadband and cellular. Some AMR vendors offer products that use existing power lines to transmit collected data while others are working to develop systems that rely on satellites and other more exotic technologies that have yet to prove themselves as either practical or cost effective. The AMR industry also features meter data collection technologies to serve residential, commercial, and industrial customers equipped with more advanced solid-state electric meters.

From radio-equipped handheld terminals to vehicle-based systems to large fixed networks, these automatic meter-reading systems offer a wide range of data collection functionality at a wide range of costs. The suitability and cost-effectiveness of a particular AMR technology depends on a number of variables; the type of service territory (urban, suburban, or rural), the type of customer (residential, commercial, or industrial), and the data collection needs of a particular utility. These needs can vary greatly.

Many utilities are deploying integrated AMR solutions that combine different collection technologies (e.g., network, mobile, and telephone), to deliver the desired level of data collection functionality for different service areas and customer segments in the most cost-effective manner. Each of these technologies—handheld computers, mobile vehicle-based systems, wireless networks, telephone-based systems and powerline carrier—has its own set of strengths depending on a utility's operational and strategic objectives.

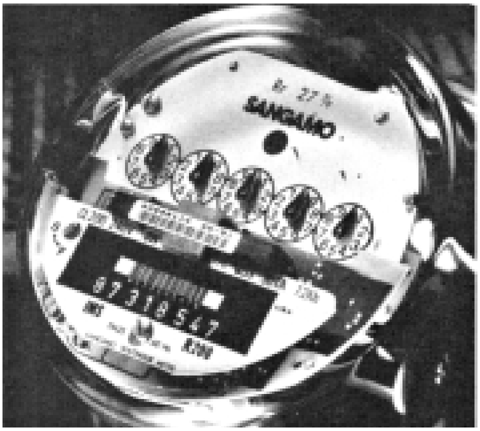


Figure 17-10a. Meter Equipped for Remote Reading by Radio.

Figure 17-10b. Handheld Terminal for Remote Reading by Radio.

Radio-Based Mobile Automatic Meter Reading

With a radio-based system, each meter is adapted with a compact, low-power transmitter/receiver that upon request, broadcasts a radio signal containing metering and tamper data.

These meters are polled by a mobile handheld terminal or vehicle-based transmitter/receiver that collects meter readings from many meters and carries the readings back to the central office. At the end of the day, the readings are loaded directly into the utility's billing computer. The mobile transceiver can be in a handheld terminal, or a higher-powered unit installed in a truck that is driven down streets, polling meters and recording replies. Depending on the service environment, meter density, memory capacity, and the type of meter readings collected, handheld terminals are typically capable of reading several hundred meters or more in a day. More powerful vehicle-based units raise meter reading efficiency even further by reading thousands of meters in a single day.

Figure 17-10a shows a watthour meter adapted for automatic meter reading by radio. A small semicircular circuit board with a transceiver (difficult to see in the photo) has been installed immediately under the glass cover. The portable terminal shown in Figure 17-10b can read meters at a distance of several hundred feet.

Radio-based meter reading is fast, efficient, and generally reliable. Some meter installations inside metal buildings create difficulties for radio transmission but these site-related problems can often be solved by re-locating the meter antenna.

Network Meter Reading

Radio-based fixed networks offer the most advanced data collection functionality of any wireless meter-reading technology. There are many variations in the network data collection products available from different vendors. Most wireless network meter reading systems involve installing a fixed communications network over a population of meters equipped with radio transmitters to send the data through the network to the host processor. Companies apply a variety of communications strategies for their network products that utilize private dedicated wireless networks, public networks, or some combination of the two.

Though more costly than handheld and mobile automatic meter reading systems, these networks provide electric utilities with state-of-the-art automatic meter reading functionality, including consumption reads, on-request reads, tamper reporting, time-of-use, demand metering, load profile/interval reads, virtual connect/disconnect capabilities, outage detection and restoration reporting, consumption monitoring, and aggregation capabilities.

Until now the handful of electric utilities that have deployed network meter reading systems have done so mostly on a large-scale, territory-wide basis to spread the cost of the network over a large number of meters—typically more than 100,000. However, recently several new more scalable and flexible network products have emerged that enable electric utilities to deploy advanced network meter reading technology on a more selective and cost-effective basis to serve specific meter populations or specific customer segments (such as commercial and industrial customers with advanced solid-state meters). To reduce both implementation and ongoing operations costs, these new networks combine private, dedicated RF communication networks to gather data from designated populations of automated meters and then use public communications networks to back haul the data from local collection points to the host processor. While its penetration has been limited thus far, deployment of network meter reading and data collection technology will likely accelerate in the years to come as costs come down and the need for utilities to gather more advanced metering data increases.

Telephone-Based Automatic Meter Reading

Telephone Dial-Out System

With a telephone dial-out system, the utility's computer initiates outbound calls to the meters. With this approach, the utility has the flexibility to poll meters at any time. It is a convenient solution for capturing initial readings, final readings, re-readings after a high-bill complaint, and testing for special conditions such as peak or off-peak consumption.

Dial-out meter reading systems require assistance from the local telephone company. To call customers without ringing their telephones, the telephone company injects special tones into the telephone call, signals originally intended to test telephone lines without disturbing customers. These test signals are created at the telephone company's central office and are not available to the public. With these signals, a meter reading can be taken even when the telephone is disconnected.

To place outbound telephone calls, the utility's host computer maintains a directory of telephone numbers of all customers. This can be a challenge with the increasing popularity of unlisted telephone numbers and the frequent turnover in telephone listings.

Telephone Dial-In System

With a telephone dial-in system, each meter calls the utility at specified times and reports its information. The meter, in effect, calls home at programmed times to report the latest readings. During that telephone call, the host computer can reprogram the meter's calling schedule and parameters, verify the meter's clock and calendar, test for other conditions, and update the meter module software if necessary. Dial-in systems typically use existing customer telephone lines. Each meter acts like a telephone extension on the line, or is the only instrument when installed on a dedicated line. Dial-in systems are installed and operated without special assistance from the local telephone company.

Dial-in systems usually place calls at night when the line is not likely to be in use. If the line is busy, or becomes busy during the call, the dialer in the meter hangs up immediately and tries again later. The telephone calls can be set up to call a toll-free number so there is no per-call cost to the customer. When no telephone exists, the utility can pay to install a phone line specifically for meter reading. This investment can be cost effective for reading meters installed in remote and low density locations, or for meters which require more frequent and advanced data collection or outage detection capability.

Electronic meters can be programmed to dial-in if a special event occurs, such as an out-of-range reading (suggesting a damaged circuit), suspected meter tampering, or a power outage.

Dial-in systems generally rely on customer telephone lines and are vulnerable to interruptions in that service. Some of these systems do not work when the customer's telephone is disconnected.

Automatic Meter Reading Using Power Lines

Electric power lines can also be used for the transmission of meter data. Information collected by the meter is encoded and then sent through the power lines to special receivers typically located at area substations. There are many different forms of Power Line Communication technology. But in all cases the power line is the network path for the data. Technology is advancing in this area and its use is increasing as a cost effective solution for acquiring meter data.

Power Line Communication Technology has typically been a variant of a high frequency carrier system design. Those systems usually require extensive line conditioning to allow signals to pass through distribution line equipment. A unique power line carrier system uses an ultra narrow band technology that relies on current rather than voltage, the transmission of data is not affected by line length or distribution line devices, such as transformers and capacitors. Another Power Line Communication Technology that is widely used relies not on an injected carrier frequency, but by creating aberrations to the voltage and current waveform near the zero crossing. The patterns of waveform aberrations create data bits that form a communication protocol for two-way communication. This technology is also not affected by line length or distribution line devices.

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