than one battery is used, the batteries are usually connected in parallel. The voltage is equal to that of one battery, but the ampere-hour capacity is increased. The total capacity is the sum of the ampere-hour ratings for the individual batteries.

Factors Affecting Lead-acid Battery Life

Various factors cause deterioration of a battery and shorten its service life. These include over-discharging, which causes excess sulphation and too rapid charging or discharging, resulting in overheating of the plates and shedding of active material. The accumulation of shedded material, in turn, causes shorting of the plates and results in internal discharge. A battery that remains in a low or discharged condition for a long period of time may be permanently damaged. In addition to causing deterioration of the battery, these factors also decrease battery capacity.

Lead-acid Battery Testing Methods

The state of charge of a storage battery depends upon the condition of its active materials, primarily the plates. However, the state of charge of a battery is indicated by the density of the electrolyte and is checked by a hydrometer, an instrument which measures the specific gravity (weight as compared with water) of liquids.

The hydrometer commonly used consists of a small sealed glass tube weighted at its lower end so it will float upright, as shown in figure 8–109. Within the narrow stem of the tube is a paper scale with a range of 1.100 to 1.300. When a hydrometer is used, a quantity of electrolyte sufficient to float the hydrometer is drawn up into the syringe. The depth to which the hydrometer sinks into the electrolyte is determined by the density of the electrolyte, and the scale value indicated at the level of the electrolyte is its specific gravity. The more dense the electrolyte, the higher the hydrometer will float; therefore, the highest number on the scale (1.300) is at the lower end of the hydrometer scale.

In a new, fully charged aircraft storage battery, the electrolyte is approximately 30 percent acid and 70 percent water (by volume) and is 1.300 times as heavy as pure water. During discharge, the solution (electrolyte) become less dense and its specific gravity drops below 1.300. A specific gravity reading between 1.300 and 1.275 indicates a high state of charge; between 1.275 and 1.240, a medium state of charge; and between 1.240 and 1.200, a low state of charge. Aircraft batteries are generally of small capacity but are subject to heavy loads. The values specified for state of charge are therefore rather high. Hydrometer tests are made periodically on all storage batteries installed in aircraft. An aircraft battery in a low state of charge may have perhaps 50 percent charge remaining, but is nevertheless considered low in the face of heavy demands which would soon exhaust it. A battery in such a state of charge is considered in need of immediate recharging.

When a battery is tested using a hydrometer, the temperature of the electrolyte must be taken into consideration. The specific gravity readings on the hydrometer will vary from the actual specific gravity as the temperature changes. No correction is necessary when the temperature is between 70° F. and 90° F., since the variation is not great enough to be considered. When temperatures are greater than 90° F. or less than 70° F., it is necessary to apply a correction factor. Some hydrometers are equipped with a correction scale inside the tube. With other hydrometers it is necessary to refer to a chart provided by the manufacturer.

In both cases, the corrections should be added to, or subtracted from, the reading shown on the hydrometer.

The specific gravity of a cell is reliable only if nothing has been added to the electrolyte except occasional small amounts of distilled water to replace that lost as a result of normal evaporation. Hydrometer readings should always be taken before adding distilled water, never after. This is necessary to allow time for the water to mix thoroughly with the electrolyte and to avoid drawing up into the hydrometer syringe a sample which does not represent the true strength of the solution.

Extreme care should be exercised when making the hydrometer test of a lead-acid cell. The electrolyte should be handled carefully, for sulphuric acid will burn clothing and skin. If the acid does contact the skin the area should be washed thoroughly with water and then bicarbonate of soda applied.

Lead-acid Battery Charging Methods

A storage battery may be charged by passing direct current through the battery in a direction opposite to that of the discharge current. Because of the internal resistance (*IR*) in the battery, the

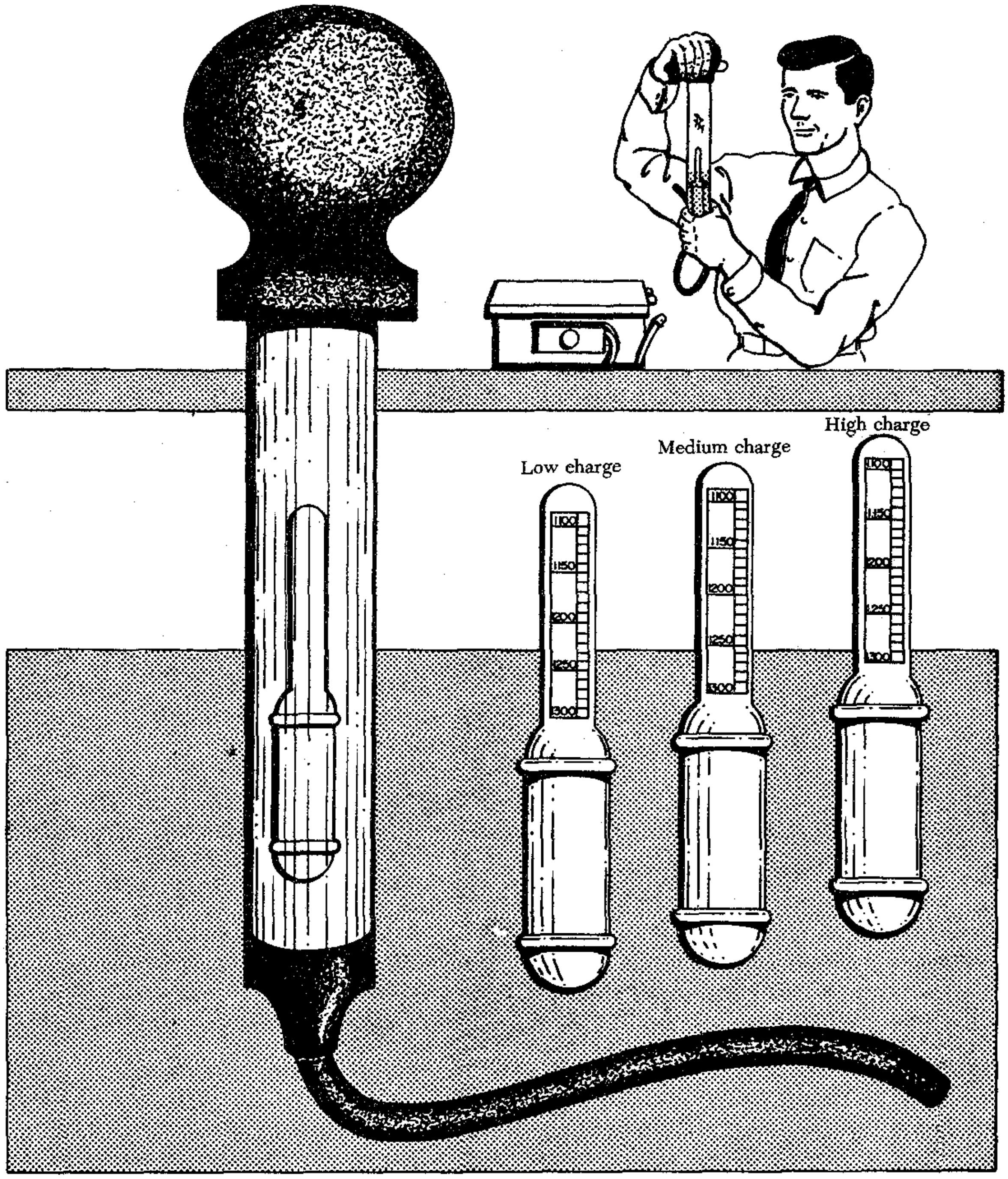


FIGURE 8–109. Hydrometer (specific gravity readings).

voltage of the external charging source must be greater than the open-circuit voltage. For example, the open-circuit voltage of a fully charged 12-cell, lead-acid battery is approximately 26.4 volts (12 × 2.2 volts), but approximately 28 volts are required to charge it. This larger voltage is needed for charging because of the voltage drop in the battery caused by the internal resistance. Hence, the charging voltage of a lead-acid battery must equal the open-circuit voltage plus the *IR* drop within the battery (product of the charging current and the internal resistance).

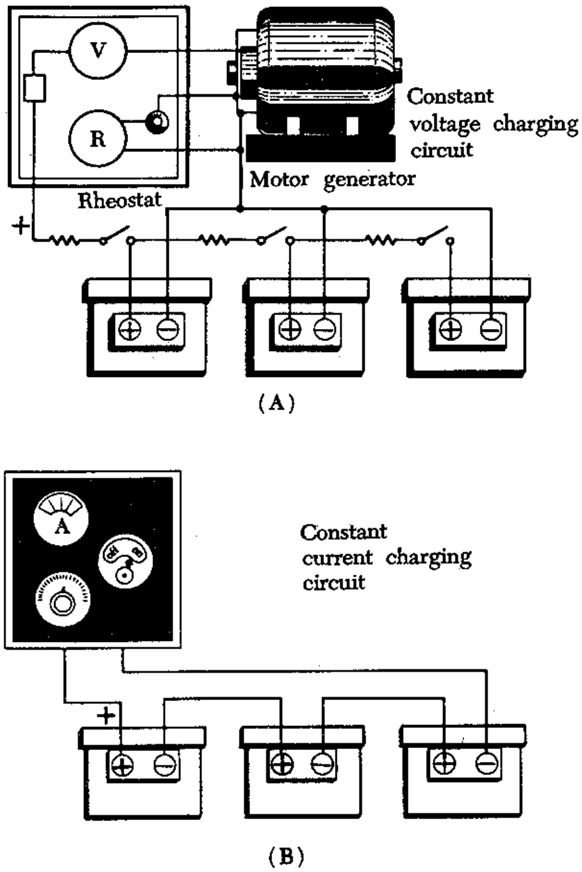


Figure 8–110. Battery charging methods.

Batteries are charged by either the constant-voltage or constant-current method. In the constant-voltage method (A of figure 8–110), a motor-generator set with a constant, regulated voltage forces the current through the battery. In this method, the current at the start of the process is high but automatically tapers off, reaching a value of approximately 1 ampere when the battery is fully charged. The constant-voltage method requires less time and supervision than does the constant-current method.

In the constant-current method (B of figure 8–110), the current remains almost constant during the entire charging process.

This method requires a longer time to charge a battery fully and, toward the end of the process, presents the danger of overcharging, if care is not exercised.

In the aircraft, the storage battery is charged by direct current from the aircraft generator system. This method of charging is the constant-voltage method, since the generator voltage is held constant by use of a voltage regulator.

When a storage battery is being charged, it generates a certain amount of hydrogen and oxygen. Since this is an explosive mixture, it is important that steps be taken to prevent ignition of the gas mixture. The vent caps should be loosened and left in place. No open flames, sparks, or other source of ignition should be permitted in the vicinity. Before disconnecting or connecting a battery to the charge, always turn off the power by means of a remote switch.

NICKEL-CADMIUM BATTERIES

Nickel-cadmium batteries have been available for some time, but they did not come into extensive use in aviation until the increase in the number of commercial and executive jet aircraft made them economically practicable. The many advantages of the nickel-cadmium battery were well known, but its initial cost was several times that of the lead-acid battery. The increasing use of the nickel-cadmium battery (often referred to as "ni-cad") stems largely from the low maintenance cost derived from the long service life of the battery. Additionally, the nickel-cadmium battery has a short recharge time, excellent reliability, and good starting capability.

Nickel-Cadmium Cell Construction

As in the lead-acid type, the cell is the basic unit of the nickel-cadmium battery. It consists of positive and negative plates, separators, electrolyte, cell vent, and cell container. The positive plates are made from a porous plaque on which nickel-hydroxide has been deposited. The negative plates are made from similar plaques on which cadmium-hydroxide is deposited. In both cases the porous plaque is obtained by sintering nickel powder to a fine-mesh wire screen. Sintering is a process which fuses together extremely small granules of powder at a high temperature. After the active positive and negative materials are deposited on the plaque, it is formed and cut into the proper plate size. A nickel tab is then welded to a corner of each plate and the plates are assembled with the tabs welded to the proper terminals. The plates are separated from each other by a continuous strip of porous plastic.

The electrolyte used in the nickel-cadmium battery is a 30 percent solution (by weight) of potassium hydroxide (KOH) in distilled water. The specific gravity of the electrolyte remains between 1.240 and 1.300 at room temperature. No appreciable changes occur in the electrolyte during charge or discharge. As a result, the battery charge cannot be determined by a specific gravity check of the electrolyte. The electrolyte level should be maintained just above the tops of the plates.

Operation of Nickel-Cadmium Cells

When a charging current is applied to a nickel-cadmium battery, the negative plates lose oxygen and begin forming metallic cadmium. The active material of the positive plates, nickel-hydroxide, becomes more highly oxidized. This process continues while the charging current is applied or until all the oxygen is removed from the negative plates and only cadmium remains.

Toward the end of the charging cycle the cells emit gas. This will also occur if the cells are overcharged. This gas is caused by decomposition of the water in the electrolyte into hydrogen at the negative plates and oxygen at the positive plates. The voltage used during charging, as well as the temperature, determines when gassing will occur. To completely charge a nickel-cadmium battery, some gassing, however slight, must take place; thus, some water will be used.

The chemical action is reversed during discharge. The positive plates slowly give up oxygen, which is regained by the negative plates. This process results in the conversion of the chemical energy into electrical energy. During discharge the plates absorb a quantity of the electrolyte. On recharge, the level of the electrolyte rises and, at full charge, the electrolyte will be at its highest level. Therefore, water should be added only when the battery is fully charged.

The nickel-cadmium battery is usually interchangeable with the lead-acid type. When replacing a lead-acid battery with a nickel-cadmium battery, the battery compartment must be clean, dry, and free of all traces of acid from the old battery. The compartment must be washed out and neutralized with ammonia or boric acid solution, allowed to dry thoroughly, and then painted with an alkali-resisting varnish.

The pad in the battery sump jar should be saturated with a three percent (by weight) solution of boric acid and water before connecting the battery vent system.

Servicing Nickel-Cadmium Batteries

There are significant differences in the servicing methods required for the nickel-cadmium batteries and those of the lead-acid batteries. The most important points to be observed are as follows:

(1) A separate storage and maintenance area should be provided for nickel-cadmium batteries. The electrolyte is chemically opposite to the sulphuric acid used in a lead-acid battery. Fumes from a lead-acid battery can contaminate the electrolyte in a nickel-cadmium battery. This precaution should include equipment, such as hand tools and syringes, used with lead-acid batteries. Indeed, every possible precaution must be taken to keep anything containing acid away from the nickel-cadmium battery shop.

(2) The potassium hydroxide electrolyte used in nickel-cadmium batteries is extremely corrosive. Protective goggles, rubber gloves, and rubber aprons should be used to handle and service batteries. Suitable washing facilities should be provided in case electrolyte is spilled on clothing or the skin. Such exposures should be rinsed immediately with water or vinegar, lemon juice, or a boric acid solution. When potassium hydroxide and distilled water are mixed to make electrolyte, the potassium hydroxide should be added slowly to the water, not vice versa.

(3) Severe arcing may result if a wire brush is used to clean a battery. The vent plugs should be closed during the cleaning process and the battery should never be cleaned with acids, solvents, or any chemical solution. Spilled electrolyte can react with carbon dioxide to form crystals of potassium carbonate. These, which are nontoxic and noncorrosive, can be loosened with a fiber brush and wiped off with a damp cloth. When potassium carbonate forms on a properly serviced battery, it may indicate the battery is overcharging because the voltage regulator is out of adjustment.

(4) Additional water should never be added to the battery earlier than three or four hours after it has been fully charged. Should it be necessary to add water, use only distilled or demineralized water.

(5) Since the electrolyte does not react chemically with the cell plates, the specific gravity of the electrolyte does not change appreci-

ably. Thus, it is not possible to determine the state of charge of the battery with a hydrometer; nor can the charge be determined by a voltage test because the voltage of a nickel-cadmium battery remains constant during 90 percent of the discharge cycle.

(6) Nickel-cadmium batteries should be serviced at regular intervals based on experience since water consumption varies with ambient temperature and operating methods. At greater intervals the battery should be removed from the aircraft and given a bench check in the shop. If a battery is completely discharged, some cells may reach zero potential and charge in the reverse direction, affecting the battery in such a manner that it will not retain a full capacity charge. In such cases, the battery should be discharged and each cell short-circuited to obtain a zero potential cell balance before recharging the battery. This process is called "equalization."

(7) Charging can be accomplished by either the constant-voltage or the constant-current method. For the constant potential charging, maintain the charging voltage constant until the charging current decays to 3 amperes or less assuring that the battery cell temperature does not exceed 100° F. For constant current charging start the charge and continue until the voltage reaches the desired potential, then reduce the current level to 4 amperes continuing the charging until its desired voltage or until the battery temperature exceeds 100° F. and the voltage begins to decline.

The troubleshooting chart outlined in figure 8-111 can be used as a guide in troubleshooting battery malfunctions.

CIRCUIT PROTECTIVE AND CONTROL DEVICES

Electricity, when properly controlled, is of vital importance to the operation of aircraft. When it is not properly controlled, it can become dangerous and destructive. It can destroy aircraft components or complete aircraft; it can injure personnel and even cause their death. It is of the greatest importance, then, that all necessary precautions be taken to protect the electrical circuits and units in the aircraft and to keep this force under proper control at all times.

Protective Devices

When an aircraft is built, the greatest care is taken to ensure that each electrical circuit is fully insulated from all others so that the current in a circuit will follow its intended individual path. Once the aircraft is put into service, however, there are many things that can happen to alter the original circuitry. Some of these changes can cause serious trouble if not detected and corrected in time.

Perhaps the most serious trouble in a circuit is a direct short. The term, "direct short," describes a situation in which some point in the circuit, where full system voltage is present, comes in direct contact with the ground or return side of the circuit. This establishes a path for current flow that contains no resistance other than that present in the wires carrying the current, and these wires have very little resistance.

According to Ohm's law, if the resistance in a circuit is small, the current will be great. When a direct short occurs, there will be an extremely heavy current flowing through the wires. Suppose, for instance, that the two leads from a battery to a motor came in contact with each other. Not only would the motor stop running because of the current going through the short, but the battery would become discharged quickly (perhaps destroyed); there would also be danger of fire.

The battery cables in this example would be very large wires, capable of carrying very heavy currents. Most wires used in aircraft electrical circuits are considerably smaller and their current-carrying capacity is quite limited. The size of the wires used in any given circuit is determined by the amount of current the wires are expected to carry under normal operating condidions. Any current flow greatly in excess of normal, such as the case of a direct short, would cause a rapid generation of heat.

If the excessive current flow caused by the short is left unchecked, the heat in the wire will continue to increase until something gives way. Perhaps a portion of the wire will melt and open the circuit so that nothing is damaged other than the wires involved. The probability exists, however, that much greater damage would result. The heat in the wires could char and burn their insulation and that of other wires bundled with them, which could cause more shorts. If a fuel or oil leak is

OBSERVATION	PROBABLE CAUSE	CORRECTIVE ACTION
High trickle charge—When charging at constant voltage of 28.5 (±0.1) volts, current does not drop below 1 amp after a 30-minute charge.	Defective cells.	While still charging, check individual cells. Those below .5 volts are defective and should be replaced. Those between .5 and 1.5 volts may be defective or may be unbalanced, those above 1.5 volts are all right.
High trickle charge after replacing defective cells, or battery fails to meet amp-hour capacity check.	Cell imbalance.	Discharge battery and short out individual cells for eight hours. Charge battery using constant current method. Check capacity and if O.K., recharge using constant current method.
Battery fails to deliver rated capacity.	Cell imbalance or faulty cells.	Repeat capacity check, discharge and constant current charge a maximum of three times. If capacity does not develop, replace faulty cells.
No potential available.	Complete battery failure.	Check terminals and all electrical connections. Check for dry cell. Check for high trickle charge.
Excessive white crystal deposits on cells. (There will always be some potassium carbonate present due to normal gassing.)	Excessive spewage.	Battery subject to high charge current, high temperature or high liquid level. Clean battery, constant current charge and check liquid level. Check charger operation.
Distortion of cell case.	Overcharge or high heat.	Replace cell.
Foreign material in cells—black or gray particles.	Impure water, high heat, high concentration of KOH or improper water level.	Adjust specific gravity and electrolyte level. Check battery for cell imbalance or replace defective cell.
Excessive corrosion of hardware.	Defective or damaged plating.	Replace parts.
Heat or blue marks on hardware.	Loose connections causing overheating of intercell connector or hardware.	Clean hardware and properly torque connectors.
Excessive water consumption. Dry cell.	Cell imbalance.	Proceed as above for cell imbalance.

FIGURE 8–111. Nickel-cadmium troubleshooting chart.

near any of the hot wires, a disastrous fire might be started.

To protect aircraft electrical systems from damage and failure caused by excessive current, several kinds of protective devices are installed in the systems. Fuses, circuit breakers, and thermal protectors are used for this purpose.

Circuit protective devices, as the name implies, all have a common purpose—to protect the units and the wires in the circuit. Some are designed primarily to protect the wiring and to open the circuit in such a way as to stop the current flow when the current becomes greater than the wires can safely carry. Other devices are designed to protect a unit in the circuit by stopping the current flow to it when the unit becomes excessively warm.

Fuses

A fuse is a strip of metal that will melt when current in excess of its carefully determined capacity flows through it. The fuse is installed in the circuit so that all the current in the circuit passes through it. In most fuses, the strip of metal is made of an alloy of tin and bismuth. Other fuses are made of copper and are called current limiters; these are used primarily to sectionalize an aircraft circuit.

A fuse melts and breaks the circuit when the current exceeds the rated capacity of the fuse, but a current limiter will stand a considerable overload for a short period of time. Since the fuse is intended to protect the circuit, it is quite important that its capacity match the needs of the circuit in which it is used. When a fuse is replaced, the applicable manufacturer's instructions should be consulted to be sure a fuse of the correct type and capacity is installed. Fuses are installed in two type fuse holders in aircraft. "Plug-in holders" are used for small type and low capacity fuses. "Clip" type holders are used for heavy high capacity fuses and current limiters.

Circuit Breakers

A circuit breaker is designed to break the circuit and stop the current flow when the current exceeds a predetermined value. It is commonly used in place of a fuse and may sometimes eliminate the need for a switch. A circuit breaker differs from a fuse in that it "trips" to break the circuit and it may be reset, while a fuse melts and must be replaced.

There are several types of circuit breakers in general use in aircraft systems. One is a magnetic type. When excessive current flows in the circuit, it makes an electromagnet strong enough to move a small armature which trips the breaker. Another type is the thermal overload switch or breaker. This consists of a bimetallic strip which, when it becomes overheated from excessive current, bends away from a catch on the switch lever and permits the switch to trip open.

Most circuit breakers must be reset by hand. When the circuit breaker is reset, if the overload condition still exists, the circuit breaker will trip again to prevent damage to the circuit.

Thermal Protectors

A thermal protector, or switch, is used to protect a motor. It is designed to open the circuit automatically whenever the temperature of the motor becomes excessively high. It has two positions, open and closed. The most common use for a thermal switch is to keep a motor from overheating. If a malfunction in the motor causes it to overheat, the thermal switch will break the circuit intermittently.

The thermal switch contains a bimetallic disk, or strip, which bends and breaks the circuit when it is heated. This occurs because one of the metals expands more than the other when they are subjected to the same temperature. When the strip or disk cools, the metals contract and the strip returns to its original position and closes the circuit.

Control Devices

The units in the electrical circuits in an aircraft are not all intended to operate continuously or automatically. Most of them are meant to operate at certain times, under certain conditions, to perform very definite functions. There must be some means of controlling their operation. Either a switch or a relay, or both, may be included in the circuit for this purpose.

SWITCHES

Switches control the current flow in most aircraft electrical circuits. A switch is used to start, to stop, or to change the direction of the current flow in the circuit. The switch in each circuit must be able to carry the normal current of the circuit and must be insulated heavily enough for the voltage of the circuit.

Knife switches are seldom used on aircraft. They

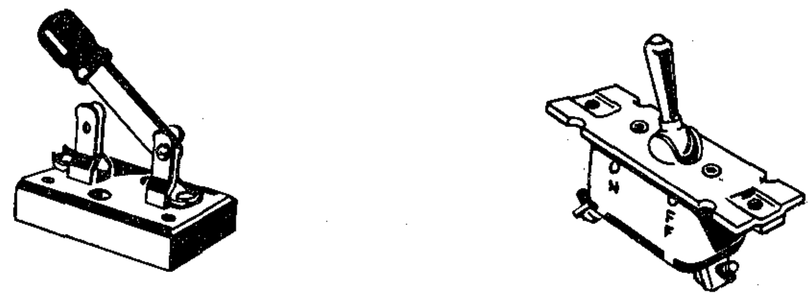


FIGURE 8–112. Single-pole single-throw knife and toggle switches.

are included here to simplify the operation of the toggle switch. Toggle switches operate much the same as knife switches, but their moving parts are enclosed. They are used in aircraft circuits more than any other kind of switch.

Toggle switches, as well as some other type of switches, are designated by the number of poles, throws, and positions they have. A pole of a switch is its movable blade or contactor. The number of poles is equal to the number of circuits, or paths for current flow, that can be completed through the switch at any one time. The throw of a switch indicates the number of circuits, or paths for current, that it is possible to complete through the switch with each pole or contactor. The number of positions a switch has is the number of places at which the operating device (toggle, plunger, etc.) will come to rest and at the same time open or close one or more circuits.

As shown in figure 8–112, when it is possible to complete only one circuit through a switch, the switch is a single-pole single-throw (spst) switch. A single-pole switch through which two circuits can be completed (not at the same time) is a single-pole double-throw (spdt) switch. (See figure 8–113.)

A switch with two contactors, or poles, each of which completes only one circuit, is a double-pole single-throw (dpst) switch. Double-pole single-throw knife and toggle switches are illustrated in figure 8–114.

A double-pole switch that can complete two circuits, one circuit at a time through each pole, is a double-pole double-throw (dpdt) switch. Both a knife and a toggle switch illustrating this type of switch are shown in figure 8–115.

The schematic representations for the most commonly used switches are shown in figure 8–116.

A toggle switch that is spring-loaded to the OFF position and must be held in the ON position to complete the circuit is a momentary contact two-position switch. One that will come to rest at either of two positions, opening the circuit in one position and closing it in another, is a two-position switch. A toggle switch that will come to rest at any one of three positions is a three-position switch.

A switch that stays open, except when it is held in the closed position, is a normally open switch (usually identified as NO). One that stays closed, except when it is held in the open position, is a normally closed switch (NC). Both kinds are spring-loaded to their normal position and will return to that position as soon as they are released.

Push-Button Switches

Push-button switches have one stationary contact and one movable contact. The movable

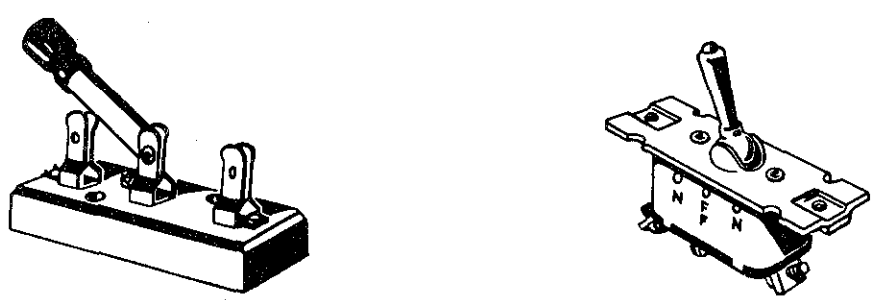


FIGURE 8–113. Single-pole double-throw knife and toggle switches.

FIGURE 8–114. Double-pole single-throw knife and toggle switches.

contact is attached to the push button. The push button is either an insulator itself or is insulated from the contact. This switch is spring-loaded and designed for momentary contact.

Microswitches

A microswitch will open or close a circuit with a very small movement of the tripping device (1/16 inch or less). This is what gives the switch its name, since micro means small.

Microswitches are usually push-button switches. They are used primarily as limit switches to provide automatic control of landing gears, actuator motors, and the like. The diagram in figure 8–117 shows a normally closed microswitch in cross section and illustrates how these switches operate. When the operating plunger is pressed in, the spring and the movable contact are pushed, opening the contacts and the circuit.

Rotary-Selector Switches

A rotary-selector switch takes the place of several switches. As shown in figure 8–118, when the knob of the switch is rotated, the switch opens one circuit and closes another. Ignition switches and voltmeter selector switches are typical examples of this kind of switch.

Relays

Relays, or relay switches, are used for remote control of circuits carrying heavy currents, A relay is connected in the circuit between the unit controlled and the nearest source of power (or power bus bar) so that the cables carrying heavy current will be as short as possible.

A relay switch consists of a coil, or solenoid, an iron core, and both fixed and movable contacts. A small wire connects one of the coil terminals (which is insulated from the housing) to the source of power through a control switch usually located in the cockpit. The other coil terminal is usually grounded to the housing. When the control switch is closed, an electromagnetic field is set up around the coil.

In one type of relay switch, an iron core is fixed firmly in place inside the coil. When the control switch is closed, the core is magnetized and pulls a soft iron armature toward it, closing the main contacts. The contacts are spring-loaded to the open position as shown in figure 8–119. When the control switch is turned off, the magnetic field collapses and the spring opens the contacts.

In another type of relay switch, part of the core is movable. A spring holds the movable part a short distance away from the fixed part, as illus-

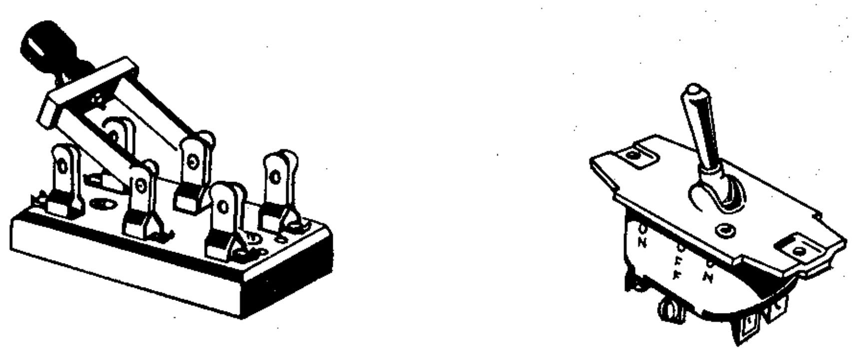


FIGURE 8–115. Double-pole double-throw knife and toggle switches.

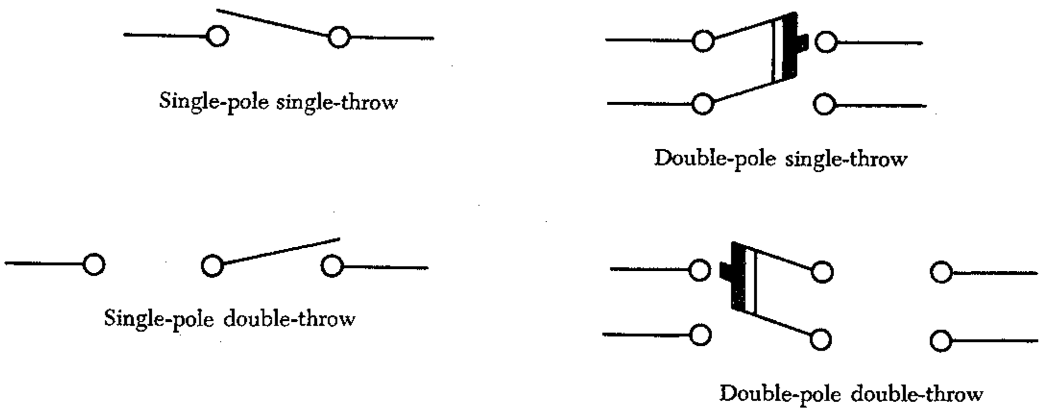


FIGURE 8–116. Schematic representation for typical switches.

trated in figure 8–120. When the coil is energized, the magnetic field tries to pull the movable part of the core into the coil. This pull overcomes the spring tension. As the core moves inward, it brings the movable contacts, which are attached to but insulated from it, down against the stationary contacts. This completes the main circuit. When the control switch is turned off, the magnetic field collapses and the spring returns the movable core to its original position, opening the main contacts.

Relays vary in construction details according to their intended use. When selecting a relay to be installed in a circuit, make sure it is designed for the job it is intended to do.

Some relay switches are made to operate continuously, while others are designed to operate only intermittently. The starter-relay switch is made to operate intermittently and would overheat if used continuously. The battery-relay switch can be operated continuously because its coil has a fairly high resistance which prevents overheating.

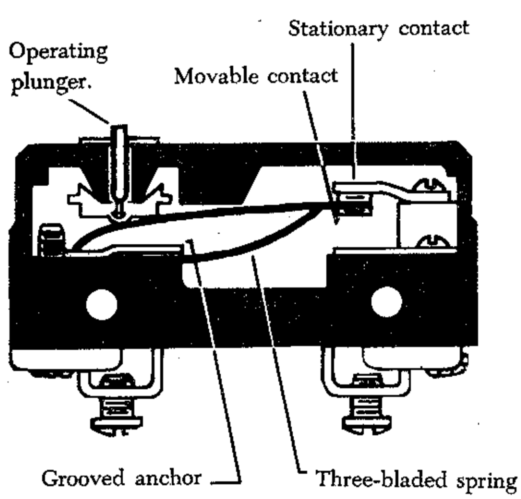


FIGURE 8–117. Cross section of a microswitch.

In a circuit carrying a large current, the more quickly the circuit is opened the less it will arc at the relay, and the less the switch contacts will be burned. Relays used in circuits with large motors have strong return springs to open the circuit quickly.

Most of the relays use in the a.c. circuitry of an aircraft are energized by d.c. current. These devices will be discussed, as necessary, in the appropriate areas covering alternating current devices.

D. C. MEASURING INSTRUMENTS

Understanding the functional design and operation of electrical measuring instruments is very important, since they are used in repairing, maintaining, and troubleshooting electrical circuits. While some meters can be used for both d.c. and a.c. circuit measurement, only those used as d.c. instruments are discussed in this section. The meters used for a.c., or for both a.c. and d.c., are discussed in the study of a.c. theory and circuitry.

Effects of Current

The effect of current may be classified as follows: chemical, physiological, photoelectric, piezoelectric, thermal, or electromagnetic.

Chemical

When an electric current is passed through certain solutions, a chemical reaction takes place and

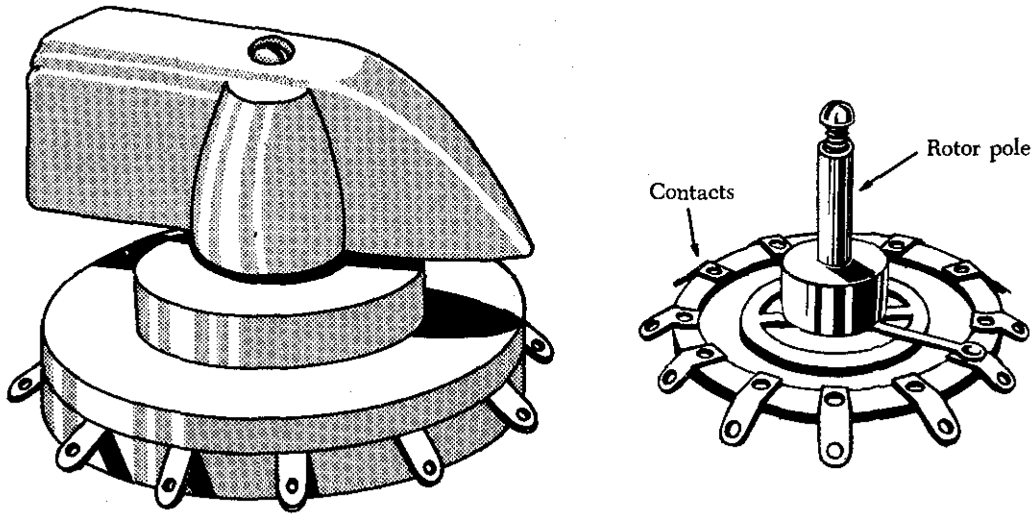


FIGURE 8–118. Rotary-selector switch.

a deposit forms on one electrode. The amount of this deposit is proportional to the amount of current. Industrially, this process is useful in electroplating and electrolysis. Although the chemical effect is useful in defining the standard ampere (the amount of current which causes .001118 grams of silver to be deposited in one second from a 15 percent solution of silver nitrate), it is of no practical use in meters.

Physiological

The physiological effect of current refers to the reaction of the human body to an electric current. An electric shock, although painful at times, is too difficult to evaluate quantitatively and is, therefore, not practical for use in meters.

Photoelectric

When electrons strike certain materials, a glow appears at the point of contact. The picture tube of a television set and the scope of a radar set illustrate this effect. Using the intensity of the light produced as a means of measuring the amount of current is neither accurate nor practical.

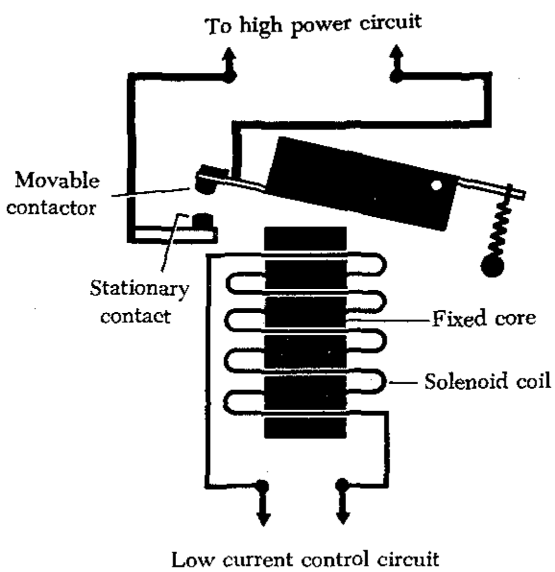


FIGURE 8–119. Fixed-core relay.

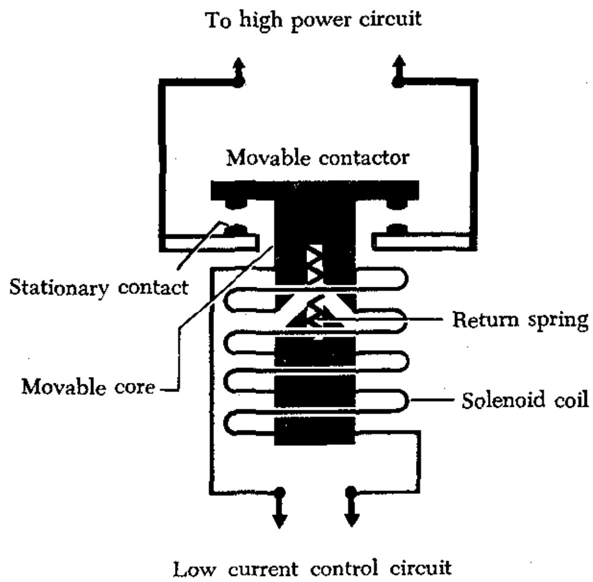


FIGURE 8–120. Movable-core relay.

Piezoelectric

Certain crystals such as quartz and Rochelle salts become deformed when a voltage is applied across two of the crystal faces. This effect is not visible to the human eye and is, therefore, impractical for use in meters.

Thermal

When a current flows through a resistance, heat is produced. The amount of heat produced is equal to I^2R. This relationship establishes that heat varies as the square of the current. Meters which employ the thermal effect in their operation are common.

Electromagnetic

Whenever electrons flow through a conductor, a magnetic field proportional to the current is created. This effect is useful for measuring current and is employed in many practical meters.

The first four effects discussed are of no practical importance as electrical measuring devices. The last two effects, thermal and magnetic, are of practical use in meters. Since most of the meters in use have D'Arsonval movements, which operate because of the magnetic effect, only this type will be discussed in detail.

D'Arsonval Meter

The basic d.c. meter movement is known as the D'Arsonval meter movement because it was first employed by the French scientist, D'Arsonval, in making electrical measurement. This type of meter movement is a current-measuring device which is used in the ammeter, voltmeter, and ohmmeter. Basically, both the ammeter and the voltmeter are current-measuring instruments, the principal difference being the method in which they are connected in a circuit. While an ohmmeter is also basically a current-measuring instrument, it differs from the ammeter and voltmeter in that it provides its own source of power and contains other auxiliary circuits.

Ammeter

The D'Arsonval ammeter is an instrument designed for measuring direct current flowing in an electrical circuit and consists of the following parts: a permanent magnet, a moving element

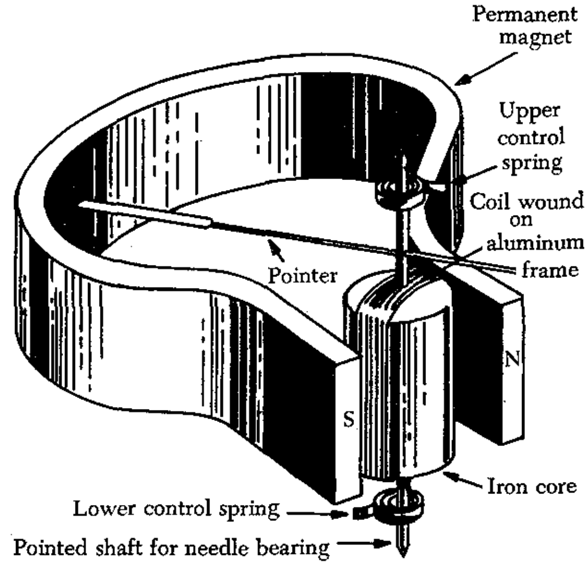


FIGURE 8–121. Moving-coil element with pointer and springs.

mounting, bearings, and a case which includes terminals, a dial, and screws. Each part and its function are described in the discussion which follows.

The permanent magnet furnishes a magnetic field which will react with the magnetic field set up by the moving element.

The moving element is mounted so that it is free to rotate when energized by the current to be measured. A pointer which moves across a calibrated scale is attached to this element. A moving-coil mechanism is shown in figure 8–121. The controlling element is a spring, or springs, whose main function is to provide a counter or restoring force. The strength of this force increases with the turning of the moving element and brings the pointer to rest at some point on the scale. Two springs are generally used; they are wound in opposite drections to compensate for the expansion and contraction of the spring material due to temperature variation. The springs are made of nonmagnetic material and conduct current to and from the moving coil in some meters.

The moving element consists of a shaft with very hard pivot points to carry the moving coil or other movable element (figure 8–121). The pivot points are so fitted into highly polished jewels or very hard glass bearings that the moving element can rotate with very little friction. Another type of mounting has been

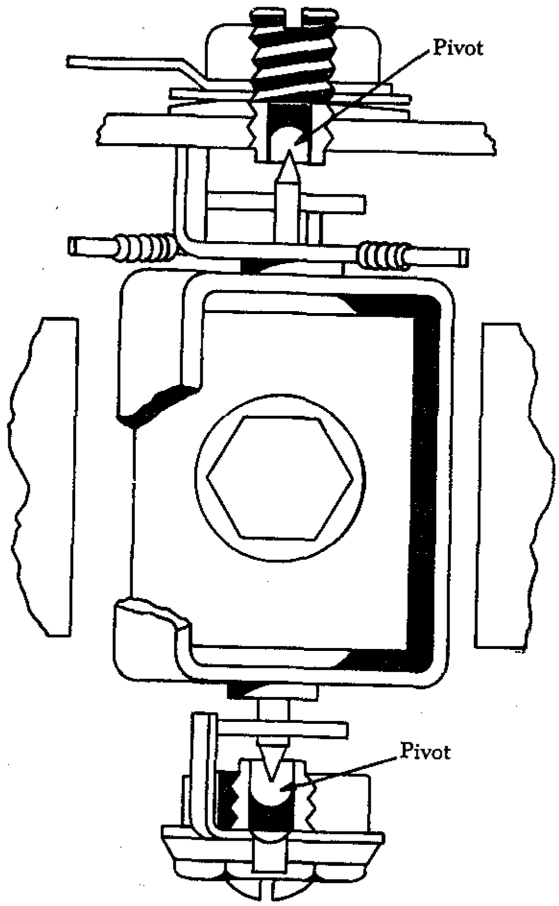


FIGURE 8–122. Method of mounting moving elements.

designed in which the pivot points are reversed and the bearings are inside the moving-coil assembly. A method of mounting moving elements is shown in figure 8–122.

The bearings are highly polished jewels such as sapphires, synthetic jewels, or very hard glass. These are usually round and have a conical depression in which the pivots rotate. They are set in threaded nuts which allow adjustment. The radius of the depression in the jewel is greater than the radius of the pivot point. This limits the area of contact surfaces and provides a bearing which, when operated dry, probably has the lowest constant friction value of any known type of bearing.

The case houses the instrument movement and protects it from mechanical injury and exposure. It also has a window for viewing the movement of the pointer across a calibrated scale. The dial has printed on it pertinent information such as the

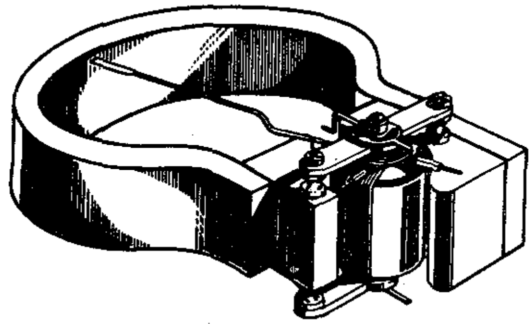


FIGURE 8–123. D'Arsonval meter movement.

scale, units of measurement, and meter uses. The terminals are made of materials having very low electrical resistance. Their function is to conduct the required current into and away from the meter.

Operation of the Meter Movement

The major units are mounted in their relationship to one another (figure 8–123). Note that the coil portion of the moving element is in the magnetic field of the permanent magnet.

In order to understand how the meter works, assume that the coil of the moving element is placed in a magnetic field as shown in figure 8–124.

The coil is pivoted so that it is able to rotate back and forth within the magnetic field set up by the magnet. When the coil is connected in a circuit, current flows through the coil in the direction indicated by the arrows and sets up a magnetic field within the coil. This field has the same polarity as the adjacent poles of the magnet. The interaction of the two fields causes the coil to rotate to a position so that the two magnetic fields are aligned. This force of rotation (torque) is proportional to the interaction between the like poles of the coil and the magnet and, therefore, to

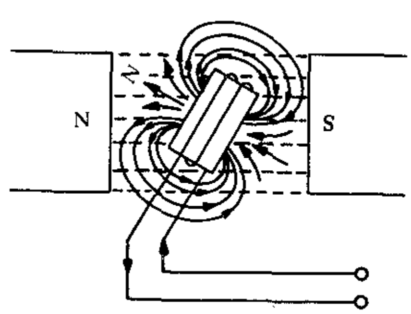


FIGURE 8–124. Effect of a coil in a magnetic field.

the amount of current flow in the coil. As a result, a pointer attached to the coil will indicate the amount of current flowing in the circuit as it moves across a graduated scale.

In the arrangement just discussed, note that any torque sufficient to overcome the inertia and friction of moving parts causes the coil to rotate until the fields align. This uncontrolled movement would cause inaccruate current readings. Therefore, the turning motion of the coil is opposed by two springs. The value of the current flowing through the coil determines the turning force of the coil. When the turning force is equal to the opposition of the springs, the coil stops moving and the pointer indicates the current reading on a calibrated scale. In some meters the springs are made of conducting material and conduct current to and from the coil. The pole pieces of the magnet form a circular air gap within which the coil is pivoted.

To obtain a clockwise rotation, the north pole of the permanent magnet and that of the coil must be adjacent. The current flowing through the coil must, therefore, always be in the same direction. The D'Arsonval movement can be used only for d.c. measurements and the correct polarity must be observed. If the current is allowed to flow in the wrong direction through the coil, the coil will rotate counterclockwise and the pointer will be damaged. Since the movement of the coil is directly proportional to the current through the coil, the scale is normally a linear scale.

Damping

In order that meter readings can be made quickly and accurately, it is desirable that the moving pointer overshoot its proper position only a small amount and come to rest after not more than one or two small oscillations. The term "damping" is applied to methods used to bring the pointer of an electrical meter to rest after it has been set in motion. Damping may be accomplished by electrical means, by mechanical means, or by a combination of both.

Electrical Damping

A common method of damping by electrical means is to wind the moving coil on an aluminum frame. As the coil moves in the field of the permanent magnet, eddy currents are set up in the aluminum frame. The magnetic field produced by the eddy currents opposes the motion of the coil. The pointer will therefore swing more slowly to its proper position and come to rest quickly with very little oscillation.

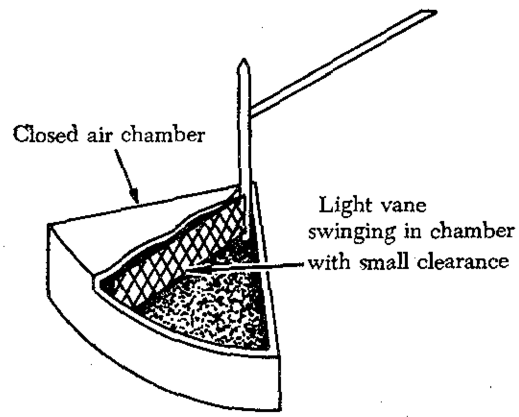


FIGURE 8–125. Air damping.

Mechanical Damping

Air damping is a common method of damping by mechanical means. As shown in figure 8–125, a vane is attached to the shaft of the moving element and enclosed in an air chamber. The movement of the shaft is retarded because of the resistance which the air offers to the vane. Effective damping is achieved if the vane nearly touches the walls of the chamber.

Meter Sensitivity

The sensitivity of a meter movement is usually expressed as the amount of current required to give full-scale deflection. In addition, the sensitivity may be expressed as the number of millivolts across the meter when full-scale current flows through it. This voltage drop is obtained by multiplying the full-scale current by the resistance of the meter movement. A meter movement, whose resistance is 50 ohms and which requires 1 milliampere (ma.) for full-scale reading, may be described as a 50-millivolt 0–1 milliammeter.

Extending the Range of an Ammeter

A 0–1 milliammeter movement may be used to measure currents greater than 1 ma. by connecting a resistor in parallel with the movement. The parallel resistor is called a shunt because it bypasses a portion of the current around the movement, extending the range of the ammeter.

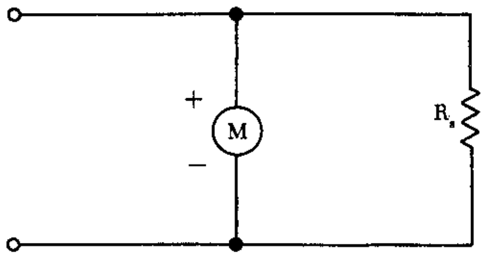


FIGURE 8–126. Meter movement with shunt.

A schematic drawing of a meter movement with a shunt connected across it to extend its range is shown in figure 8–126.

Determining the Value of a Shunt

The value of a shunt resistor can be computed by applying the basic rules for parallel circuits. If a 50 millivolt 0–1 milliammeter is to be used to measure values of current up to 10 ma., the following procedure can be used: The first step involves drawing a schematic of the meter shunted by a resistor labeled R_s (shunt resistor), as shown in figure 8–127.

Since the sensitivity of the meter is known, the meter resistance can be computed. The circuit is then redrawn as shown in figure 8–128, and the branch currents can be computed, since a maximum of 1 ma. can flow through the meter. The voltage drop across R_s is the same as that across the meter, R_m:

$$E = IR$$

$$= 0.001 \times 50$$

$$= 0.050 \text{ volt.}$$

R_s can be found by applying Ohm's law:

$$R_s = \frac{E_{rs}}{I_{rs}}$$

$$= \frac{0.050}{0.009}$$

$$= 5.55 \text{ ohms.}$$

The value of the shunt resistor (5.55 Ω) is very small, but this value is critical. Resistors used as shunts musts must have close tolerances, usually 1 percent.

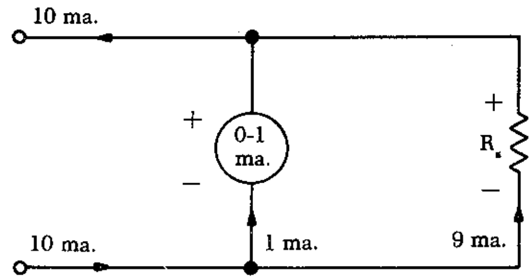


FIGURE 8–127. Circuit schematic for shunt resistor.

Universal Ammeter Shunt

The schematic drawing in figure 8–129, the universal shunt, shows an arrangement whereby two or more ranges are provided by tapping the shunt resistor at the proper points. In this arrangement, a 0–5 ma. movement with a resistance of 20 ohms is shunted to provide a 0–25 ma. range and a 0–50 ma. range.

Ammeters having a number of internal shunts are called multirange ammeters. A scale for each range is provided on the meter face (figure 8–130). Some multimeters avoid internal switching through the use of external shunts. Changing ammeter ranges involves the selection and installation on the meter case of the proper size shunt.

MULTIMETERS

Ammeters are commonly incorporated in multiple-purpose instruments such as multimeter or volt-ohm-milliammeters. These instruments vary somewhat according to the design used by different manufacturers, but most incorporate the functions of an ammeter, a voltmeter, and an ohmmeter in one unit. A typical multimeter is shown in figure 8–131. This multimeter has two

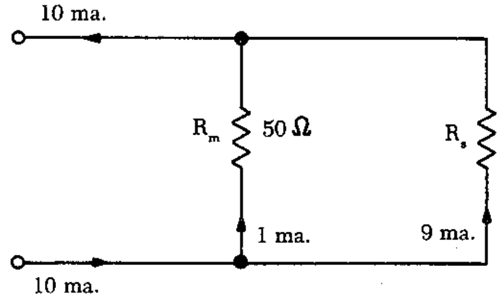


FIGURE 8–128. Equivalent meter circuit.

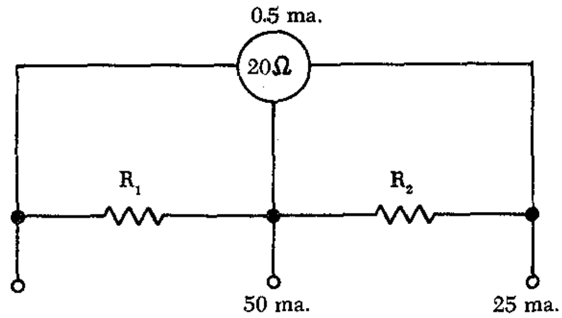


FIGURE 8–129. Universal ammeter shunt.

selector switches: a function switch and a range switch. Since a multimeter is actually three meters in one case, the function switch must be placed in proper position for the type of measurement to be made. In figure 8–131, the function switch is shown in the ammeter position to measure d.c. milliamperes and the range switch is set at 1000. Set in this manner, the ammeter can measure up to 1,000 milliamperes or 1 ampere.

Multimeters have several scales, and the one used should correspond properly to the position of the range switch. If current of unknown value is to be measured, always select the highest possible range to avoid damage to the meter. The test leads should always be connected to the meter in the manner prescribed by the manufacturer. Usually the red lead is positive and the black lead is negative, or common. Many multimeters employ color coded jacks as an aid

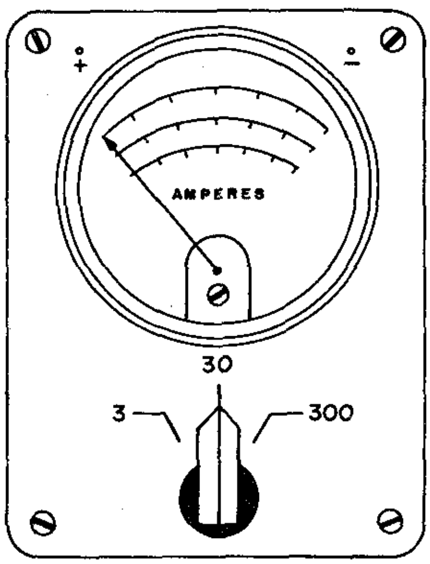


FIGURE 8–130. A multirange ammeter.

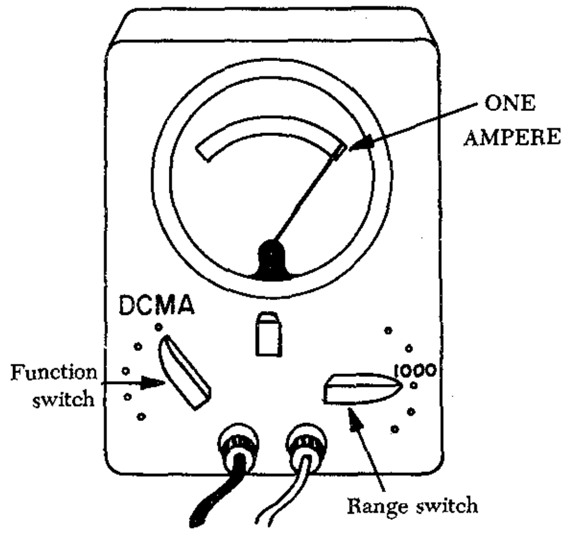


FIGURE 8–131. A multimeter set to measure one ampere.

in connecting the meter into the circuit to be tested. In figure 8–132, a multimeter properly set to measure current flow is connected into a circuit.

The precautions to be observed when using an ammeter are summarized as follows:

1. Always connect an ammeter in series with the element through which the current flow is to be measured.
2. Never connect an ammeter across a source of voltage, such as a battery or generator. Remember that the resistance of an ammeter, particularly on the higher ranges, is extremely low and that any voltage, even a volt or so, can cause very high current to flow through the meter, causing damage to it.
3. Use a range large enough to keep the deflection less than full scale. Before measuring a current, form some idea of its magnitude. Then switch to a large enough scale or start with the highest range and work down until the appropriate scale is reached. The most accurate readings are obtained at approximately half-scale deflection. Many milliammeters have been ruined by attempts to measure amperes. Therefore, be sure to read the lettering either on the dial or on the switch positions and choose proper scale before connecting the meter in the circuit.
4. Observe proper polarity in connecting the meter in the circuit. Current must flow

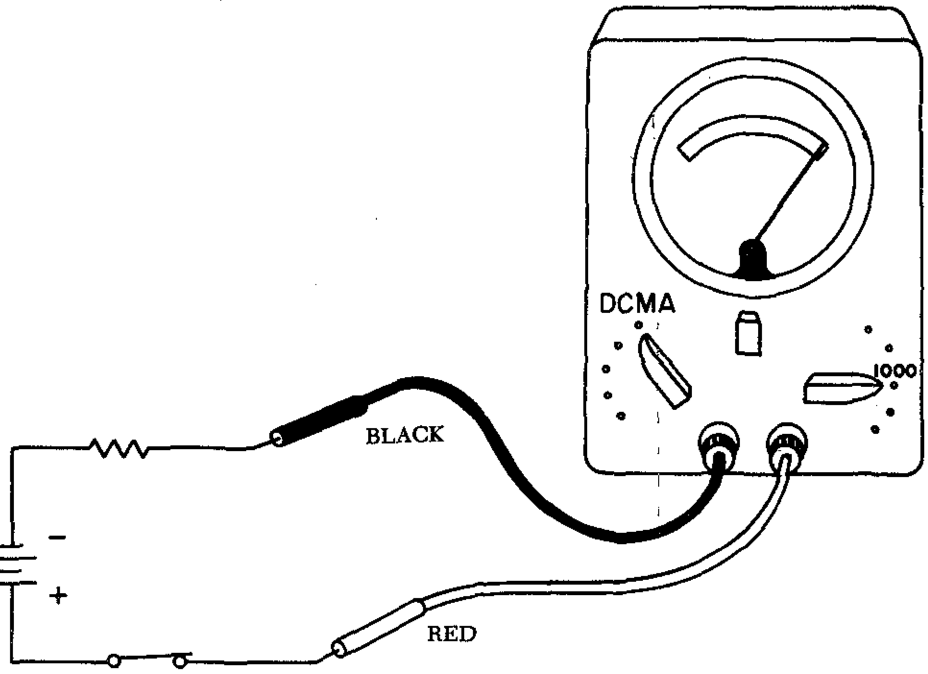


FIGURE 8–132. A multimeter set to measure current flow.

through the coil in a definite direction in order to move the indicator needle up-scale. Current reversal because of incorrect connection in the circuit results in a reversed meter deflection and frequently causes bending of the meter needle. Avoid improper meter connections by observing the polarity markings on the meter.

VOLTMETER

The D'Arsonval meter movement can be used either as an ammeter or a voltmeter (figure 8–133). Thus, an ammeter can be converted to a voltmeter by placing a resistance in series with the meter coil and measuring the current flowing through it. In other words, a voltmeter is a current-measuring instrument, designed to indicate voltage by measuring the current flow through a resistance of known value. Various voltage ranges can be obtained by adding resistors in series with the meter coil. For low-range instruments, this resistance is mounted inside the case with the D'Arsonval movement and usually consists of resistance wire having a low temperature coefficient which is wound either on spools or card frames. For higher voltage ranges, the series resistance may be connected externally. When this is done, the unit containing the resistance is commonly called a multiplier.

Extending the Voltmeter Range

The value of the necessary series resistance is determined by the current required for full-scale deflection of the meter and by the range of voltage

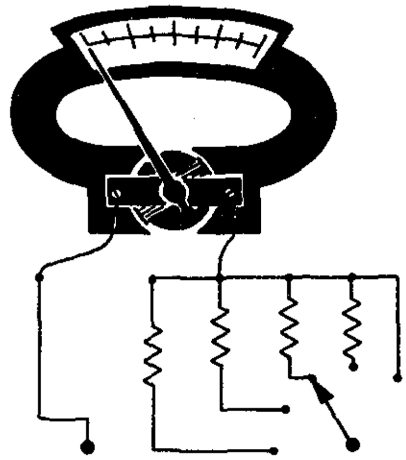


FIGURE 8–133. Simplified diagram of a voltmeter.

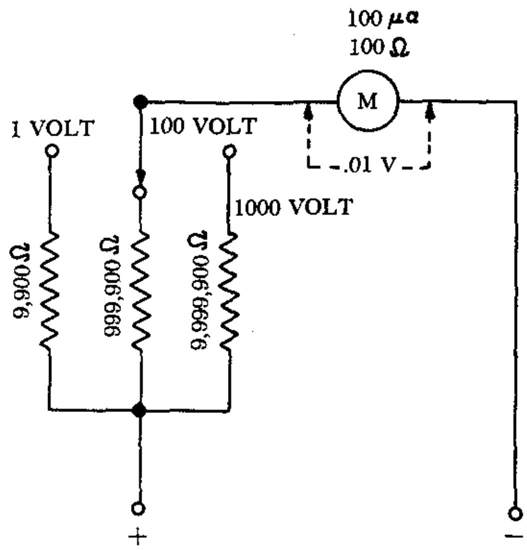


FIGURE 8–134. Multirange voltmeter schematic.

to be measured. Because the current through the meter circuit is directly proportional to the applied voltage, the meter scale can be calibrated directly in volts for a fixed series resistance.

For example, assume that the basic meter (microammeter) is to be made into a voltmeter with a full-scale reading of 1 volt. The coil resistance of the basic meter is 100 ohms, and 0.0001 ampere (100 microamperes) causes a full-scale deflection. The total resistance, R, of the

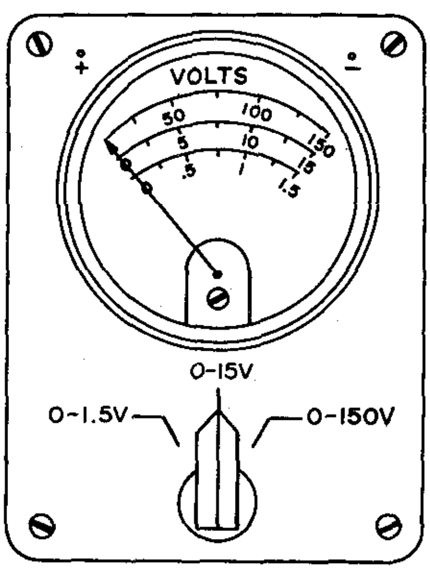


FIGURE 8–135. Typical multirange voltmeter.

meter coil and the series resistance is

$$R = \frac{E}{I} = \frac{1}{0.0001} = 10{,}000 \text{ ohms},$$

and the series resistance alone is

$$R_s = 10{,}000 - 100 = 9{,}900 \text{ ohms}.$$

Multirange voltmeters utilize one meter movement with the required resistances connected in series with the meter by a convenient switching arrangement. A multirange voltmeter circuit with three ranges is shown in figure 8–134. The total circuit resistance for each of the three ranges beginning with the 1-volt range is:

$$R = \frac{E}{I} = \frac{1}{100} = 0.01 \text{ megohm}$$

$$\frac{100}{100} = 1 \text{ megohm}$$

$$\frac{1{,}000}{100} = 10 \text{ megohms}.$$

Multirange voltmeters, like multirange ammeters, are used frequently. They are physically very similar to ammeters, and their multipliers are usually located inside the meter with suitable switches or sets of terminals on the outside of the meter for selecting ranges (see figure 8–135).

Voltage-measuring instruments are connected across (in parallel with) a circuit. If the approximate value of the voltage to be measured is not known, it is best, as in using the ammeter, to start with the highest range of the voltmeter and progressively lower the range until a suitable reading is obtained.

In many cases, the voltmeter is not a central-zero indicating instrument. Thus, it is necessary to observe the proper polarity when connecting the instrument to the circuit, as is the case when connecting the d.c. ammeter. The positive terminal of the voltmeter is always connected to the positive terminal of the source, and the negative terminal to the negative terminal of the source, when the source voltage is being measured. In any case, the voltmeter is connected so that electrons will flow into the negative terminal and out of the positive terminal of the meter. In figure 8–136 a multimeter is properly connected to a circuit to measure the voltage drop across a resistor. The function switch is set at the d.c. volts position and the range switch is placed in the 50-volt position.

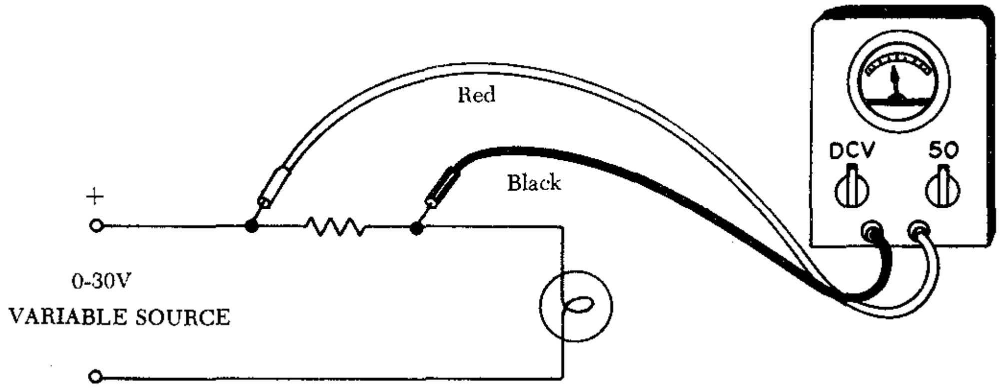


FIGURE 8–136. A multimeter connected to measure a circuit voltage drop.

The function of a voltmeter is to indicate the potential difference between two points in a circuit. When the voltmeter is connected across a circuit, it shunts the circuit. If the voltmeter has low resistance, it will draw an appreciable amount of current. The effective resistance of the circuit will be lowered, and the voltage reading will consequently be lowered.

When voltage measurements are made in high-resistance circuits, it is necessary to use a high-resistance voltmeter to prevent the shunting action of the meter. The effect is less noticeable in low-resistance circuits because the shunting effect is less.

Voltmeter Sensitivity

The sensitivity of a voltmeter is given in ohms per volt (Ω/E) and is determined by dividing the resistance (R_m) of the meter plus the series resistance (R_s) by the full-scale reading in volts. Thus,

$$\text{sensitivity} = \frac{R_m + R_s}{E}.$$

This is the same as saying that the sensitivity is equal to the reciprocal of the current (in amperes); that is,

$$\text{sensitivity} = \frac{\text{ohms}}{\text{volts}} = \frac{1}{\frac{\text{volts}}{\text{ohms}}} = \frac{1}{\text{amperes}}$$

Thus, the sensitivity of a 100-microampere movement is the reciprocal of 0.0001 ampere, or 10,000 ohms per volt.

The sensitivity of a voltmeter can be increased by increasing the strength of the permanent magnet, by using lighter weight materials for the moving element (consistent with increased number of turns on the coil), and by using sapphire jewel bearings to support the moving coil.

Voltmeter Accuracy

The accuracy of a meter is generally expressed in percent. For example, a meter with an accuracy of 1 percent will indicate a value within 1 percent of the correct value. The statement means that, if the correct value is 100 units, the meter indication may be anywhere within the range of 99 to 101 units.

OHMMETERS

Two instruments are commonly used to check the continuity or to measure the resistance of a circuit or circuit element. These instruments are the ohmmeter and the megger, or megohmmeter. The ohmmeter is widely used to measure resistance and to check the continuity of electrical circuits and devices. Its range usually extends to a few megohms. The megger is widely used for measuring insulation resistance, such as the resistance between the windings and the frame of electric machinery, and for measuring the insulation resistance of cables, insulators, and bushings. Its range may extend to more than 1,000 megohms. When measuring very high resistances of this nature, it is not necessary to find the exact value of resistance, but rather to know that the insulation is either above or below a certain standard. When precision measurements are required, some type of bridge circuit is used. Ohmmeters may be of the series or shunt type.

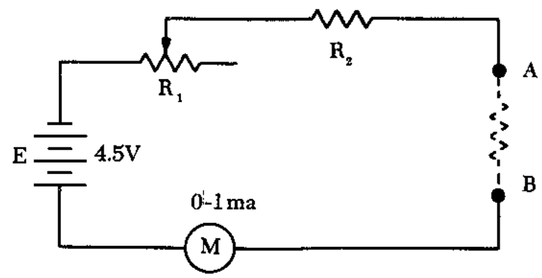


FIGURE 8–137. Ohmmeter circuit.

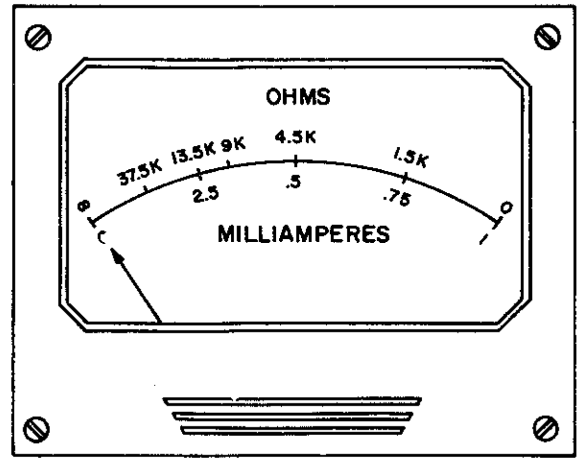


FIGURE 8–138. A typical ohmmeter scale.

Series-type Ohmmeters

A simplified schematic of an ohmmeter is shown in figure 8–137. E is a source of EMF; R_1 is a variable resistor used to zero the meter; R_2 is a fixed resistor used to limit the current in the meter movement; and A and B are test terminals across which the resistance to be measured is placed.

If A and B are connected together (short-circuited), the meter, the battery, and resistors R_1 and R_2 form a simple series circuit. With R_1 adjusted so that the total resistance in the circuit is 4,500 ohms, the current through the meter is 1 ma. and the needle deflects full scale. Since there is no resistance between A and B, this position of the needle is labeled zero (figure 8–138). If a resistance equal to 4,500 ohms is placed between terminals A and B, the total resistance is 9,000 ohms and the current is .5 ma.

This causes the needle to deflect half scale. This half-scale reading, labeled 4.5 K ohms, is equal to the internal resistance of the meter, in this instance 4,500 ohms. If a resistance of 9,000 ohms is placed between terminals A and B, the needle deflects one-third scale. Resistances of 13.5 K and 1.5 K placed between terminals A and B will cause a deflection of one-fourth and three-fourths scale, respectively.

If terminals A and B are not connected (open-circuited), no current flows and the needle does not move. The left side of the scale is, therefore, labeled infinity to indicate an infinite resistance.

A typical ohmmeter scale is shown in figure 8–138. Note that the scale is not linear and is crowded at the high resistance end. For this reason, it is good practice to use an ohmmeter range in which the readings are not too far from mid-scale. A good rule is to use a range in which the reading obtained does not exceed ten times, or is not less than one-tenth, the mid-scale reading. The useful range of the scale shown is, by this rule, from 450 ohms to 45,000 ohms.

Most ohmmeters have more than one scale. Additional scales are made possible by using various values of limiting resistors and battery voltages. Some ohmmeters have a special scale called a low-ohm scale for reading low resistances. A shunt-type ohmmeter circuit is used for this scale.

Shunt-Type Ohmmeter

Shunt-type ohmmeters are used to measure small values of resistance. In the circuit shown in figure 8–139, E (voltage) is applied across a limiting resistor R and a meter movement in series. Resistance and battery values are chosen so that the meter movement deflects full scale when terminals A and B are open. When the terminals are short-circuited, the meter reads zero; the short circuit conducts all the current around the meter. The unknown resistance R_x is placed between terminals A and B in parallel with the meter movement. The smaller the resistance value being measured, the less current flows through the meter movement.

The value of the limiting resistor R is usually made large compared to the resistance of the meter movement. This keeps the current drawn from the battery practically constant. Thus, the value of R_x determines how much of this constant current flows through the meter and how much through R_x.

Note that in a shunt-type ohmmeter, current is always flowing from the battery through the meter

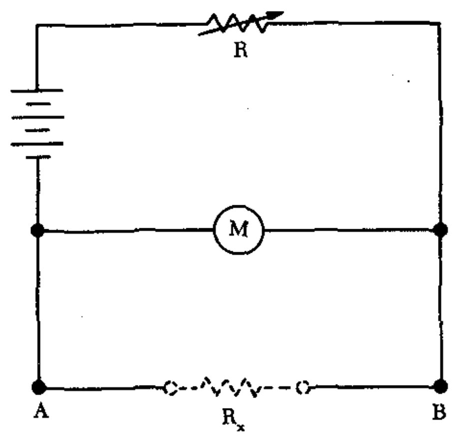


FIGURE 8–139. Shunt-type ohmmeter circuit.

movement and the limiting resistor. Therefore, when using an ohmmeter with a low-ohm scale, do not leave the switch in low-ohm position.

Use of the Ohmmeter

The ohmmeter is not as accurate a measuring device as the ammeter or the voltmeter because of the associated circuitry. Thus, resistance values cannot be read with greater than 5 to 10 percent accuracy. While there are instruments which read the resistance of an element with very great accuracy, they usually are more complicated to use.

In addition to measuring the resistance, the ohmmeter is a very useful instrument for checking continuity in a circuit. Often, when troubleshooting electronic circuits or wiring a circuit, visual inspections of all parts of the current path cannot be readily accomplished. Therefore, it is not always apparent whether a circuit is complete or whether current might be flowing in the wrong part of the circuit because of contact with adjacent circuits. The best method of checking a circuit under these conditions is to send a current through the circuit. The ohmmeter is the ideal instrument for checking circuits in this manner. It provides the power and the meter to indicate whether the current is flowing.

Observe the following precautions when using an ohmmeter:

(1) Choose a scale which will contain the resistance of the element to be measured. In general, use a scale in which the reading will fall in the upper half of the scale (near full-scale deflection).

(2) Short the leads together and set the meter to read zero ohms by setting the zero adjustment. If the scale is changed, readjust to zero ohms.

(3) Connect the unknown resistance between the test leads and read its resistance from the scale. Never attempt to measure resistance in a circuit while it is connected to a source of voltage. Disconnect at least one end of the element being measured to avoid reading the resistance of parallel paths.

Megger (Megohmmeter)

The megger, or megohmmeter, is a high-range ohmmeter containing a hand-operated generator. It is used to measure insulation resistance and other high resistance values. It is also used for ground, continuity, and short-circuit testing of electrical power systems. The chief advantage of the megger over an ohmmeter is its capacity to measure resistance with a high potential, or "breakdown" voltage. This type of testing ensures that insulation or a dielectric material will not short or leak under potential electrical stress.

The megger (figure 8–140) consists of two primary elements, both of which are provided with individual magnetic fields from a common permanent magnet: (1) A hand-driven d.c. generator, *G*, which supplies the necessary current for making the measurement and (2) the instrument portion, which indicates the value of the resistance being measured. The instrument portion is of the opposed-coil type. Coils *A* and *B* are mounted on the movable member with a fixed angular relationship to each other and are free to turn as a unit in a magnetic field. Coil *B* tends to move the pointer counterclockwise and coil *A*, clockwise. The coils are mounted on a light, movable frame that is pivoted in jewel bearings and free to move about axis 0.

Coil *A* is connected in series with R3 and the

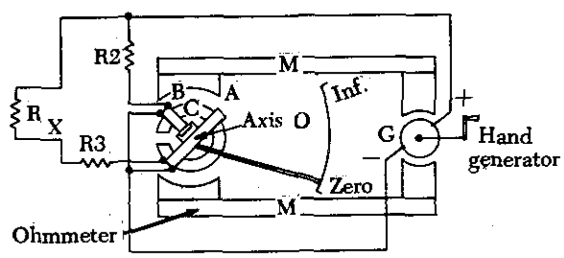


FIGURE 8–140. Simplified megger circuit.

unknown resistance, R_x, to be measured. The series combination of coil A, R3, and R_x is connected between the + and − brushes of the d.c. generator. Coil B is connected in series with R2 and this combination is also connected across the generator. There are no restraining springs on the movable member of the instrument portion of the megger. When the generator is not in operation, the pointer floats freely and may come to rest at any position on the scale.

If the terminals are open-circuited, no current flows in coil A, and the current in coil B alone controls the movement of the moving element. Coil B takes a position opposite the gap in the core (since the core cannot move and coil B can), and the pointer indicates infinity on the scale. When a resistance is connected between the terminals, current flows in coil A, tending to move the pointer clockwise. At the same time, coil B tends to move the pointer counterclockwise. Therefore, the moving element, composed of both coils and the pointer, comes to rest at a position at which the two forces are balanced. This position depends upon the value of the external resistance, which controls the relative magnitude of current of coil A. Because changes in voltage affect both coil A and B in the same proportion, the position of the moving element is independent of the voltage. If the terminals are short-circuited, the pointer rests at zero because the current in A is relatively large. The instrument is not damaged under these circumstances because the current is limited by R3.

There are two types of hand-driven meggers: the variable type and the constant-pressure type. The speed of the variable-pressure megger is dependent on how fast the hand crank is turned. The constant-pressure megger utilizes a centrifugal governor, or slip clutch. The governor becomes effective only when the megger is operated at a speed above its slip speed, at which speed its voltage remains constant.

BASIC CIRCUIT ANALYSIS AND TROUBLESHOOTING

Troubleshooting is the process of locating causes for malfunctions or trouble in a circuit. The following definitions serve as a guide in the troubleshooting discussion:

(1) Short circuit—a low resistance path. It can be across the power source or between the sides of a circuit. It usually creates high current flow which will burn out or cause damage to the circuit conductor or components.

(2) Open circuit—a circuit that is not complete or continuous.

(3) Continuity—the state of being continuous, or connected together; said of a circuit that is not broken or does not have an open.

(4) Discontinuity—the opposite of continuity, indicating that a circuit is broken or not continuous.

Figure 8–141 includes some of the most common sources of open circuits (commonly called "opens" or "an open"). A loose connection or no connection is a frequent cause of an open circuit. In A of figure 8–141, the end of a conductor has separated from the battery terminal. This type of malfunction opens a circuit and stops the flow of current. Another type of malfunction that will cause an open circuit is a burned-out resistor, shown in B of figure 8–141. When a resistor overheats, its resistance value changes; and, if the current flow through it is great enough, it can burn and open the circuit. In C, D, and E of figure 8–141, three more likely causes of open circuits are shown.

The opens shown can often be located by visual inspection; however, many circuit opens cannot be seen. In such cases, a meter must be used.

The circuit shown in figure 8–142 is designed to cause current to flow through a lamp, but because of the open resistor, the lamp will not light. To locate this open, a voltmeter or an ohmmeter can be used.

If a voltmeter is connected across the lamp, as shown in figure 8–143, the voltmeter will read zero. Since no current can flow in the circuit because of the open resistor, there is no voltage drop across the lamp. This illustrates a troubleshooting rule that should be remembered: When a voltmeter is connected across a good (not defective) component in an open circuit, the voltmeter will read zero.

Next, the voltmeter is connected across the open resistor, as shown in figure 8–144. The voltmeter has closed the circuit by shunting (paralleling) the burned-out resistor, allowing current to flow. Current will flow from the negative terminal of the battery, through the switch, through the voltmeter and the lamp, back to the positive terminal of the battery. However, the resistance of the voltmeter is so high that only a very small current flows in the circuit. The current is too small to light the lamp, but the voltmeter will read the battery voltage. Another troubleshooting point worth

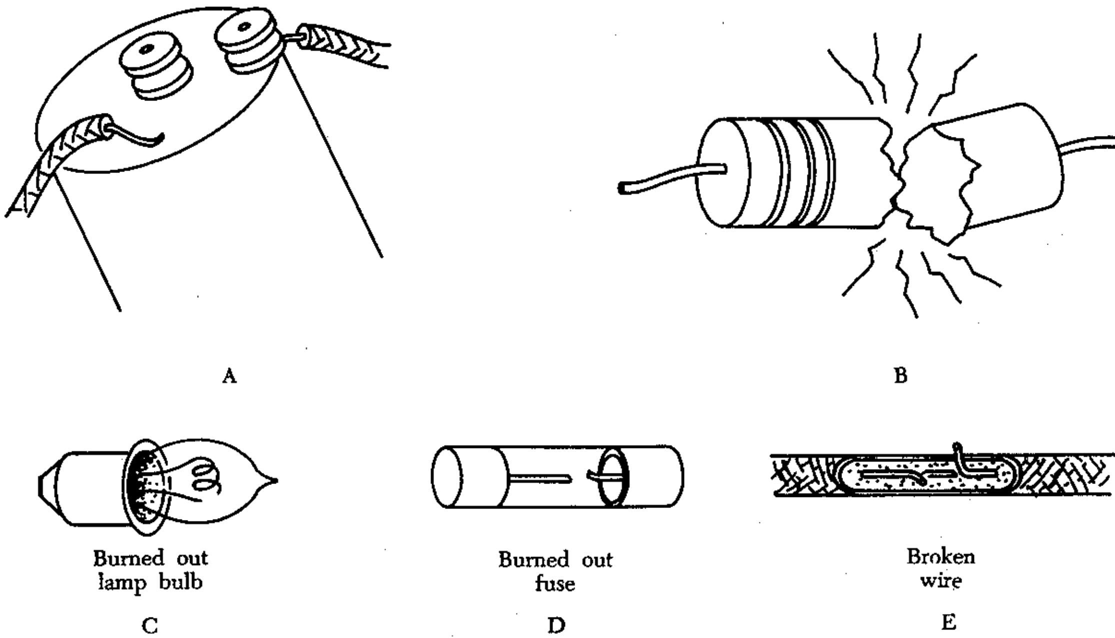


FIGURE 8–141. Common causes of open circuits.

remembering is: When a voltmeter is placed across an open component in a series circuit, it will read the battery, or applied voltage.

This type of open circuit malfunction can also be traced by using an ohmmeter. When an ohmmeter is used, the circuit component to be tested must be isolated and the power source removed from the circuit. In this case, as shown in figure 8–145, these requirements can be met by opening the circuit switch. The ohmmeter is zeroed and placed across (in parallel with) the lamp. In this circuit, some value of resistance is read. This illustrates another important troubleshooting point: when an ohmmeter is properly connected across a circuit component and a resistance reading is obtained, the component has continuity and is not open.

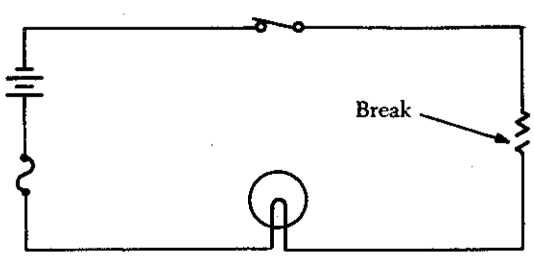


FIGURE 8–142. An open circuit.

When the ohmmeter is connected across the open resistor, as shown in figure 8–146, it indicates infinite resistance, or a discontinuity. Thus, the circuit open has been located with both a voltmeter and an ohmmeter.

An open in a series circuit will cause the current flow to stop. A short circuit, or "short," will cause the opposite effect. A short across a series circuit produces a greater than normal current flow. Some examples of shorts, as shown in figure 8–147, are two bare wires in a circuit that are touching each other, two terminals of a resistor connected together, etc. Thus, a short can be described as a

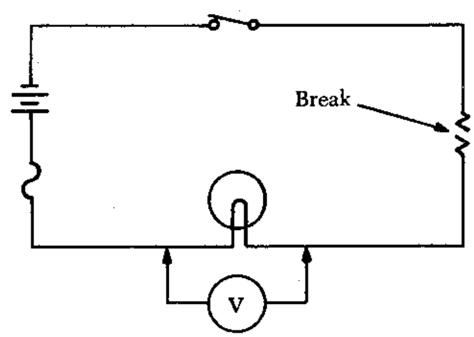


FIGURE 8–143. Voltmeter across a lamp in an open circuit.

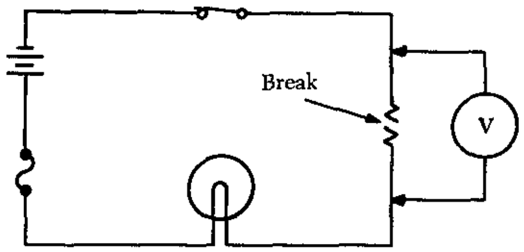


FIGURE 8–144. Voltmeter across a resistor in an open circuit.

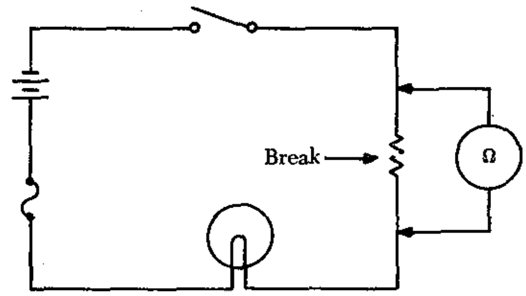


FIGURE 8–146. Using an ohmmeter to locate an open in a circuit component.

connection of two conductors of a circuit through a very low resistance.

In figure 8–148, a circuit is designed to light a lamp. A resistor is connected in the circuit to limit current flow. If the resistor is shorted, as shown in the illustration, the current flow will increase and the lamp will become brighter. If the applied voltage were high enough, the lamp would burn out, but in this case the fuse would protect the lamp by opening first.

Usually a short circuit will produce an open circuit by either blowing (opening) the fuse or burning out a circuit component. But in some circuits, such as that illustrated in figure 8–149, there may be additional resistors which will not allow one shorted resistor to increase the current flow enough to blow the fuse or burn out a component. Thus, with one resistor shorted out, the circuit will still function since the power dissipated by the other resistors does not exceed the rating of the fuse.

To locate the shorted resistor while the circuit is functioning, a voltmeter could be used. When it is connected across any of the unshorted resistors, a portion of the applied voltage will be indicated on the voltmeter scale. When it is connected across the shorted resistor, the voltmeter will read zero.

The shorted resistor shown in figure 8–150 can be located with an ohmmeter. First the switch is opened to isolate the circuit components. In figure 8–150, this circuit is shown with an ohmmeter connected across each of the resistors. Only the ohmmeter connected across the shorted resistor shows a zero reading, indicating that this resistor is shorted.

The procedures used in troubleshooting a parallel circuit are sometimes different from those used in a series circuit. Unlike a series circuit, a parallel circuit has more than one path in which current flows. A voltmeter cannot be used, since, when it is placed across an open resistor, it will read the voltage drop in a parallel branch. But an ammeter or the modified use of an ohmmeter can be employed to detect an open branch in a parallel circuit.

If the open resistor shown in figure 8–151 was not visually apparent, the circuit would appear to be functioning properly, since current would continue to flow in the other two branches of the circuit. To determine that the circuit is not operating properly, the total resistance, total current, and the branch currents of the circuit should be calculated as if there were no open in the circuit:

$$R_t = \frac{N}{R}$$

$$= \frac{30}{3}$$

$$= 10\ \Omega \text{ total resistance.}$$

Since the voltage applied to the branches is the same and the value of each branch resistance is

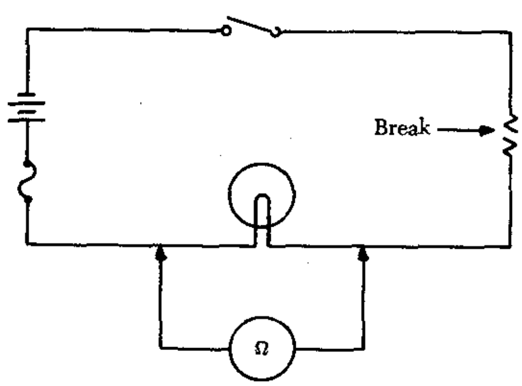


FIGURE 8–145. Using an ohmmeter to check a circuit component.

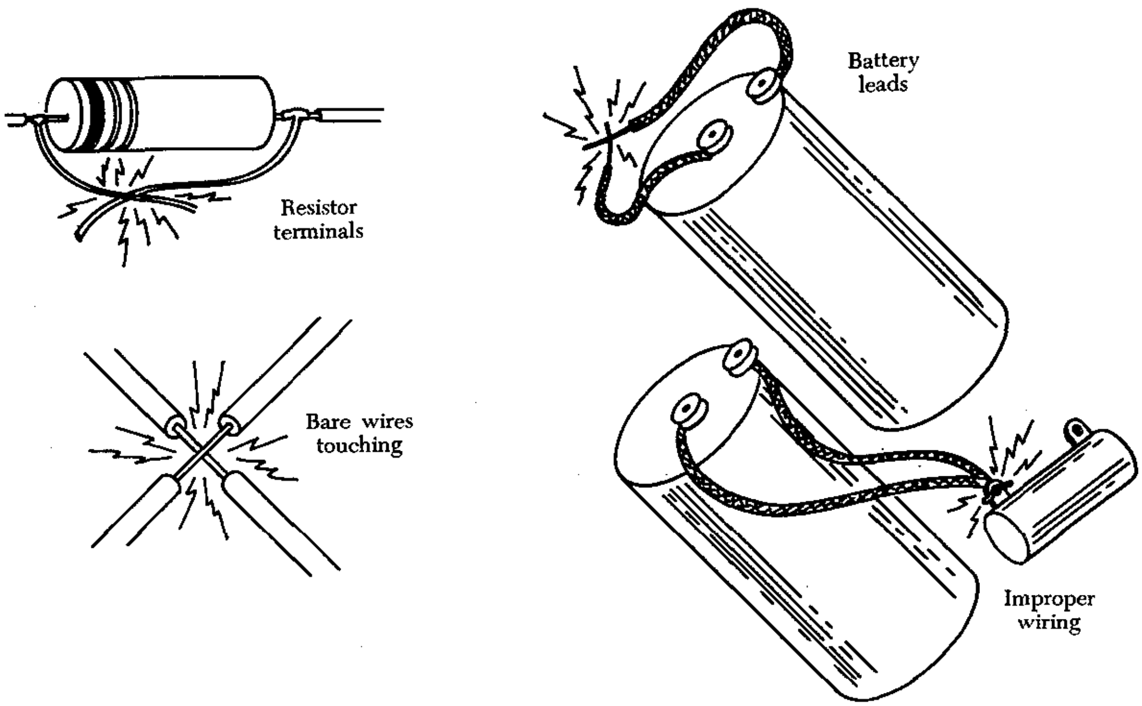


FIGURE 8–147. Common causes of short circuits.

known,

$$I_1 = \frac{E_1}{R_1} = \frac{30\text{V}}{30\ \Omega} = 1 \text{ ampere.} \qquad I_2 = \frac{E_2}{R_2} = \frac{30\text{V}}{30\ \Omega} = 1 \text{ ampere.}$$

$$I_3 = \frac{E_3}{R_3} = \frac{30\text{V}}{30\ \Omega} = 1 \text{ ampere.} \qquad I_T = \frac{E_T}{R_T} = \frac{30\text{V}}{10\ \Omega} = 3 \text{ amperes (total current).}$$

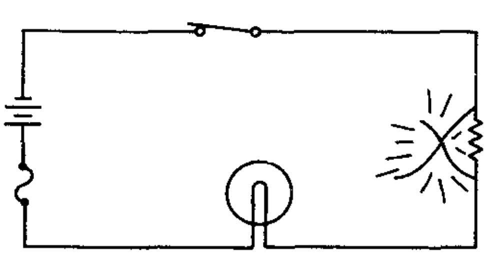


FIGURE 8–148. A shorted resistor.

An ammeter placed in the circuit to read total current would show 2 amperes instead of the calculated 3 amperes. Since 1 ampere of current should be flowing through each branch, it is obvious that one branch is open. If the ammeter is connected into the branches, one after another, the open branch will be located by a zero ammeter reading.

A modified use of the ohmmeter can also locate this type of open. If the ohmmeter is connected across the open resistor, as shown in figure 8–152, an erroneous reading of continuity would be obtained. Even though the circuit switch is open, the open resistor is still in parallel with R_1 and R_2, and the ohmmeter would indicate the open

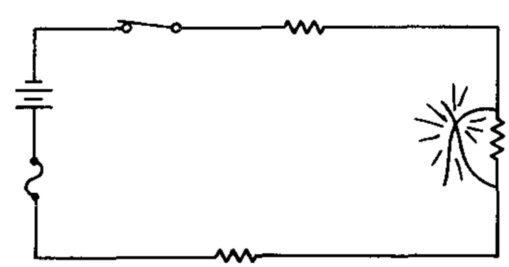


FIGURE 8–149. A short that does not open the circuit.

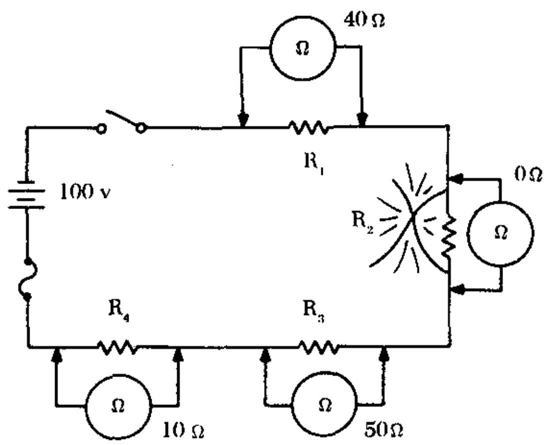


FIGURE 8–150. Using an ohmmeter to locate a shorted resistor.

resistor had a resistance of 15 ohms, the equivalent resistance of the parallel combination of R_1 and R_2. Thus, it is necessary to open the circuit as shown in figure 8–153 in order to check the resistance of R_3. In this way the resistor is not shunted (paralleled) and the reading on the ohmmeter will indicate infinite resistance. On the other hand, if an open should occur in this circuit (figure 8–153) between the battery and point A, or between the battery and point B, current would not flow in the circuit.

As in a series circuit, a short in a parallel circuit will usually cause an open circuit by blowing the fuse. But, unlike a series circuit, one shorted component in a parallel circuit will stop current flow by causing the fuse to open. This can be seen by referring to the circuit in figure 8–154. If resistor R_3 is shorted, a path of almost zero resistance will be offered the current, and all the circuit current will flow through the branch containing the shorted resistor. Since this is practically the same as connecting a wire between the terminals of the battery, the current will rise

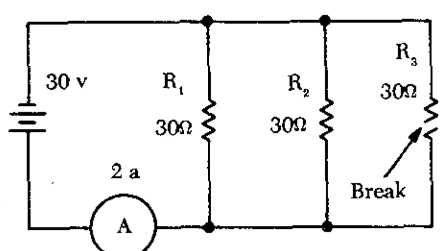


FIGURE 8–151. Finding an open branch in a parallel circuit.

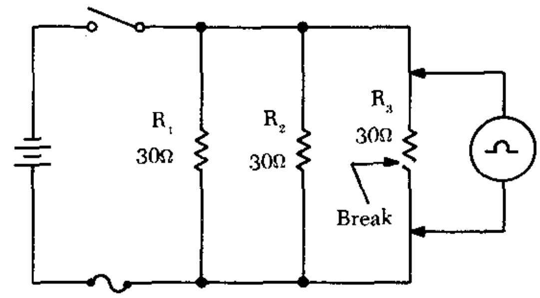


FIGURE 8–152. A misleading ohmmeter indication.

to an excessive value, and the fuse will open. Since the fuse opens almost as soon as a resistor shorts out, there is no time to perform a current or voltage check. Thus, troubleshooting a parallel d.c. circuit for a shorted component should be accomplished with an ohmmeter. But, as in the case of checking for an open resistor in a parallel circuit, a shorted resistor can be detected with an ohmmeter only if one end of the shorted resistor is disconnected.

Troubleshooting a series-parallel resistive circuit involves locating malfunctions similar to those found in a series or a parallel circuit.

In the circuit shown in figure 8–155, an open has occurred in the series portion of the circuit. When an open occurs anywhere in the series portion of a series-parallel circuit, current flow in the entire circuit will stop. In this case, the circuit will not function, and the lamp, L_1, will not be lit.

If an open occurs in the parallel portion of a series-parallel circuit, as shown in figure 8–156, part of the circuit will continue to function. In this case, the lamp will continue to burn, but its brightness will diminish, since the total resistance

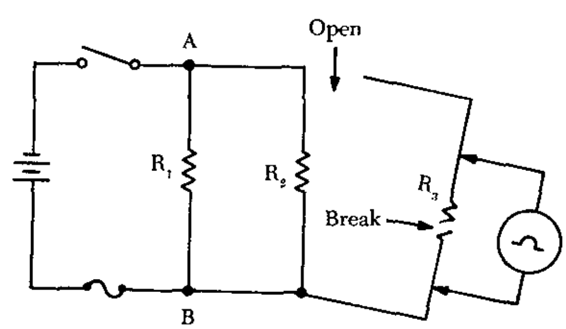


FIGURE 8–153. Opening a branch circuit to obtain an accurate ohmmeter reading.

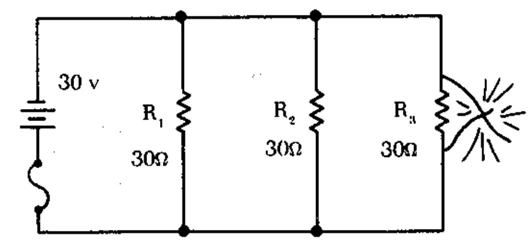


FIGURE 8–154. A shorted component causes the fuse to open.

of the circuit has increased and the total current has decreased.

If a break occurs in the branch containing the lamp, as shown in figure 8–157, the circuit will continue to function with increased resistance and decreased current, but the lamp will not burn.

To explain how the voltmeter and ohmmeter can be used to troubleshoot series-parallel circuits, the circuit shown in figure 8–158 has been labeled at various points. By connecting a voltmeter between points *A* and *D*, the battery and switch can be checked for opens. By connecting the voltmeter between points *A* and *B*, the voltage drop across R_1 can be checked. This voltage drop is a portion of the applied voltage. Also, if R_1 is open, the reading between *B* and *D* will be zero. The conductor between the positive terminal of the battery and point *E*, as well as the fuse, can be checked for continuity by connecting the voltmeter between points *A* and *E*. If the conductor or fuse is open, the voltmeter will read zero.

If the lamp is burning, it is obvious that no open exists in the branch containing the lamp, and the voltmeter could be used to detect an open in the branch containing R_2 by removing lamp, L_1, from the circuit.

Troubleshooting the series portion of a series-parallel circuit presents no difficulties, but in the

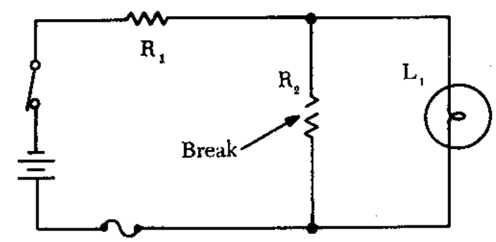


FIGURE 8–156. An open in the parallel portion of a series-parallel circuit.

parallel portion of the circuit misleading readings can be obtained.

An ohmmeter can be used to troubleshoot this same circuit. With the switch open, the series portion of the circuit can be checked by placing the ohmmeter leads between points *A* and *B*. If R_1 or the conductor is open, the ohmmeter will read infinity; if not, the value of the resistor will be indicated on the ohmmeter. Between points *D* and *E* the fuse and conductor can be checked for continuity, but in the parallel portion of the circuit, care must be exercised, since misleading ohmmeter indications can be obtained. To check between points *B* and *E*, the branch must be disconnected at one of these points, and while one of these points and the switch are open, the branch containing the lamp can be checked with the ohmmeter.

A short in the series part of a series-parallel circuit will cause a decrease in total resistance, which will cause total current to increase. In the circuit shown in figure 8–159, the total resistance is 100 ohms and the total current is 2 amperes. If R_1 became shorted, total resistance would become 50 ohms, and the total current would double to 4 amperes. In the circuit shown, this would cause the 3-amp fuse to blow, but with a 5-amp fuse the circuit would continue to function. The result would be the same if R_2 or R_3 were to become shorted. The total resistance in either case would

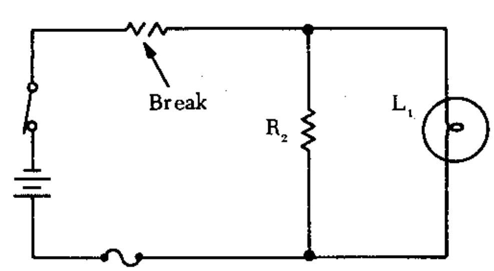


FIGURE 8–155. An open in the series portion of a series-parallel circuit.

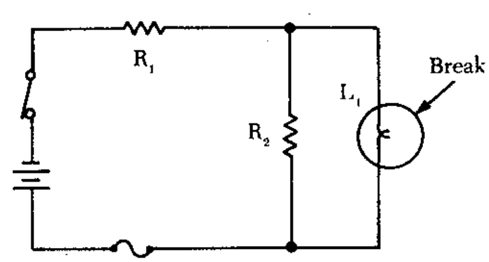


FIGURE 8–157. An open lamp in a series-parallel circuit.

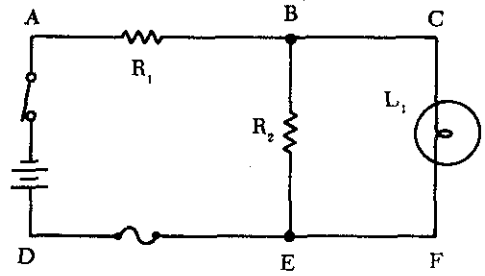


FIGURE 8–158. Using the voltmeter to troubleshoot a series-parallel circuit.

drop to 50 ohms. From this, it can be stated that when a short occurs in a series-parallel circuit, the total resistance will decrease and the total current will increase. A short will normally cause an open circuit by either blowing the fuse or burning out a circuit component. And, as in the case of an open, a short in a series-parallel circuit can be detected with either an ohmmeter or a voltmeter.

ALTERNATING CURRENT AND VOLTAGE

Alternating current has largely replaced direct current in commercial power systems for a number of reasons. It can be transmitted over long distances more readily and more economically than direct current, since a.c. voltages can be increased or decreased by means of transformers.

Because more and more units are being operated electrically in airplanes, the power requirements are such that a number of advantages can be realized by using a.c. Space and weight can be saved, since a.c. devices, especially motors, are smaller and simpler than d.c. devices. In most a.c. motors no brushes are required, and commutation trouble at high altitude is eliminated. Circuit breakers will operate satisfactorily under load at high altitudes in an a.c. system, whereas arcing is so excessive on d.c. systems that circuit breakers must be replaced frequently. Finally, most airplanes using a 24-volt d.c. system have special equipment which requires a certain amount of 400-cycle a.c. current.

A. C. and D. C. Compared

Many of the principles, characteristics, and effects of alternating current are similar to those of direct current. Similarly, there are a number of differences which are explained later. Direct current flows constantly in only one direction with a constant polarity. It changes magnitude only when the circuit is opened or closed, as shown in the d.c. wave form in figure 8–160. Alternating current changes direction at regular intervals, increases in value at a definite rate from zero to a maximum positive strength, and decreases back to zero; then it flows in the opposite direction, similarly increasing to a maximum negative value, and again decreasing to zero. D.C. and a.c. wave forms are compared in figure 8–160.

Since alternating current constantly changes direction and intensity, two effects take place in a.c. circuits that do not occur in d.c. circuits. They are inductive reactance and capacitive reactance. Both are discussed later in this chapter.

Generator Principles

After the discovery that an electric current flowing through a conductor creates a magnetic field around the conductor, there was considerable scientific speculation about whether a magnetic field could create a current flow in a conductor. In 1831, the English scientist, Michael Faraday, demonstrated this could be accomplished. This discovery is the basis for the operation of the generator, which signalled the beginning of the electrical age.

To show how an electric current can be created by a magnetic field, a demonstration similar to that illustrated in figure 8–161 can be used. Several turns of a conductor are wrapped around a cylindrical form, and the ends of the conductor are connected together to form a complete circuit which includes a galvanometer. If a simple bar magnet is plunged into the cylinder, the galvanometer can be observed to deflect in one direction from its zero (center) position (*A* of figure 8–161). When the magnet is at rest inside the cylinder, the

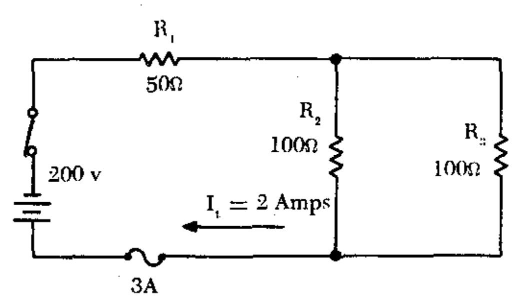


FIGURE 8–159. Finding a short in a series-parallel circuit.

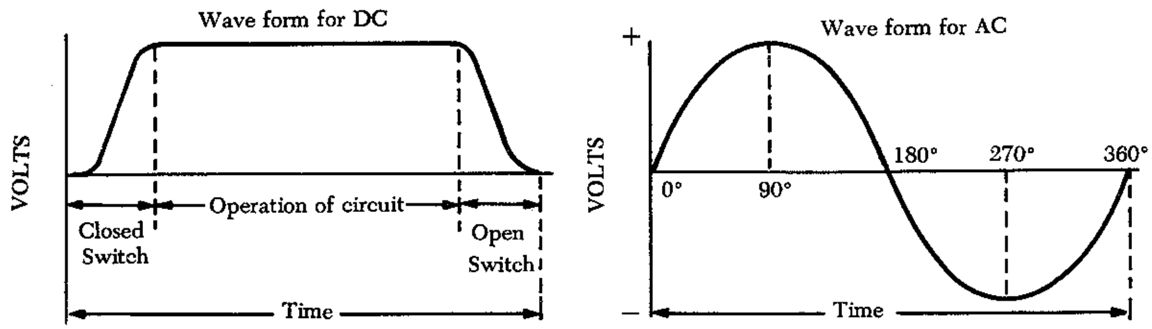


FIGURE 8–160. D.C. and a.c. voltage curves.

galvanometer shows a reading of zero, indicating that no current is flowing (*B* of figure 8–161).

In *C* of figure 8–161, the galvanometer indicates a current flow in the opposite direction when the magnet is pulled from the cylinder.

The same results may be obtained by holding the magnet stationary and moving the cylinder over the magnet, indicating that a current flows when there is relative motion between the wire coil and the magnetic field. These results obey a law first stated by the German scientist, Heinrich Lenz. Lenz's law states that the induced current caused by the relative motion of a conductor and a magnetic field always flows in such a direction that its magnetic field opposes the motion.

When a conductor is moved through a magnetic field, as shown in figure 8–162, an electromotive force (e.m.f.) is induced in the conductor. The direction (polarity) of the induced e.m.f. is determined by the magnetic lines of force and the direction the conductor is moved through the magnetic field. The generator left-hand rule (not to be confused with the left-hand rules used with a coil) can be used to determine the direction of the induced e.m.f., as shown in figure 8–163. The first finger of the left hand is pointed in the direction of the magnetic lines of force (north to south), the thumb is pointed in the direction of movement of the conductor through the magnetic field, and the second finger points in the direction of the induced

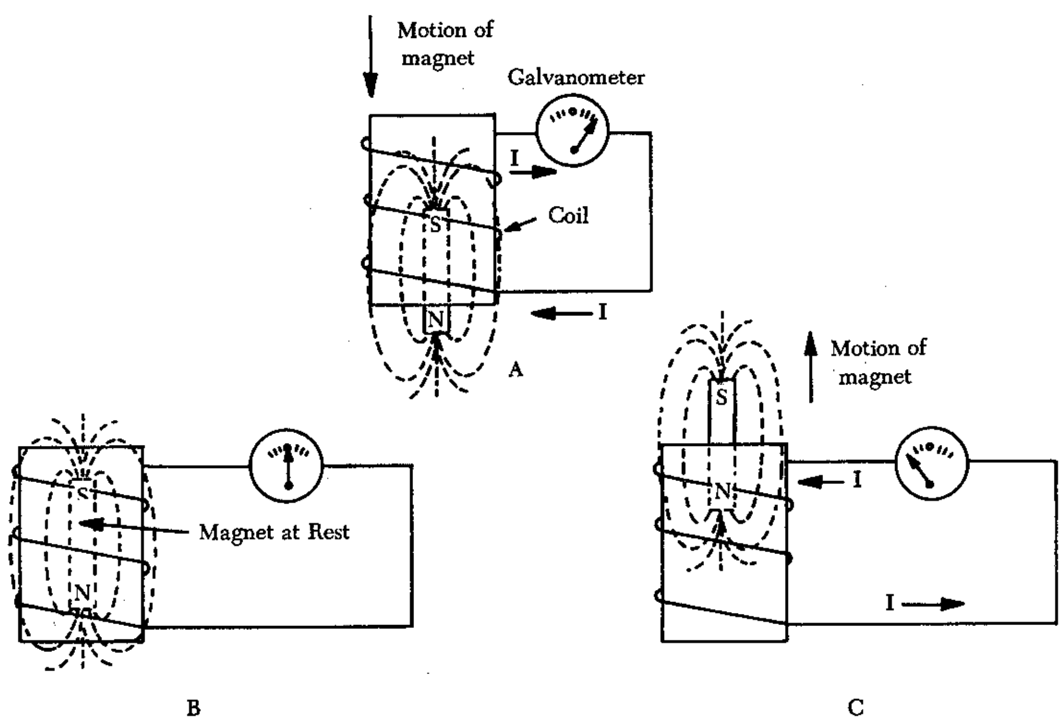


FIGURE 8–161. Inducing a current flow.

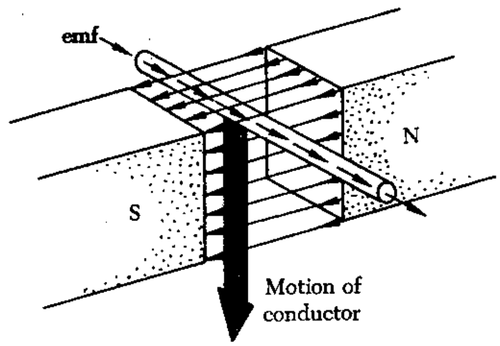


FIGURE 8–162. Inducing an e.m.f. in a conductor.

e.m.f. When two of these three factors are known, the third may be determined by the use of this rule.

When a loop conductor is rotated in a magnetic field (see figure 8–164), a voltage is induced in each side of the loop. The two sides cut the magnetic field in opposite directions, and although the current flow is continuous, it moves in opposite directions with respect to the two sides of the loop. If sides A and B and the loop are rotated half a turn and the sides of the conductor have exchanged positions, the induced e.m.f. in each wire reverses its direction, since the wire formerly cutting the lines of force in an upward direction is now moving downward.

The value of an induced e.m.f. depends on three factors:

(1) The number of wires moving through the magnetic field.
(2) The strength of the magnetic field.
(3) The speed of rotation.

Generators of Alternating Current

Generators used to produce an alternating current are called a.c. generators or alternators.

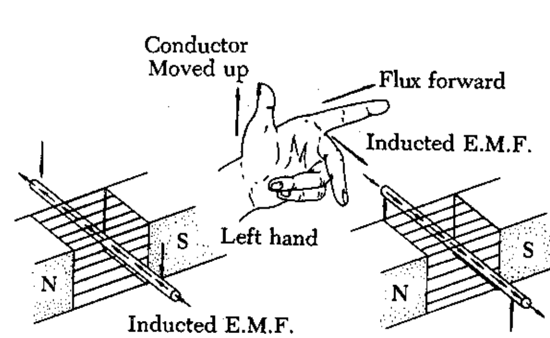


FIGURE 8–163. An application of the generator left-hand rule.

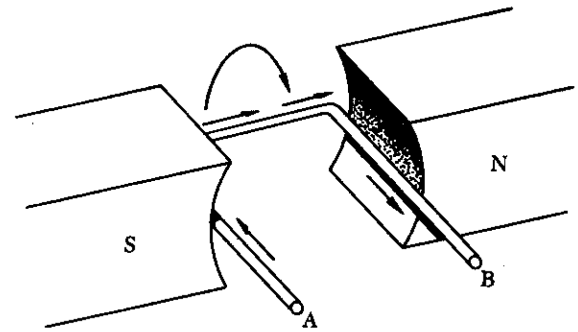


FIGURE 8–164. Voltage induced in a loop.

The simple generator shown in figure 8–165 constitutes one method of generating an alternating voltage. It consists of a rotating loop, marked A and B, placed between two magnetic poles, N and S. The ends of the loop are connected to two metal slip rings (collector rings), C_1 and C_2. Current is taken from the collector rings by brushes. If the loop is considered as separate wires A and B, and the left-hand rule for generators (not to be confused with the left-hand rule for coils) is applied, then it can be observed that as wire A moves up across the field, a voltage is induced which causes the current to flow inward. As wire B moves down across the field, a voltage is induced which causes the current to flow outward. When the wires are formed into a loop, the voltages induced in the two sides of the loop are combined. Therefore, for explanatory purposes, the action of either conductor, A or B, while rotating in the magnetic field is similar to the action of the loop.

Figure 8–166 illustrates the generation of alternating current with a simple loop conductor rotating in a magnetic field. As it is rotated in a counterclockwise direction, varying values of voltages are induced in it. At position 1, conductor A moves parallel to the lines of force. Since it cuts no lines of force, the induced voltage is zero. As the conductor advances from position 1 to position 2, the voltage induced gradually increases. At 2, the conductor moves perpendicular to the flux and cuts a maximum number of lines of force; therefore, a maximum voltage is induced. As the conductor moves beyond 2, it cuts a decreasing amount of flux at each instant, and the induced voltage decreases. At 3, the conductor has made one half of a revoltion and again moves parallel to the lines of force, and no voltage is induced in the conductor. As the A conductor passes position 3, the direction of induced voltage reverses since the A conductor

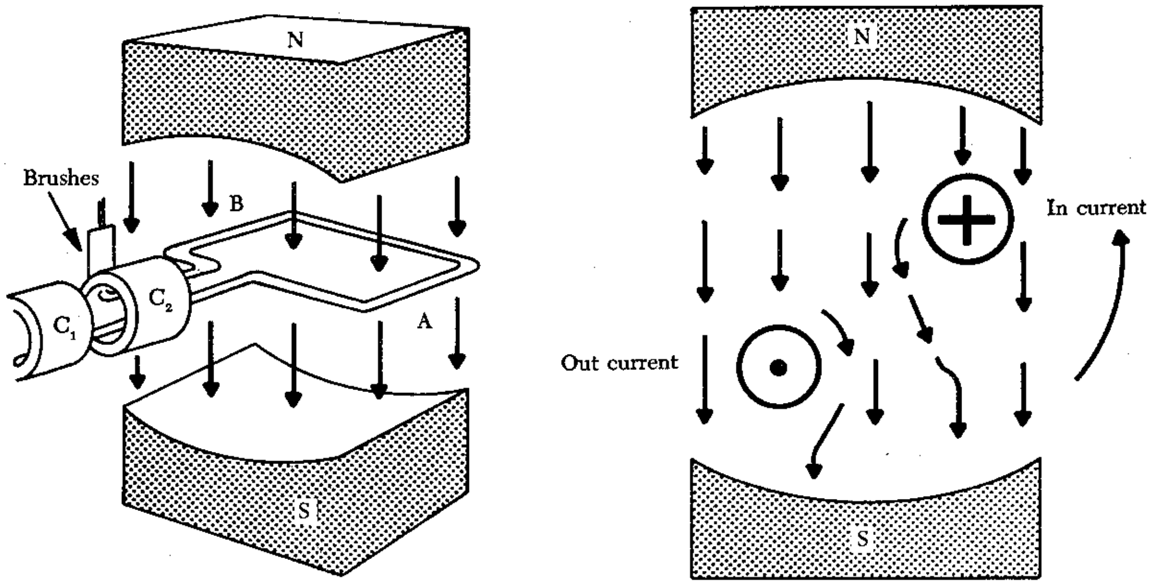


FIGURE 8–165. Simple generator.

now moves downward, cutting flux in the opposite direction. As the A conductor moves across the south pole, the induced voltage gradually increases in a negative direction, until at position 4 the conductor again moves perpendicular to the flux and generates a maximum negative voltage. From position 4 to 5, the induced voltage gradually decreases until the voltage is zero, and the conductor and wave are ready to start another cycle.

The curve shown at position 5 is called a sine wave. It represents the polarity and the magnitude of the instantaneous values of the voltages generated. The horizontal base line is divided into degrees, or time, and the vertical distance above or below the base line represents the value of voltage at each particular point in the rotation of the loop.

Cycle and Frequency

Whenever a voltage or current passes through a series of changes, returns to the starting point, and then again starts the same series of changes, the series is called a cycle. The cycle is represented by the symbol (∼). In the cycle of voltage shown in figure 8–167, the voltage increases from zero to a maximum positive value, decreases to zero; then increases to a maximum negative value, and again decreases to zero. At this point it is ready to go through the same series of changes. There are two alternations in a complete cycle, the positive alternation and the negative. Each is half a cycle.

The number of times each cycle occurs in a period of time is called the frequency. The frequency of an electric current or voltage indicates the number of times a cycle recurs in 1 second.

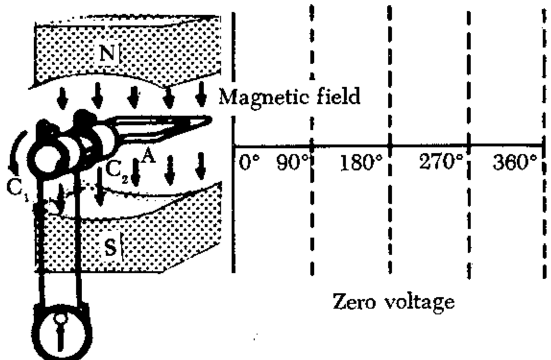
In a generator, the voltage and current pass through a complete cycle of values each time a coil or conductor passes under a north and south pole of the magnet. The number of cycles for each revolution of the coil or conductor is equal to the number of pairs of poles. The frequency, then, is equal to the number of cycles in one revolution multiplied by the number of revolutions per second. Expressed in equation form,

$$F = \frac{\text{Number of poles}}{2} \times \frac{\text{r.p.m.}}{60}$$

where $\frac{P}{2}$ is the number of pairs of poles, and $\frac{\text{r.p.m.}}{60}$ the number of revolutions per second. If in a 2-pole generator, the conductor is turning at 3,600 r.p.m., the revolutions per second are

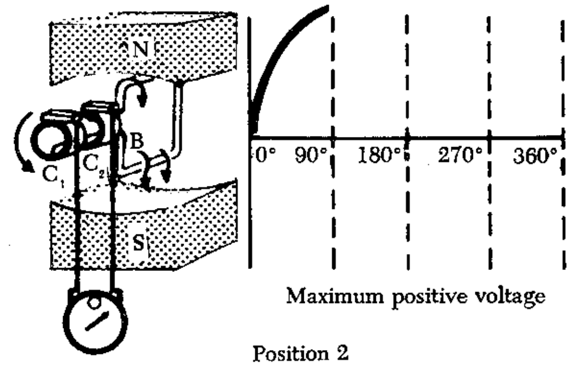
$$\text{r.p.s.} = \frac{3600}{60} = 60 \text{ revolutions per second.}$$

Since there are 2 poles, $\frac{P}{2}$ is 1, and the frequency is 60 c.p.s. In a 4-pole generator with an armature



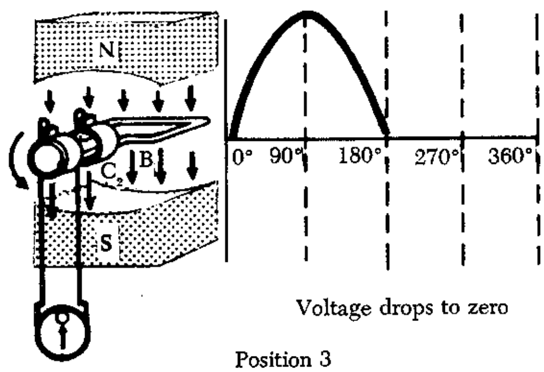
Position 1

Rotating conductors moving parallel to magnetic field, cutting minimum lines of force.



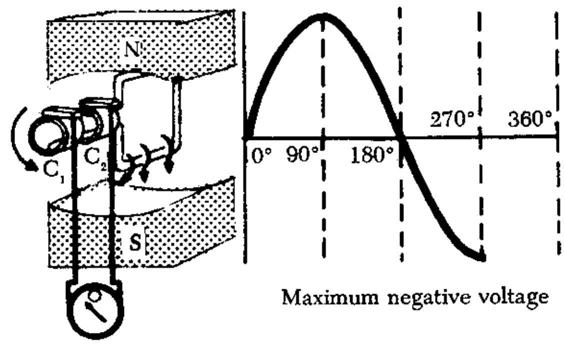
Position 2
Quarter turn completed

Conductors cutting directly across the magnetic field as conductor A passes across the North magnetic pole and B passes across the S pole.



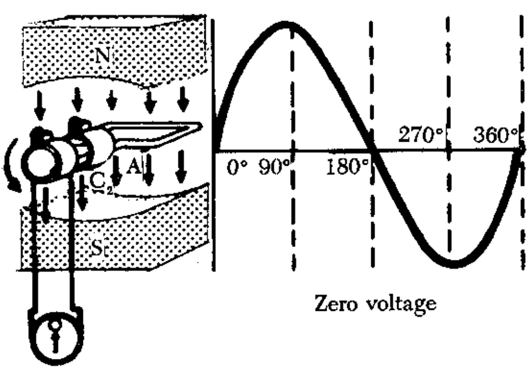
Position 3
One-half turn completed

Conductors again moving parallel to magnetic field, cutting minimum lines of force.



Position 4
Three quarter turn completed

Conductors again moving directly across magnetic field 'A" passes across South magnetic pole and "B" across N magnetic pole.



Conductor A has made one complete cycle and is in same position as in position A. The generator has generated one complete cycle of alternating voltage or current.

Position 5
Full turn completed

FIGURE 8–166. Generation of a sine wave.

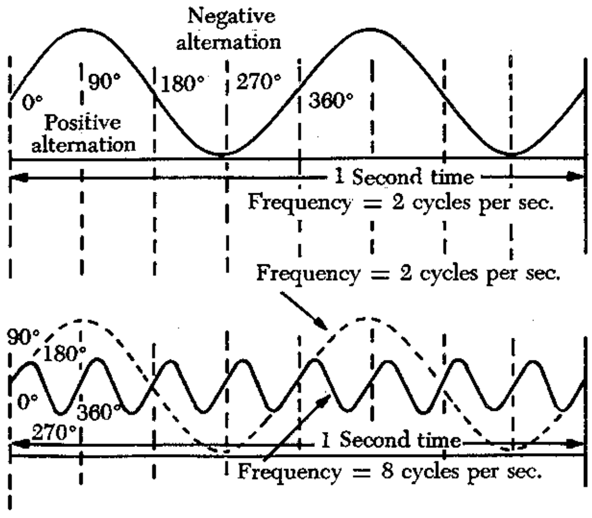


FIGURE 8–167. Frequency in cycles per second.

speed of 1,800 r.p.m., substitute in the equation,

$$F = \frac{P}{2} \times \frac{\text{r.p.m.}}{60}\text{, as follows:}$$

$$F = \frac{4}{2} \times \frac{1800}{60}$$

$$F = 2 \times 30$$

$$F = 60 \text{ c.p.s.}$$

In addition to frequency and cycle characteristics, alternating voltage and current also have a relationship called "phase." In a circuit that is fed (supplied) by one alternator, there must be a certain phase relationship between voltage and current if the circuit is to function efficiently. In a system fed by two or more alternators, not only must there be a certain phase relationship between voltage and current of one alternator, but there must be a phase relationship between the individual voltages and the individual currents. Also, two separate circuits can be compared by comparing the phase characteristics of one to the phase characteristics of the other.

When two or more sine waves pass through 0° and 180° at the same time and reach their peaks at the same time, an in-phase condition exists, as shown in figure 8–168. The peak values (magnitudes) do not have to be the same for the in-phase condition to exist. When the sine waves pass through 0° and 180° at different times and reach their peaks at different times, an out-of-phase condition exists, as shown in figure 8–169. The amount that the two sine waves are out of phase is indicated by the number of electrical degrees between corresponding peaks on the sine waves. In figure 8–169, the current and voltage are 30° out of phase.

Values of Alternating Current

There are three values of alternating current which should be considered. They are instantaneous, maximum, and effective.

An instantaneous value of voltage or current is the induced voltage or current flowing at any instant. The sine wave is a series of these values. The instantaneous value of the voltage varies from zero at 0° to maximum at 90°, back to zero at 180°, to maximum in the opposite direction at 270°, and to zero again at 360°. Any point on the sine wave is considered the instantaneous value of voltage.

The maximum value is the largest instantaneous value. The largest single positive value occurs when the sine wave of voltage is at 90°, and the largest single negative value occurs when it is at 270°. These are called maximum values. Maximum value is 1.41 times the effective value. (See figure 8–170.)

The effective value of alternating current is the same as the value of a direct current which can produce an equal heating effect. The effective value is less than the maximum value, being equal to .707 times the maximum value. Thus, the 110-volt value given for alternating current supplied to homes is only .707 of the maximum voltage of this supply. The maximum voltage is approximately 155 volts ($110 \times 1.41 = 155$ volts maximum).

In the study of alternating current, any values given for current or voltage are assumed to be effective values unless otherwise specified, and in

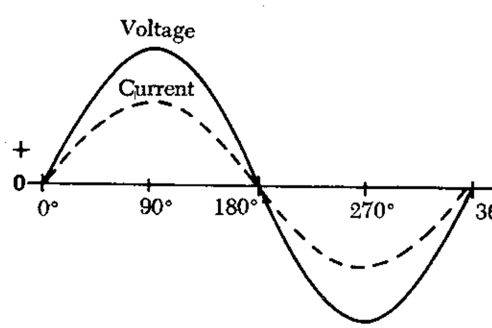


FIGURE 8–168. In-phase condition of current and voltage.

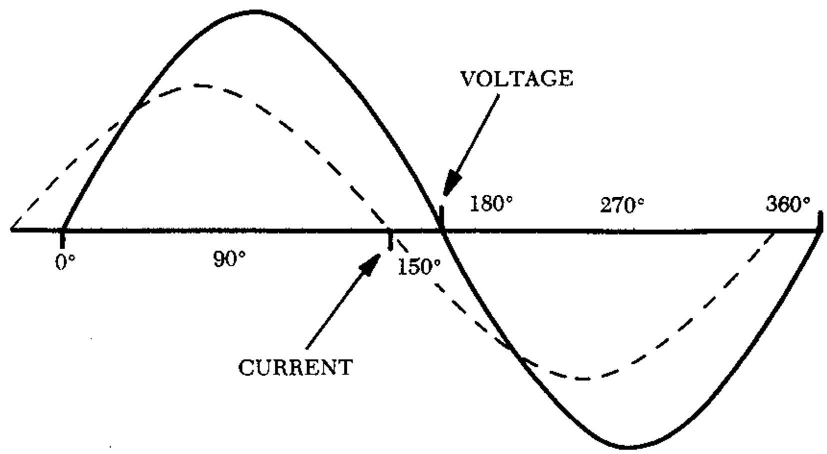


FIGURE 8–169. Out-of-phase condition of current and voltage.

practice, only the effective values of voltage and current are used. Similarly, alternating current voltmeters and ammeters measure the effective value.

INDUCTANCE

When an alternating current flows through a coil of wire, the rise and fall of the current flow, first in one direction, and then in another, sets up an expanding and collapsing magnetic field about the coil. A voltage is induced in the coil which is opposite in direction to the applied voltage and which opposes any change in the alternating current (see figure 8–171). The induced voltage is called the counter-electromotive force (abbreviated c.e.m.f.), since it opposes the applied voltage. This property of a coil to oppose any change in the current flowing through it is called inductance.

The inductance of a coil is measured in henrys. In any coil, the inductance depends on several factors, principally the number of turns, the cross-sectional area of the coil, and the material in the center of the coil or core. A core of magnetic material greatly increases the inductance of the coil.

It must be remembered, however, that even a straight wire has inductance, small though it may be when compared to that of a coil. A.C. motors, relays, and transformers contribute inductance to a circuit. Practically all a.c. circuits contain inductive elements.

The symbol for inductance in formulas is the capital letter "*L*." Inductance is measured in henrys (abbreviated *h*). An inductor (coil) has an inductance of 1 henry if an e.m.f. of 1 volt is induced in the inductor when the current through the inductor is changing at the rate of 1 ampere per second. However, the henry is a large unit of inductance and is used with relatively large inductors having iron cores. The unit used for small air-core inductors is the millihenry (***mh***). For still smaller air-core inductors the unit of

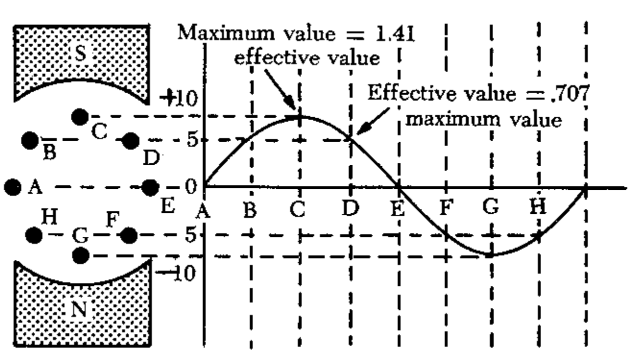


FIGURE 8–170. Effective and maximum values of voltage.

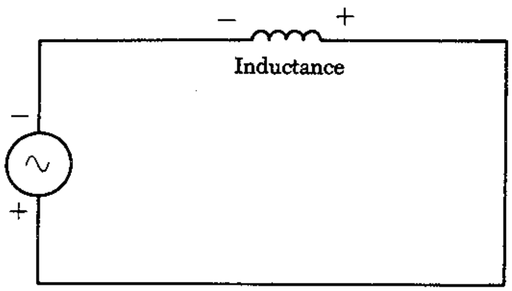


FIGURE 8–171. A.C. circuit containing inductance.

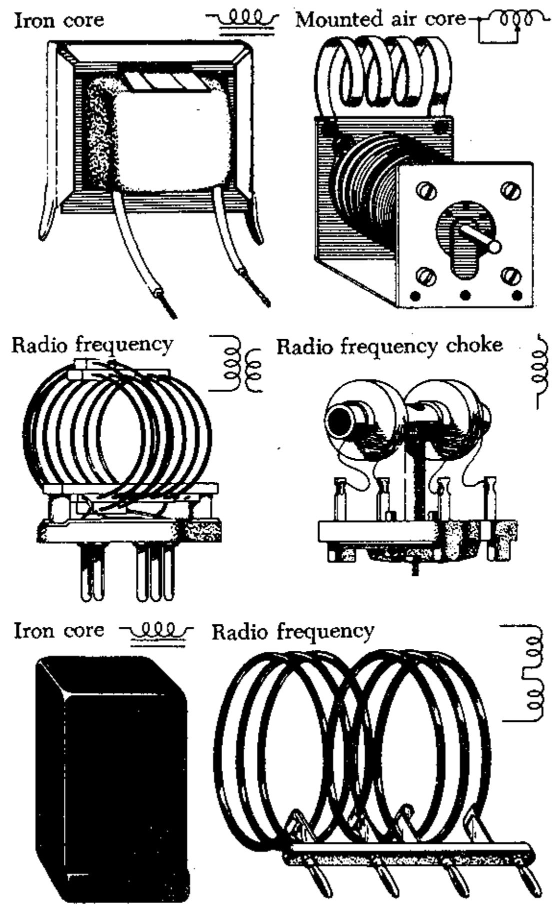


FIGURE 8–172. Various types of inductors.

inductance is the microhenry (μh). Figure 8–172 shows a few of the various types of inductors, together with their symbols.

Inductors may be connected in a circuit in the same manner as resistors. When connected in series, the total inductance is the sum of the inductances of the inductors, or

$$L_T = L_1 + L_2 + L_3\text{, etc.}$$

When two or more inductors are connected in parallel, the total inductance is, like resistances in parallel, less than that of the smallest inductor, or

$$L_T = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}}.$$

The total inductance of inductors connected in series-parallel can be computed by combining the parallel inductances and then adding the series values. In all cases, these formulas are valid, providing the magnetic fields of the inductors do not interact.

Inductive Reactance

The opposition to the flow of current which inductances put in a circuit is called inductive reactance. The symbol for inductive reactance is X_L, and is measured in ohms, just as resistance is.

In any circuit in which there is only resistance, the expression for the relationship of voltage and current is Ohm's law: $I = \frac{E}{R}$. Similarly, when there is inductance in an a.c. circuit, the relationship between voltage and current can be expressed as:

$$\text{Current} = \frac{\text{Voltage}}{\text{Reactance}}\text{, or } I = \frac{E}{X_L}.$$

Where:

X_L = inductive reactance of the circuit in ohms.

If all other circuit values remain constant, the greater the inductance in a coil, the greater the effect of self-induction, or opposition to the change in the value of current. As the frequency increases, the inductive reactance increases, since the greater the rate of current change the more the opposition to change by the coil increases. Therefore, inductive reactance is proportional to inductance and frequency or,

$$X_L = 2\pi fL.$$

Where:

X_L = inductive reactance in ohms.
f = frequency in cycles per second.
π = 3.1416.

In figure 8–173, an a.c. series circuit is assumed in which the inductance is 0.146 henry and the voltage is 110 volts at a frequency of 60 cycles per second. What is the inductive reactance and the current flow? (The symbol ⏦ represents an a.c. generator.)

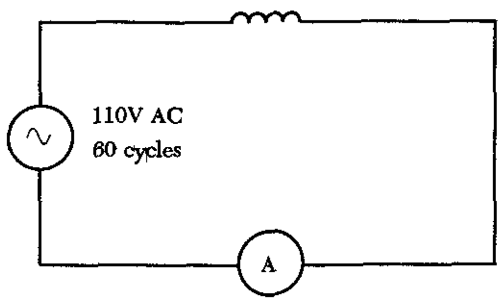


FIGURE 8–173. A.C. circuit containing inductance.

Solution:

To find the inductive reactance:

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

$$X_L = 6.28 \times 60 \times 0.146.$$

To find current:

$$I = \frac{E}{X_L}$$

$$I = \frac{110}{55}$$

$$I = 2 \text{ amperes.}$$

In a.c. series circuits (figure 8–174), inductive reactances are added like resistances in series in a d.c. circuit. Thus, the total reactance in the circuit illustrated in figure 8–174 equals the sum of the individual reactances.

The total reactance of inductors connected in parallel (figure 8–175) is found the same way as the total resistance in a parallel circuit. Thus, the total reactance of inductances connected in parallel, as shown, is expressed as,

$$(X_L)_T = \frac{1}{\frac{1}{(X_L)_1} + \frac{1}{(X_L)_2} + \frac{1}{(X_L)_3}}$$

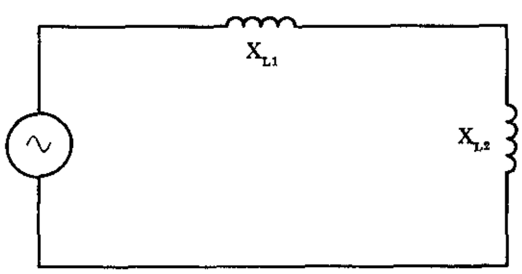


FIGURE 8–174. Inductances in series.

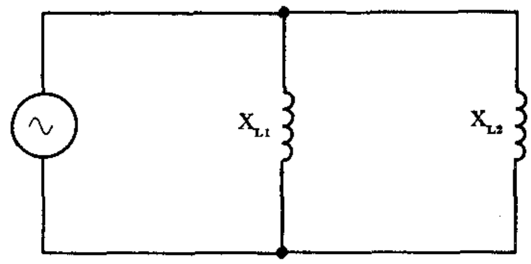


FIGURE 8–175. Inductances in parallel.

CAPACITANCE

Another important property in a.c. circuits, besides resistance and inductance, is capacitance. While inductance is represented in a circuit by a coil, capacitance is represented by a capacitor.

Any two conductors separated by a nonconductor, called a dielectric, constitute a capacitor. In an electrical circuit, a capacitor serves as a reservoir or storehouse for electricity.

When a capacitor is connected across a source of direct current, such as a storage battery in the circuit shown in figure 8–176, and the switch is then closed, the plate marked *B* becomes positively charged, and the *A* plate negatively charged. Current flows in the external circuit during the time the electrons are moving from *B* to *A*. The current flow in the circuit is maximum the instant the switch is closed, but continually decreases thereafter until it reaches zero. The current becomes zero as soon as the difference in voltage of *A* and *B* becomes the same as the voltage of the battery. If the switch is opened, the plates remain charged. However, the capacitor quickly discharges when it is short circuited.

The amount of electricity a capacitor can store depends on several factors, including the type of material of the dielectric. It is directly proportional to the plate area and inversely proportional to the distance between the plates.

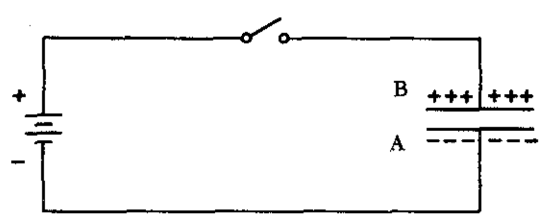


FIGURE 8–176. Capacitor in a d.c. circuit.

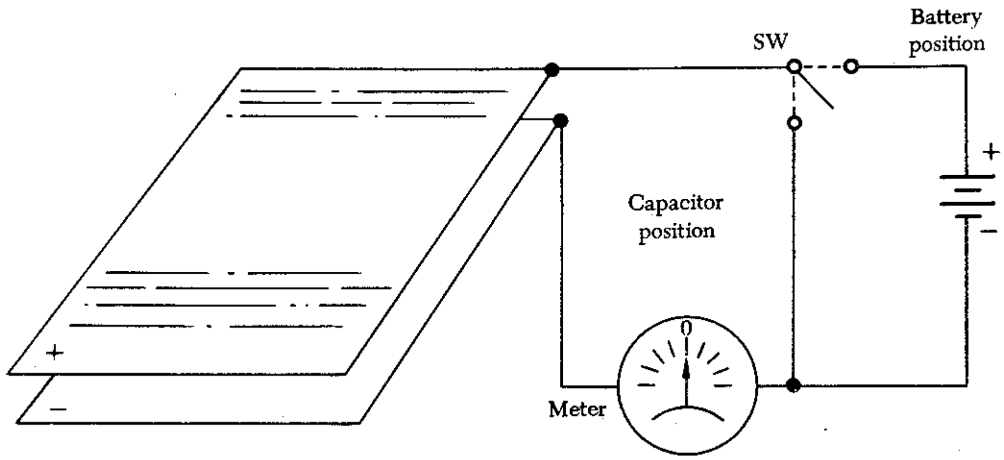


FIGURE 8–177. A basic capacitor (condenser) circuit.

In figure 8–177, two flat metal plates are placed close to each other (but not touching). Usually the plates are electrically neutral; that is, no electrical charge will be evident on either plate. At the instant the switch is closed to the battery position, the meter will show a definite current surge in one direction, but almost instantly will return to zero.

If the battery is then taken out of the circuit and the switch closed in the capacitor position, the meter again shows a momentary current surge, but this time in an opposite direction. From this experiment it is apparent that the two plates store energy when connected to a voltage source, and release the energy when short-circuited. The two plates make up a simple electrical capacitor, or condenser, and possess the property of storing electricity. The energy is actually stored in the electric, or dielectric, field between the plates.

Also, it should be clear that during the time the capacitor is being charged or discharged there is current in the circuit, even though the circuit is broken by the gap between the capacitor plates. However, there is current only during the time of charge and discharge, and this period of time is very short. There can be no continuous movement of direct current through a capacitor. A good capacitor will block direct current (not pulsating d.c.) and will pass the effects of alternating current.

The charge of electricity that can be placed on a capacitor is proportional to the applied voltage and to the capacitance of the capacitor (condenser). Capacitance depends upon the total area of the plates, the thickness of the dielectric and the composition of the dielectric.

If a thin sheet of bakelite (mica-filled) is substituted for air between the plates of a capacitor, for example, the capacitance will be increased about five times.

Any electric charge produced by applied voltage and kept in bounds by an insulator (dielectric) creates a dielectric field. Once the field is created, it tends to oppose any voltage change which would affect its original position. All circuits contain some capacitance, but unless they contain a unit called a capacitor, the capacitance, for all practical purposes, is disregarded. Two conductors, called electrodes or plates, separated by a nonconductor (dielectric) make up a simple capacitor. The plates may be made of copper, tin, or aluminum. Frequently, they are made of foil (metals compressed into thin sheets and capable of being rolled). The dielectric may be air, glass, mica, or an electrolyte made by an oxide film, but the type used will determine the amount of voltage that may be applied and the quantity of energy that will be stored. The dielectric materials have different atomic structures and present different quantities of atoms to the electrostatic field. All dielectric materials are compared to a vacuum and are given a numerical value according to the capacity ratio between them. The number given to a material is based on the same area and thickness as used in the vacuum. The numbers used to express this ratio are called dielectric constants and are expressed as the letter "K." The chart in figure 8–178 gives the K-value of some materials used.

If a source of alternating current is substituted for the battery, the capacitor acts quite differently than it does with direct current. When an