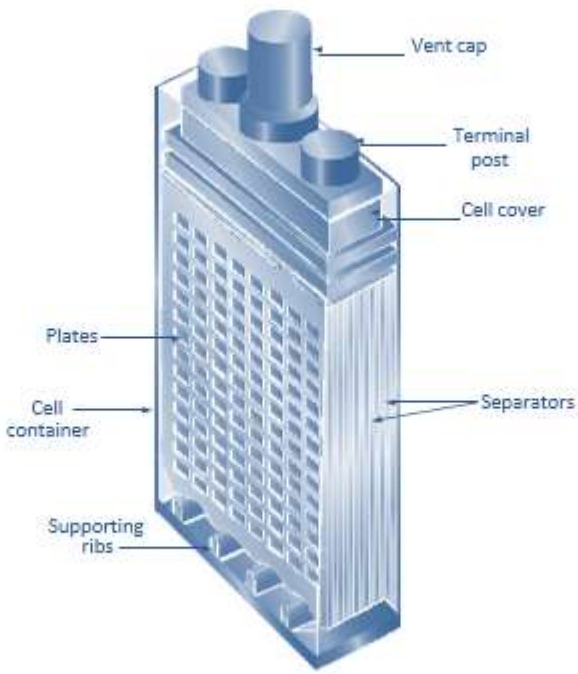
Batteries, Inverters, Semiconductors and Rectifiers



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Batteries

Primary Cell

The dry cell is the most common type of primary-cell battery and is similar in its characteristics to that of an electrolytic cell. This type of a battery is basically designed with a metal electrode or graphite rod acting as the cathode (+) terminal, immersed in an electrolytic paste. This electrode/electrolytic build-up is then encased in a metal container, usually made of zinc, which itself acts as the anode (−) terminal. When the battery is in a discharge condition an electrochemical reaction takes place resulting in one of the metals being consumed. Because of this consumption, the charging process is not reversible. Attempting to reverse the chemical reaction in a primary cell by way of recharging is usually dangerous and can lead to a battery explosion.

These batteries are commonly used to power items such as flashlights. The most common primary cells today are found in alkaline batteries, silver-oxide and lithium batteries. The earlier carbon-zinc cells, with a carbon post as cathode and a zinc shell as anode were once prevalent but are not as common.

Secondary Cell

A secondary cell is any kind of electrolytic cell in which the electrochemical reaction that releases energy is reversible. The lead-acid car battery is a secondary-cell battery. The electrolyte is sulphuric acid (battery acid), the positive electrode is lead peroxide, and the negative electrode is lead. A typical lead-acid battery consists of six lead-acid cells in a case. Each cell produces 2 volts, so the whole battery produces a total of 12 volts.

Other commonly used secondary cell chemistry types are nickel cadmium (NiCd), nickel metal hydride (NiMH), lithium ion (Li-ion), and Lithium ion polymer (Li-ion polymer).

Lead-acid batteries used in aircraft are similar to automobile batteries. The lead acid battery is made up of a series of identical cells each containing sets of positive and negative plates. Figure 10-182 illustrates each cell contains positive plates of lead dioxide (PbO_2), negative plates of spongy lead, and electrolyte (sulfuric acid and water). A practical cell is constructed with many more plates than just two in order to get the required current output. All positive plates are connected together as well as all the negatives. Because each positive plate is always positioned between two negative plates, there are always one or more negative plates than positive plates.

Between the plates are porous separators that keep the positive and negative plates from touching each other and shorting out the cell. The separators have vertical ribs on the side facing the positive plate. This construction permits the electrolyte to circulate freely around the plates. In addition, it provides a path for sediment to settle to the bottom of the cell.

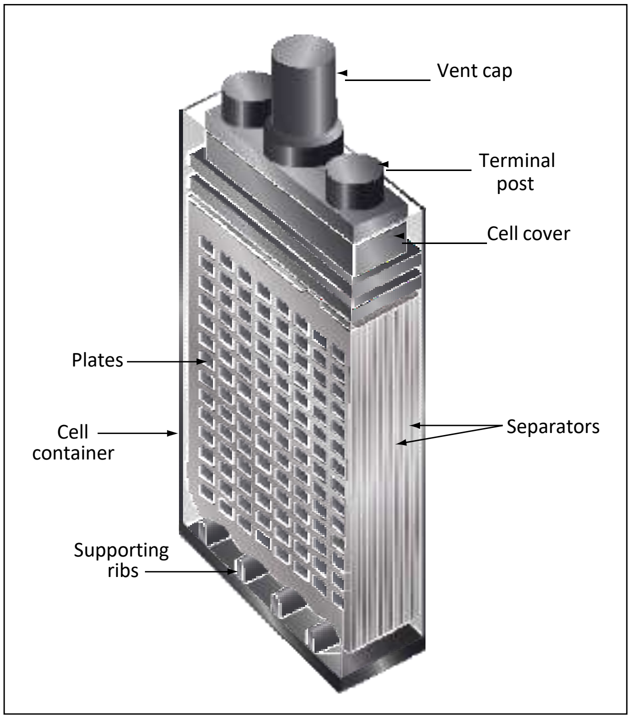

Figure 10-182. Lead-acid cell construction.

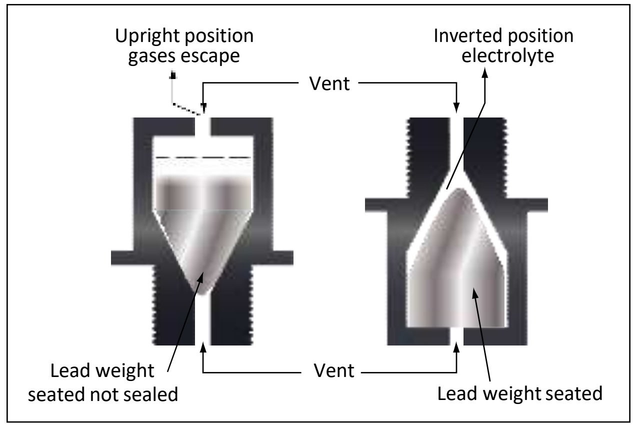

Figure 10-183. Nonspill battery vent plug.

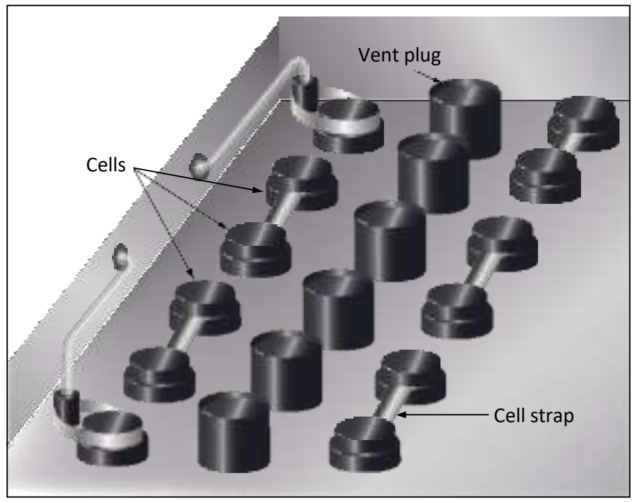

Figure 10-184. Connection of storage battery.

Each cell is seated in a hard rubber casing through the top of which are terminal posts and a hole into which is screwed a nonspill vent cap. The hole provides access for testing the strength of the electrolyte and adding water. The vent plug permits gases to escape from the cell with a minimum of leakage of electrolyte, regardless of the position the airplane might assume. Figure 10-183 shows the construction of the vent plug. In level flight, the lead weight permits venting of gases through a small hole. In inverted flight, this hole is covered by the lead weight.

The individual cells of the battery are connected in series by means of cell straps. [Figure 10-184] The complete assembly is enclosed in an acid resisting metal container (battery box), which serves as electrical shielding and mechanical protection. The battery box has a removable top. It also has a vent tube nipple at each end. When the battery is installed in an airplane, a vent tube is attached to each nipple. One tube is the intake tube and is exposed to the slipstream. The other is the exhaust vent tube and is attached to the battery drain sump, which is a glass jar containing a felt pad moistened with a concentrated solution of sodium bicarbonate (baking soda). With this arrangement, the airstream is directed through the battery case where battery gases are picked up, neutralized in the sump, and then expelled overboard without damage to the airplane.

To facilitate installation and removal of the battery in some aircraft, a quick disconnect assembly is used to connect the power leads to the battery. This assembly attaches the battery leads in the aircraft to a receptacle mounted on the side of the battery. [Figure 10-185] The receptacle covers the battery terminal posts and prevents accidental shorting during the installation and removal of the battery. The plug consists of a socket and a handwheel with a course pitch thread. It can be readily connected to the receptacle by the handwheel. Another advantage of this assembly is that the plug can be installed in only one position, eliminating the possibility of reversing the battery leads.

The voltage of lead acid cell is approximately 2 volts in order to attain the voltage required for the application. Each cell is then connected in series with heavy gage metal straps to form a battery. In a typical battery, such as that used in a aircraft for starting, the voltage required is 12 or 24 volts. This voltage is achieved by

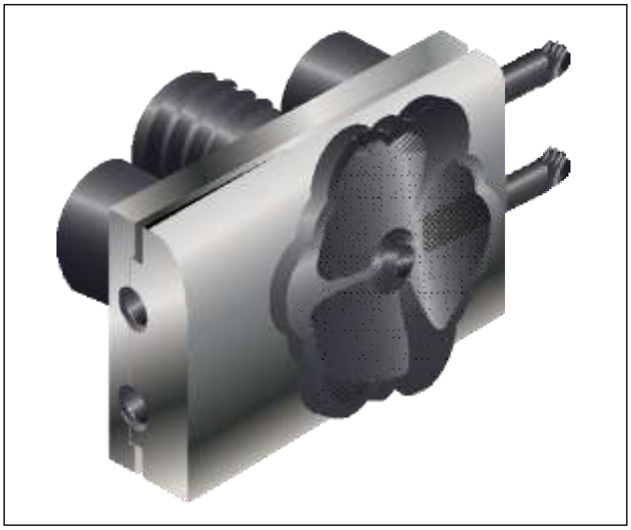

Figure 10-185. A battery quick-disconnect assembly.

connecting six cells or twelve cells respectively together in series and enclosing them in one plastic box.

Each cell containing the plates are filled with an electrolyte composed of sulphuric acid and distilled water with a specific gravity of 1.270 at 60 °F. This solution contains positive hydrogen ions and negative sulfate (SO_4) ions that are free to combine with other ions and form a new chemical compound. When the cell is discharged, electrons leave the negative plate and flow to the positive plates where they cause the lead dioxide (PbO_2) to break down into negative oxygen ions and positive lead ions. The negative oxygen ions join with positive hydrogen ions from the sulfuric acid and form water (H_2O). The negative sulfate ions join with the lead ions in both plates and form lead sulfate ($PbSO_4$). After the discharge, the specific gravity changes to about 1.150.

Battery Ratings

The voltage of a battery is determined by the number of cells connected in series to form the battery. Although the voltage of one lead-acid cell just removed from a charger is approximately 2.2 volts, a lead-acid cell is normally rated at approximately 2 volts. A battery rated at 12 volts consists of 6 lead-acid cells connected in series, and a battery rated at 24 volts is composed of 12 cells.

The most common battery rating is the amp-hour rating. This is a unit of measurement for battery capacity. It is determined by multiplying a current flow in amperes by the time in hours that the battery is being discharged.

A battery with a capacity of 1 amp-hour should be able to continuously supply a current of 1 amp to a load for exactly 1 hour, or 2 amps for 1/2 hour, or 1/3 amp for 3 hours, etc., before becoming completely discharged. Actually, the ampere-hour output of a particular battery depends on the rate at which it is discharged. Heavy discharge current heats the battery and decreases its efficiency and total ampere-hour output. For airplane batteries, a period of 5 hours has been established as the discharge time in rating battery capacity. However, this time of 5 hours is only a basis for rating and does not necessarily mean the length of time during which the battery is expected to furnish current. Under actual service conditions, the battery can be completely discharged within a few minutes, or it may never be discharged if the generator provides sufficient charge.

The ampere-hour capacity of a battery depends upon its total effective plate area. Connecting batteries in parallel increases ampere-hour capacity. Connecting batteries in series increases the total voltage but not the ampere-hour capacity.

Life Cycle of a Battery

Battery life cycle is defined as the number of complete charge/discharge cycles a battery can perform before its normal charge capacity falls below 80% of its initial rated capacity. Battery life can vary anywhere from 500 to 1,300 cycles. Various factors can cause deterioration of a battery and shorten its service life. The first is over-discharging, which causes excess sulphation; second, too-rapid charging or discharging which can result in overheating of the plates and shedding of active material. The accumulation of shed 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. The deterioration can continue to a point where cell capacity can drop to 80% after 1,000 cycles. In a lot of cases the cell can continue working to nearly 2,000 cycles but with a diminished capacity of 60% of its original state.

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 that measures the specific gravity (weight as compared with water) of liquids.

The most commonly used hydrometer consists of a small sealed glass tube weighted at its lower end so it

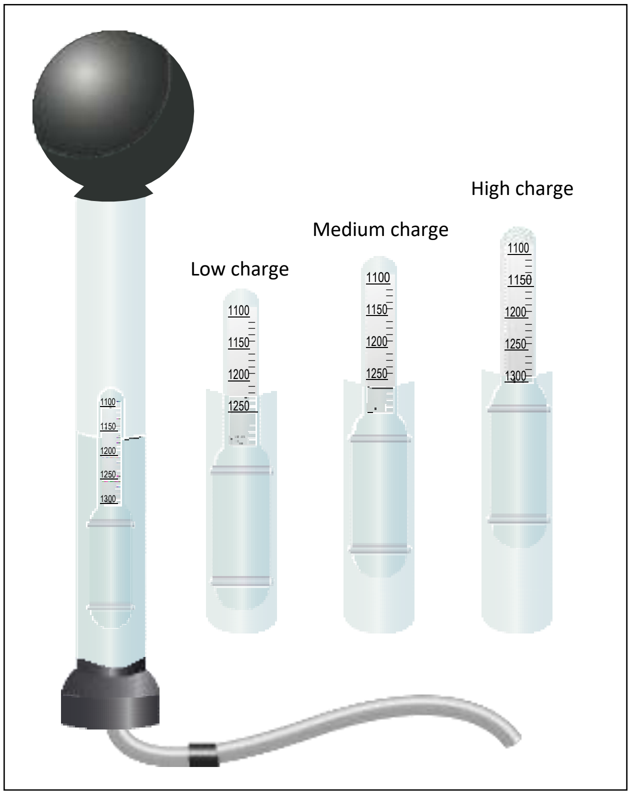

Figure 10-186. Hydrometer (specific gravity readings).

will float upright. [Figure 10-186] 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) becomes 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 that 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 consider. 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. Always take hydrometer readings 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 that does not represent the true strength of the solution.

Exercise extreme care when making the hydrometer test of a lead-acid cell. Handle the electrolyte carefully because sulfuric acid will burn clothing and skin. If the acid does contact the skin, wash the area thoroughly with water and then apply bicarbonate of soda.

Lead-Acid Battery Charging Methods

Passing direct current through the battery in a direction opposite to that of the discharge current may charge a storage battery. Because of the internal resistance (IR) in the battery, the 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).

Batteries are charged by either the constant voltage or constant current method. In the constant voltage method (Figure 10-187A), a motor generator set with

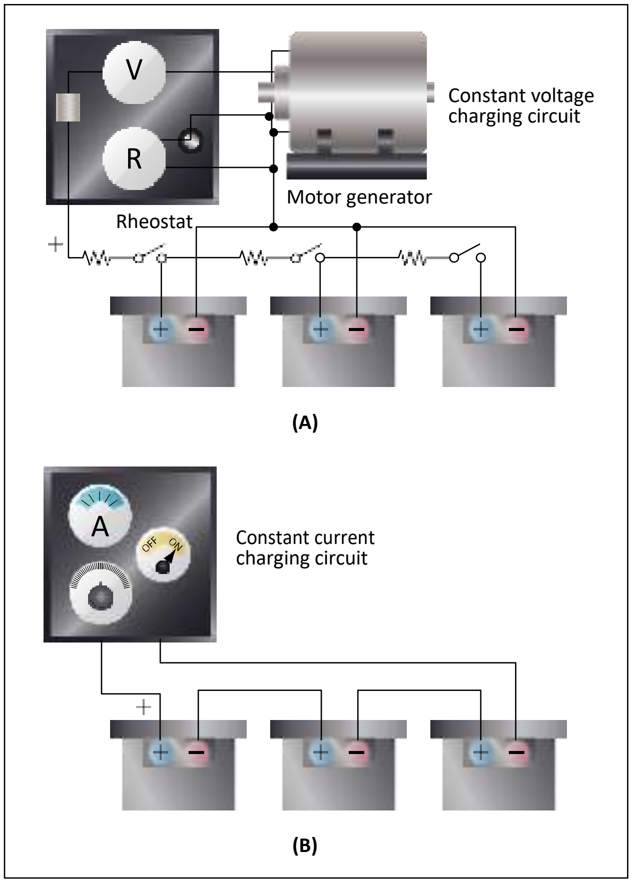

Figure 10-187. Battery charging methods.

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 (Figure 10-187B), 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 to take steps to prevent ignition of the gas mixture. Loosen the vent caps and leave in place. Do not permit open flames, sparks, or other sources of ignition 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

Chemistry and Construction

Active materials in nickel-cadmium cells (Ni-Cad) are nickel hydrate (NiOOH) in the charged positive plate (Anode) and sponge cadmium (Cd) in the charged negative plate (Cathode). The electrolyte is a potassium hydroxide (KOH) solution in concentration of 20–34 percent by weight pure KOH in distilled water.

Sintered nickel-cadmium cells have relatively thin sintered nickel matrices forming a plate grid structure. The grid structure is highly porous and is impregnated with the active positive material (nickel-hydroxide) and the negative material (cadmium-hydroxide). The plates are then formed by sintering nickel powder to fine-mesh wire screen. In other variations of the process the active material in the sintered matrix is converted chemically, or thermally, to an active state and then formed. In general, there are many steps to these cycles of impregnation and formation. Thin sintered plate cells are ideally suited for very high rate charge and discharge service. Pocket plate nickel-cadmium cells have the positive or negative active material, pressed into pockets of perforated nickel plated steel plates or into tubes. The active material is trapped securely in contact with a metal current collector so active material shedding is largely eliminated. Plate designs vary in thickness depending upon cycling service requirements. The typical open circuit cell voltage of a nickel-cadmium battery is about 1.25 volts.

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.

General Maintenance and Safety Precautions

Refer to the battery manufacturer for detailed service instructions. Below are general recommendations for maintenance and safety precautions. For vented nickel-cadmium cells, the general maintenance requirements are:

1. Hydrate cells to supply water lost during overcharging.
2. Maintain inter-cell connectors at proper torque values.
3. Keep cell tops and exposed sides clean and dry.

Electrolyte spillage can form grounding paths. White moss around vent cap seals is potassium carbonate (K_2CO_3). Clean up these surfaces with distilled water and dry. While handling the caustic potassium hydroxide electrolyte, wear safety goggles to protect the eyes. The technician should also wear plastic gloves and an apron to protect skin and clothes. In case of spillage on hands or clothes, neutralize the alkali immediately with vinegar or dilute boric acid solution (one pound per gallon of water); then rinse with clear water.

During overcharging conditions, explosive mixtures of hydrogen and oxygen develop in nickel-cadmium cells. When this occurs, the cell relief valves vent these gases to the atmosphere, creating a potentially explosive hazard. Additionally, room ventilation should be such as to prevent a hydrogen build up in closed spaces from exceeding one percent by volume. Explosions can occur at concentrations above four percent by volume in air.

Sealed Lead Acid Batteries

In many applications, sealed lead acid (SLA) batteries are gaining in use over the Ni-Cad batteries. One leading characteristic of Ni-Cad batteries is that they perform well in low voltage, full-discharge, high cycle applications. However, they do not perform as well in extended standby applications, such as auxiliary or as emergency battery packs used to power inertial reference units or stand-by equipment (attitude gyro).

It is typical during the servicing of a Ni-Cad battery to match as many as twenty individual cells in order to prevent unbalance and thus cell reversal during end of discharge. When a Ni-Cad does reverse, very high pressure and heat can result. The result is often pressure seal rupture, and in the worst case, a cell explosion. With SLA batteries, cell matching is inherent in each battery. Ni-Cads also have an undesirable characteristic caused by constant overcharge and infrequent discharges, as in standby applications. It is technically known as "voltage depression" and commonly but erroneously called "memory effect." This characteristic is only detectable when a full discharge is attempted. Thus, it is possible to believe a full charge exists, while in fact it does not. SLA batteries do not have this characteristic voltage depression (memory) phenomenon, and therefore do not require scheduled deep cycle maintenance as do Ni-Cads.

The Ni-Cad emergency battery pack requires relatively complicated test equipment due to the complex characteristics of the Ni-Cad. Sealed lead acid batteries do not have these temperamental characteristics and therefore it is not necessary to purchase special battery maintenance equipment. Some manufactures of SLA batteries have included in the battery packs a means by which the battery can be tested while still installed on the aircraft. Ni-Cads must have a scheduled energy test performed on the bench due to the inability to measure their energy level on the aircraft, and because of their notable "memory" shortcoming.

The SLA battery can be designed to alert the technician if a battery is failing. Furthermore, it may be possible to test the failure detection circuits by activating a Built in Test (BITE) button. This practice significantly reduces FAA paperwork and maintenance workload.

Inverters

An inverter is used in some aircraft systems to convert a portion of the aircraft's DC power to AC. This AC is used mainly for instruments, radio, radar, lighting, and other accessories. These inverters are usually built to supply current at a frequency of 400 cps, but some are designed to provide more than one voltage; for example, 26 volt AC in one winding and 115 volts in another.

There are two basic types of inverters: the rotary and the static. Either type can be single phase or multiphase. The multiphase inverter is lighter for the same power rating than the single phase, but there are complications in distributing multiphase power and in keeping the loads balanced.

Rotary Inverters

There are many sizes, types, and configurations of rotary inverters. Such inverters are essentially AC generators and DC motors in one housing. The generator field, or armature, and the motor field, or armature, are mounted on a common shaft that will rotate within the housing. One common type of rotary inverter is the permanent magnet inverter.

Permanent Magnet Rotary Inverter

A permanent magnet inverter is composed of a DC motor and a permanent magnet AC generator assembly. Each has a separate stator mounted within a common housing. The motor armature is mounted on a rotor and connected to the DC supply through a commutator and brush assembly. The motor field windings are mounted on the housing and connected directly to the DC supply. A permanent magnet rotor is mounted at the

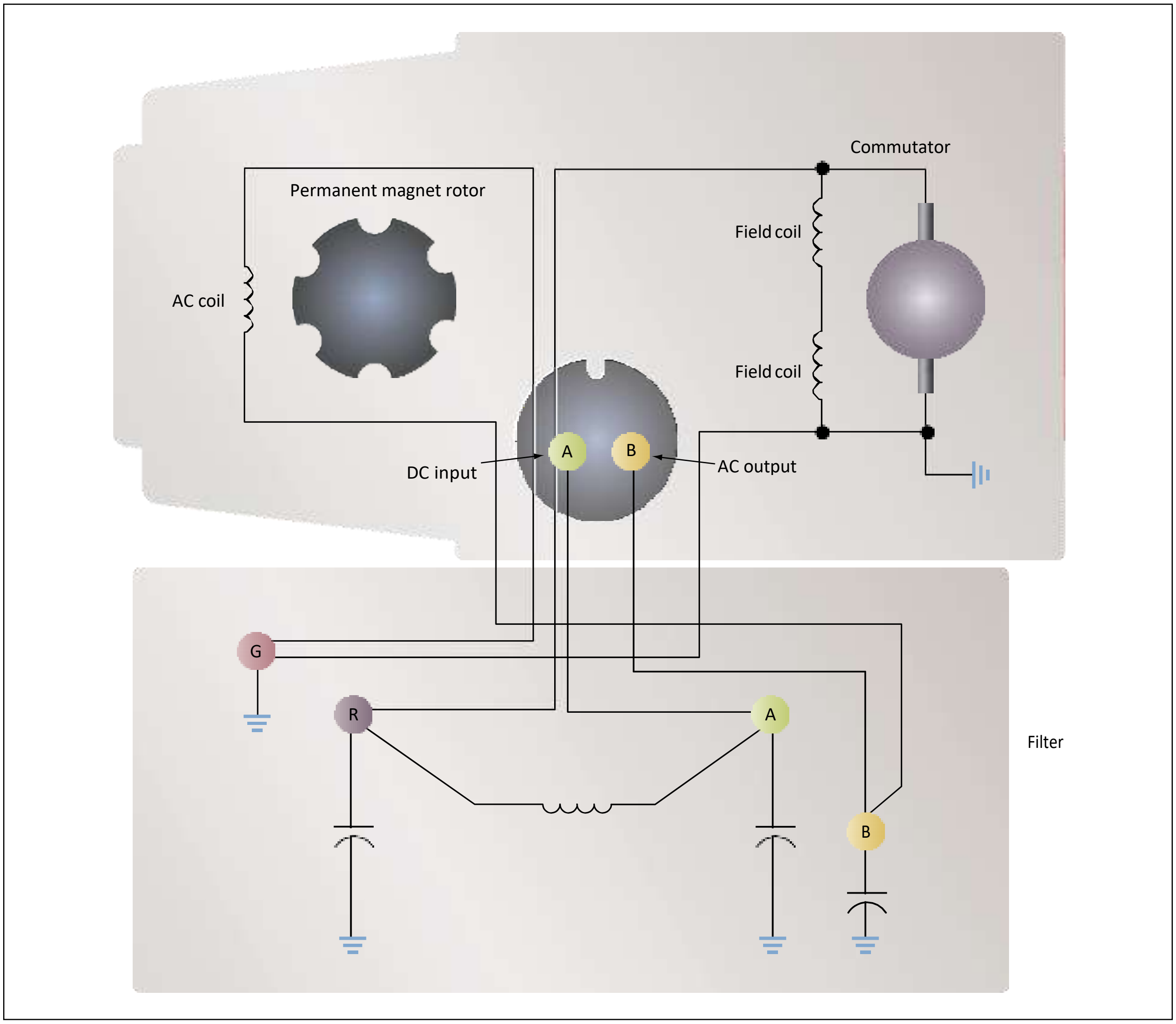

Figure 10-188. Internal wiring diagram of single-phase permanent magnet rotary inverter.

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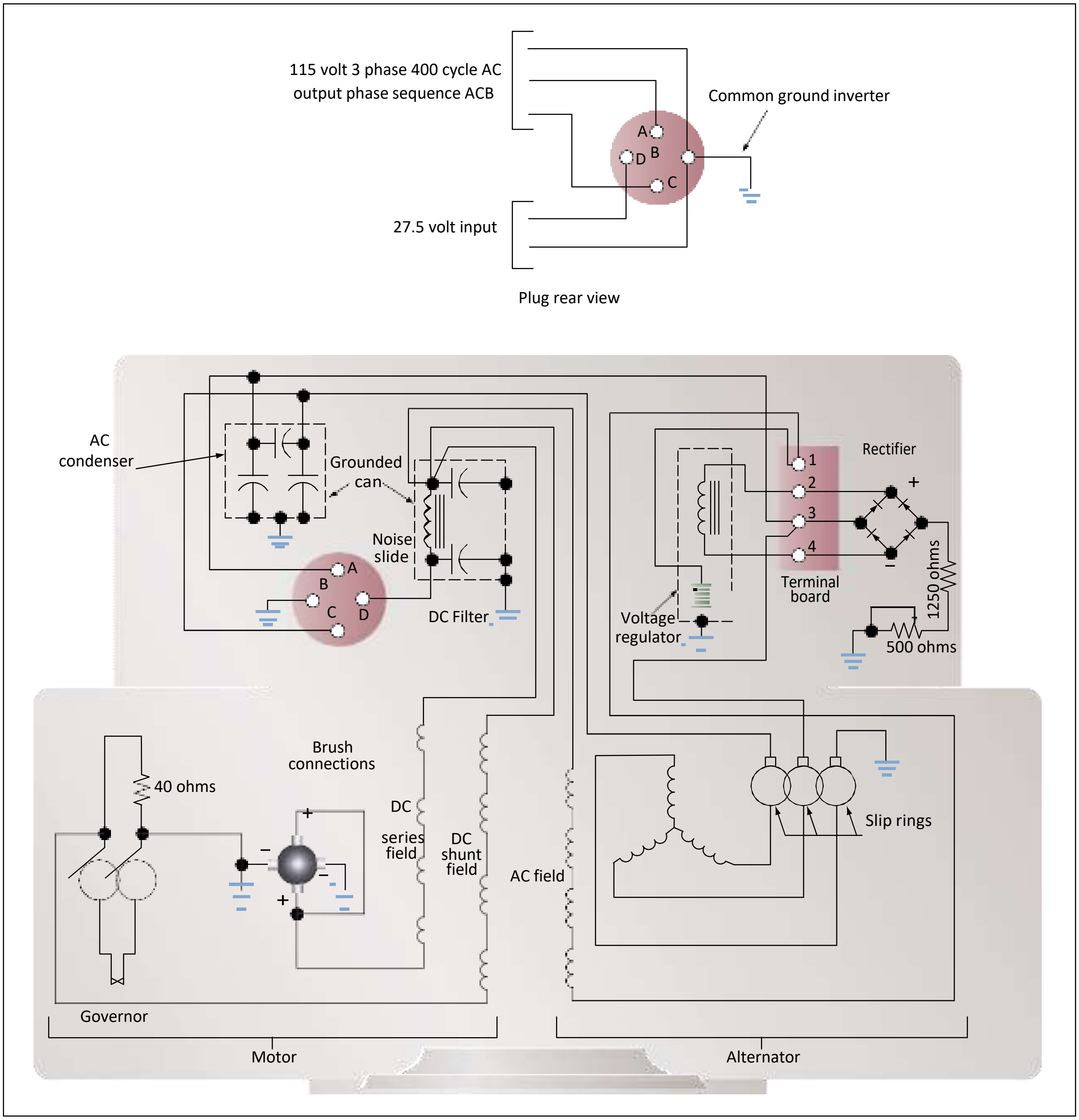

Figure 10-189. Internal wiring diagram of three-phase, revolving armature.

opposite end of the same shaft as the motor armature, and the stator windings are mounted on the housing, allowing AC to be taken from the inverter without the use of brushes. Figure 10-188 shows an internal wiring diagram for this type of rotary inverter. The generator rotor has six poles, magnetized to provide alternate north and south poles about its circumference.

When the motor field and armature are excited, the rotor will begin to turn. As the rotor turns, the permanent magnet will rotate within the AC stator coils, and the magnetic flux developed by the permanent magnets will be cut by the conductors in the AC stator coils. An AC voltage will be produced in the windings whose polarity will change as each pole passes the windings.

This type inverter may be made multiphase by placing more AC stator coils in the housing in order to shift the phase the proper amount in each coil.

As the name of the rotary inverter indicates, it has a revolving armature in the AC generator section. The illustration in Figure 10-189 shows the diagram of a revolving armature, three phase inverter.

The DC motor in this inverter is a four pole, compound wound motor. The four field coils consist of many turns of fine wire, with a few turns of heavy wire placed on top. The fine wire is the shunt field, connected to the DC source through a filter and to ground through a centrifugal governor. The heavy wire is the series field, which is connected in series with the motor armature. The centrifugal governor controls the speed by shunting a resistor that is in series with the shunt field when the motor reaches a certain speed.

The alternator is a three-phase, four-pole, star-connected AC generator. The DC input is supplied to the generator field coils and connected to ground through a voltage regulator. The output is taken off the armature through three slip rings to provide three-phase power.

The inverter would be a single-phase inverter if it had a single armature winding and one slip ring.

The frequency of this type unit is determined by the speed of the motor and the number of generator poles.

Inductor-Type Rotary Inverter

Inductor-type inverters use a rotor made of soft iron laminations with grooves cut laterally across the surface to provide poles that correspond to the number of stator poles, as illustrated in Figure 10-190. The field coils are wound on one set of stationary poles and the AC armature coils on the other set of stationary poles. When DC is applied to the field coils, a magnetic field is produced. The rotor turns within the field coils and, as the poles on the rotor align with the stationary poles, a low reluctance path for flux is established from the field pole through the rotor poles to the AC armature pole and through the housing back to the field pole. In this circumstance, there will be a large amount of magnetic flux linking the AC coils.

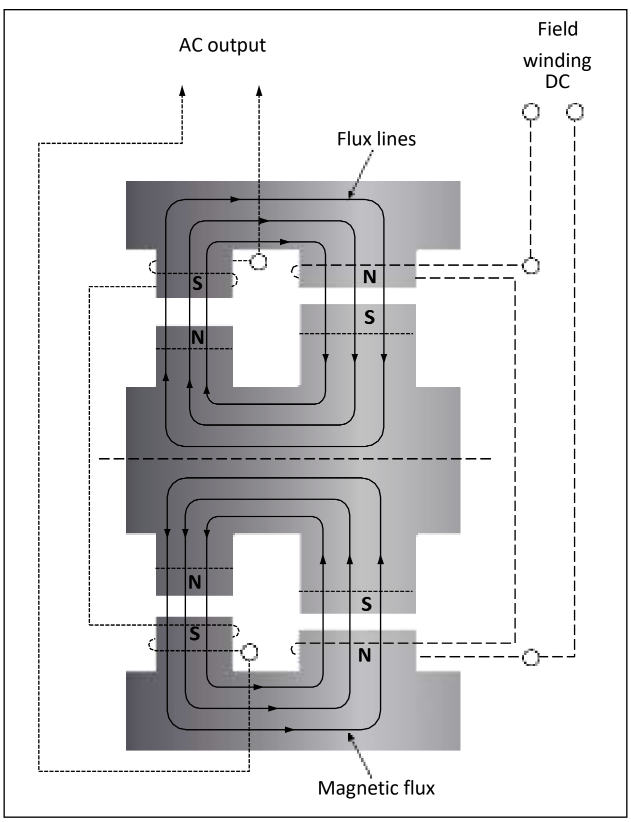

Figure 10-190. Diagram of basic inductor-type inverter.

When the rotor poles are between the stationary poles, there is a high reluctance path for flux, consisting mainly of air; then, there will be a small amount of magnetic flux linking the AC coils. This increase and decrease in flux density in the stator induces an alternating current in the AC coils.

The number of poles and the speed of the motor determine the frequency of this type of inverter. The DC stator field current controls the voltage. A cutaway view of an inductor-type rotary inverter is shown in Figure 10-191.

Figure 10-192 is a simplified diagram of a typical aircraft AC power distribution system, utilizing a main and a standby rotary inverter system.

Static Inverters

In many applications where continuous DC voltage must be converted to alternating voltage, static inverters are used in place of rotary inverters or motor generator sets. The rapid progress made by the semiconductor industry is extending the range of applications of such equipment into voltage and power ranges that would have been impractical a few years ago. Some such applications are power supplies for frequency sensitive military and commercial AC equipment, aircraft emergency AC systems, and conversion of wide frequency range power to precise frequency power.

The use of static inverters in small aircraft also has increased rapidly in the last few years, and the technology has advanced to the point that static inverters are available for any requirement filled by rotary inverters. For example, 250 VA emergency AC supplies operated from aircraft batteries are in production, as are 2,500 VA main AC supplies operated from a varying frequency generator supply. This type of equipment has certain advantages for aircraft applications, particularly the absence of moving parts and the adaptability to conduction cooling.

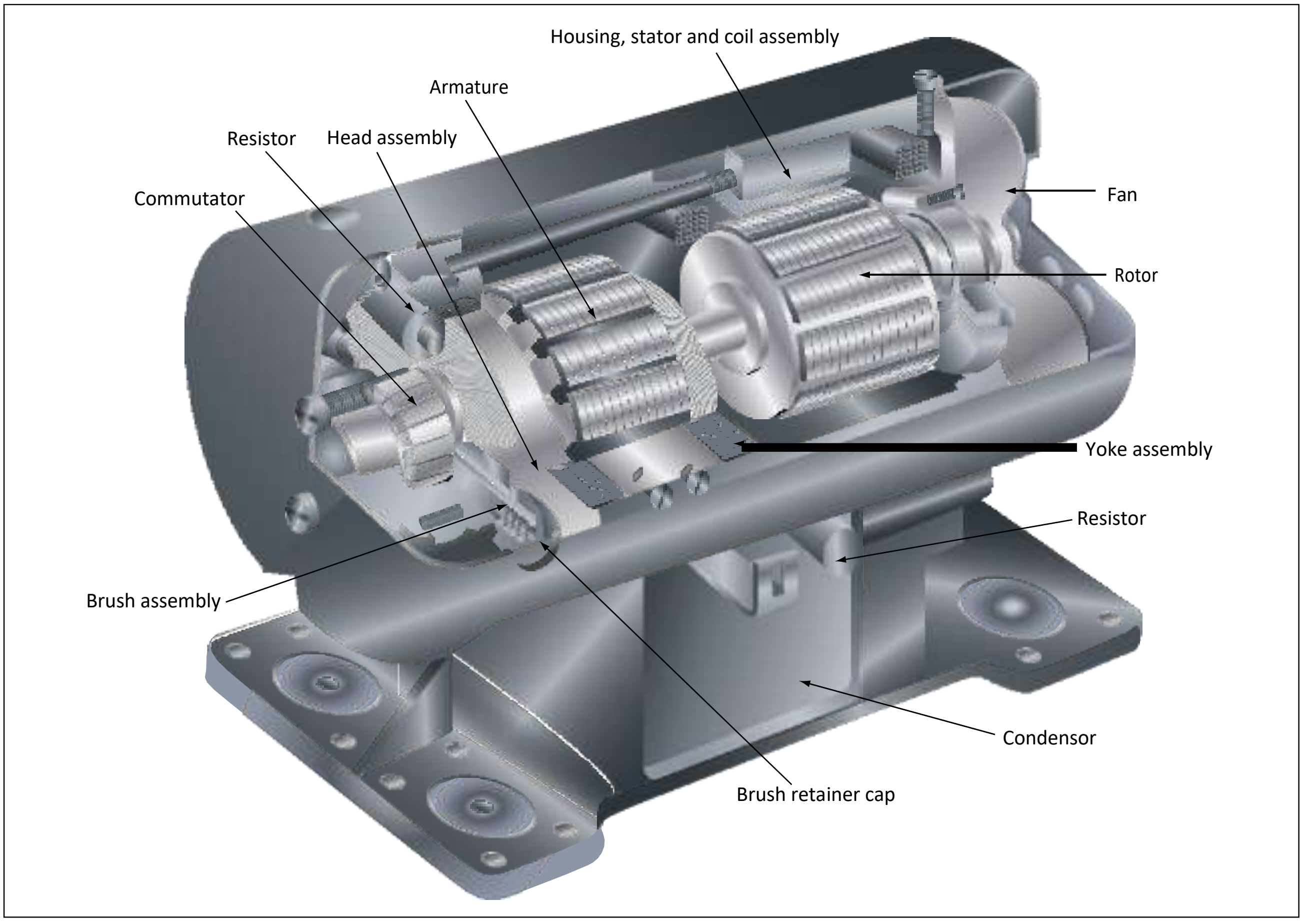

Figure 10-191. Cutaway view of inductor-type rotary inverter.

Static inverters, referred to as solid-state inverters, are manufactured in a wide range of types and models, which can be classified by the shape of the AC output waveform and the power output capabilities. One of the most commonly used static inverters produces a regulated sine wave output. A block diagram of a typical regulated sine wave static inverter is shown in Figure 10-193. This inverter converts a low DC voltage into higher AC voltage. The AC output voltage is held to a very small voltage tolerance, a typical variation of less than 1 percent with a full input load change. Output taps are normally provided to permit selection of various voltages; for example, taps may be provided for a 105, 115, and 125 volt AC outputs. Frequency regulation is typically within a range of one cycle for a 0 –100 percent load change.

Variations of this type of static inverter are available, many of which provide a square wave output.

Since static inverters use solid-state components, they are considerably smaller, more compact, and much lighter in weight than rotary inverters. Depending on the output power rating required, static inverters that are no larger than a typical airspeed indicator can be used in aircraft systems. Some of the features of static inverters are:

1. High efficiency.
2. Low maintenance, long life.
3. No warmup period required.
4. Capable of starting under load.
5. Extremely quiet operation.
6. Fast response to load changes.

Static inverters are commonly used to provide power for such frequency sensitive instruments as the attitude gyro and directional gyro. They also provide power for autosyn and magnesyn indicators and transmitters, rate gyros, radar, and other airborne applications. Figure 10-194 is a schematic of a typical small jet aircraft auxiliary battery system. It shows the battery as input to the inverter, and the output inverter circuits to various subsystems.

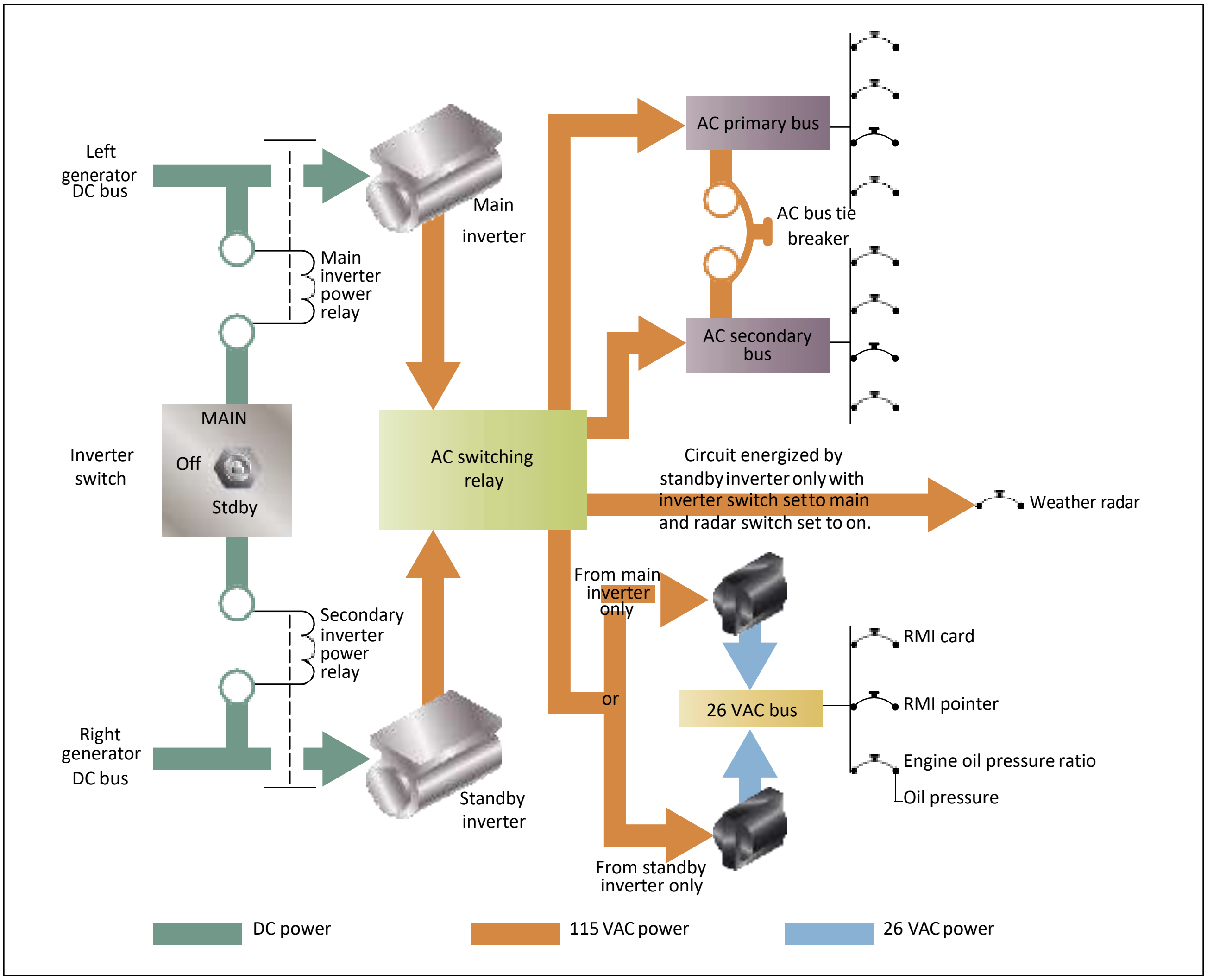

Figure 10-192. A typical aircraft AC power distribution system using main and standby rotary inverters.

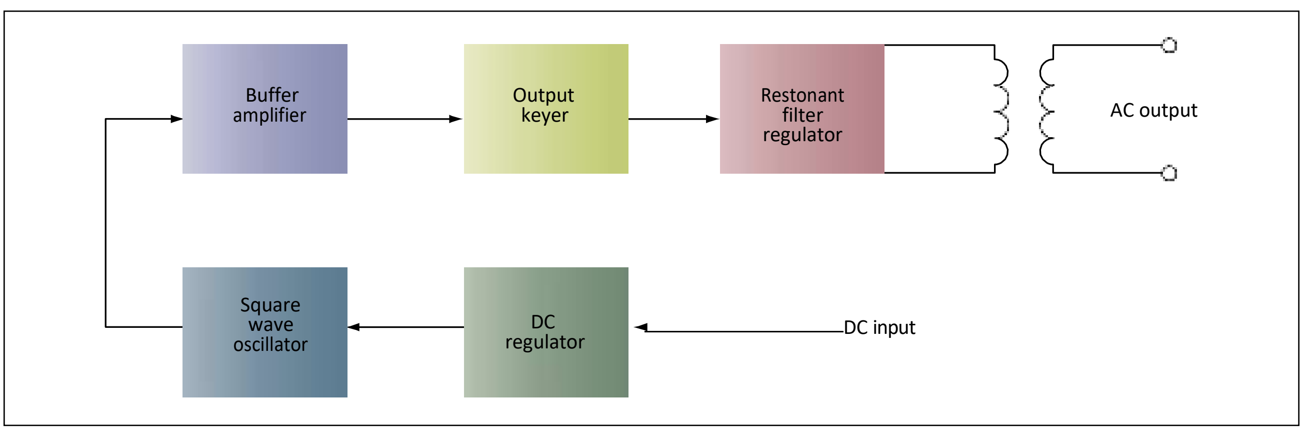

Figure 10-193. Regulated sine wave static inverter.

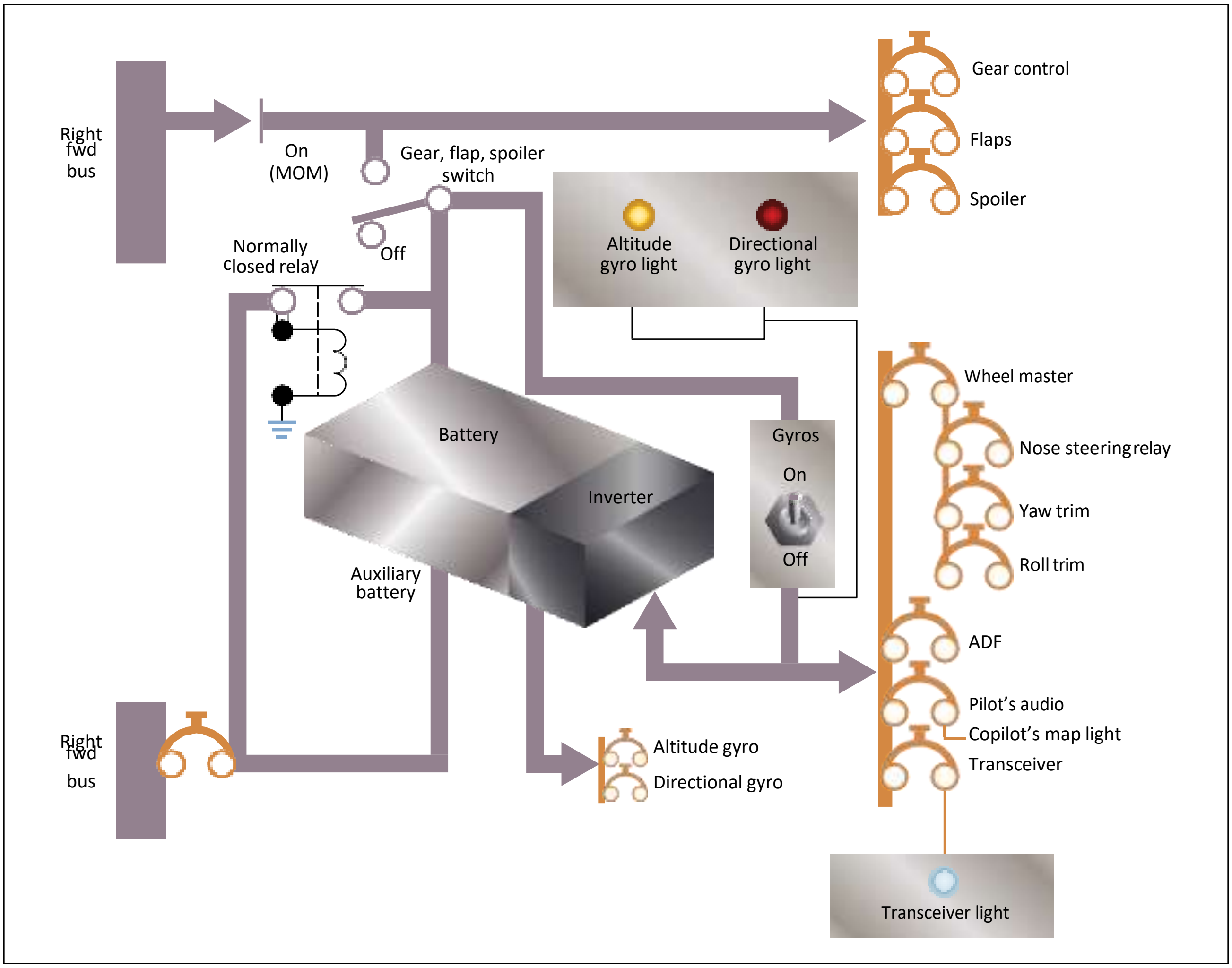

Figure 10-194. Auxiliary battery system using static inverter.

Semiconductors

To understand why solid-state devices function as they do, it is necessary to examine the composition and nature of semiconductors. The two most common materials used for semiconductors are germanium and silicon. The essential characteristic of these elements is that each atom has four valence electrons to share with adjacent atoms in forming bonds. While both elements are used in semiconductor construction, silicon is preferred in most modern applications due to its ability to operate over a wider range of temperatures. The nature of a bond between two silicon atoms is such that each atom provides one electron to share with the other. The two electrons shared are in fact shared equally between the two atoms. This form of sharing is known as a covalent bond. Such bonds are very stable, and hold the two atoms together very tightly, requiring much energy to break this bond. [Figure 10-195] In this case, all of the outer electrons are used to make covalent bonds with other silicon atoms. In this condition, because all of the outer shell atoms are used, silicon takes on the characteristic of a good insulator, due to the fact that there are no open positions available for electrons to migrate through the orbits.

For the silicon crystal to conduct electricity there must be some means available to allow some electrons to move from place to place within the crystal, regardless of the covalent bonds present between the atoms. One way to accomplish this is to introduce an impurity such as arsenic or phosphorus into the crystal structure, which will either provide an extra electron or create a vacant position in the outer shell for electrons to pass though. The method used to create this condition is called doping.

Doping

Doping is the process by which small amounts of additives called impurities are added to the semiconductor material to increase their current flow by adding a few electrons or a few holes. Once the material is doped,

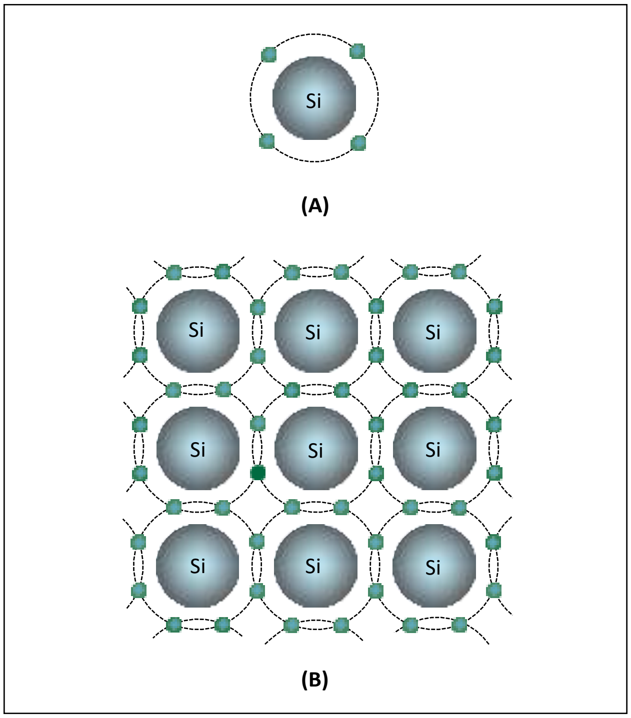

Figure 10-195. Valance electrons.

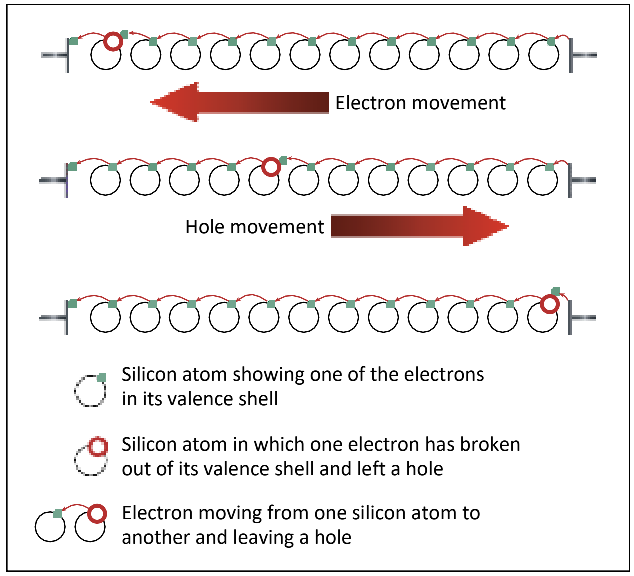

Figure 10-196. A hole moving through atoms.

it then falls into one of two categories: the N-type semiconductor and the P-type semiconductor.

An N-type semiconductor material is one that is doped with an N-type or a donor impurity. Elements such as phosphorus, arsenic and antimony are added as impurities and have five outer electrons to share with other atoms. This will cause the semiconductor material to have an excess electron. Due to the surplus of electrons, the electrons are then considered the majority current carriers. This electron can easily be moved with only a small applied electrical voltage. Current flow in an N-type silicon material is similar to conduction in a copper wire. That is, with voltage applied across the material, electrons will move through the crystal towards the positive terminal just like current flows in a copper wire.

A P-type semiconductor is one that is doped with a P-type or an acceptor impurity. Elements such as boron, aluminum, and gallium have only three electrons in the valence shell to share with the silicon atom. Those three electrons will form covalent bonds with adjacent silicon atoms. However, the expected fourth bond cannot be formed and a complete connection is impossible here, leaving a "hole" in the structure of the crystal. There is an empty place where an electron would naturally go, and often an electron will move into that space to fill it. However, the electron filling the hole left a covalent bond behind to fill this empty space, which leaves another hole behind as it moves. Another electron may then move into that particular hole, leaving another hole behind. As this progression continues, holes appear to move as positive charges throughout the crystal. This type of semiconductor material is designated P-type silicon material. Figure 10-196 shows the progression of a hole moving through a number of atoms. Notice that the hole illustrated at the far left of the top depiction of Figure 10-196 attracts the next valance electron into the vacancy, which then produces another vacancy called a hole in the next position to the right. Once again this vacancy attracts the next valance electron. This exchange of holes and electrons continues to progress, and can be viewed in one of two ways: electron movement or hole movement. For electron movement, illustrated by the top depiction of Figure 10-196, the electron is shown as moving from the right to the left through a series of holes. In the second depiction in Figure 10-196, the motion of the vacated hole can be seen as migration from the left to the right, called hole movement. The valence electron in the structure will progress along a path detailed by the arrows. Holes, however, move along a path opposite that of the electrons.

PN Junctions and the Basic Diode

A single type of semiconductor material by itself is not very useful. Useful applications are developed only when a single component contains both P-type and N-type materials. The semiconductor diode is also known as a PN junction diode. This is a two-element semiconductor device that makes use of the rectifying properties of a PN junction to convert alternating current into direct current by permitting current flow in one direction only.

Figure 10-197 illustrates the electrical characteristics of an unbiased diode, which means that no external voltage is applied. The P-side in the illustration is shown to have many holes, while the N-side shows many electrons. The electrons on the N-side tend to diffuse out in all directions. When an electron enters the P region, it becomes a minority carrier. By definition, a minority carrier is an electron or hole, whichever is the less dominant carrier in a semiconductor device. In P-type materials, electrons are the minority carrier and in N-type material, the hole is considered the minority carrier. With so many holes around the electron, the electron will soon drop into a hole. When this occurs, the hole then disappears, and the conduction band electron becomes a valence electron.

Each time an electron crosses the PN junction, it creates a pair of ions. In Figure 10-197 this is shown in the area outlined by the dash lines. The circled plus signs and the circled negative signs are the positive and negative ions, respectively. These ions are fixed in the crystal and do not move around like electrons or holes in the conduction band. Thus, the depletion zone constitutes a layer of a fixed charge. An electrostatic field, represented by a small battery in Figure 10-195, is

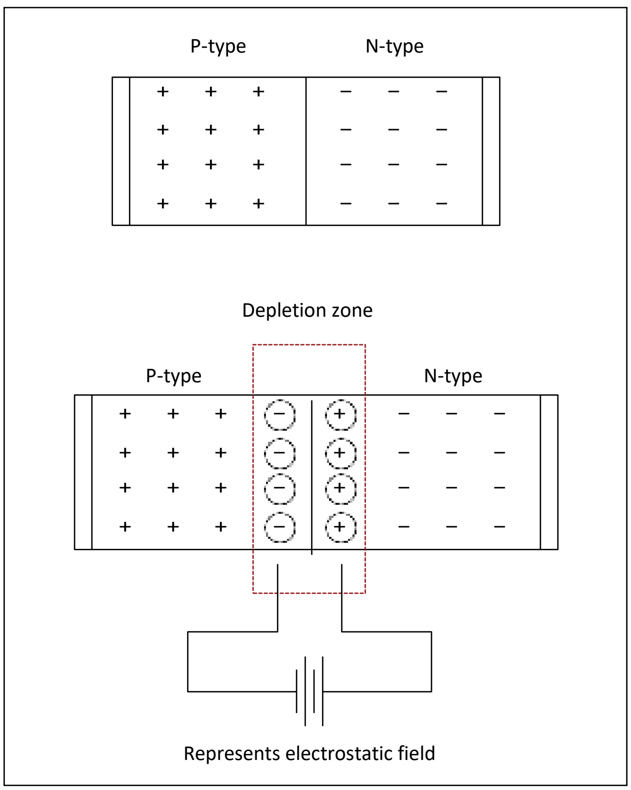

Figure 10-197. Depletion region.

established across the junction between the oppositely charged ions.

The junction barrier is an electrostatic field, which has been created by the joining of a section of N-type and P-type material. Because holes and electrons must overcome this field to cross the junction, the electrostatic field is usually called a barrier. Because there is a lack or depletion of free electrons and holes in the area around the barrier, this area is called the depletion region. [Figure 10-197] As the diffusion of electrons and holes across the junction continue, the strength of the electrostatic field will increase until it is strong enough to prevent electrons or holes from crossing over. At this point, a state of equilibrium exists, and there is no further movement across the junction. The electrostatic field created at the junction by the ions in the depletion zone is called a barrier.

Forward Biased Diode

Figure 10-198 illustrates a forward biased PN junction. When an external voltage is applied to a PN junction, it as called bias. In a forward biased PN junction or diode, the negative voltage source is connected to the N-type material and the positive voltage source is connected to the P-type material. In this configuration, the current can easily flow. If a battery is used to bias the PN junction and it is connected in such a way that the applied voltage opposes the junction field, it will have the effect of reducing the junction barrier and consequently aid in the current flow through the junction.

The electrons move toward the junction and the right end of the diode becomes slightly positive. This occurs because electrons at the right end of the diode move toward the junction and leave positively charged atoms behind. The positively charged atoms then pull

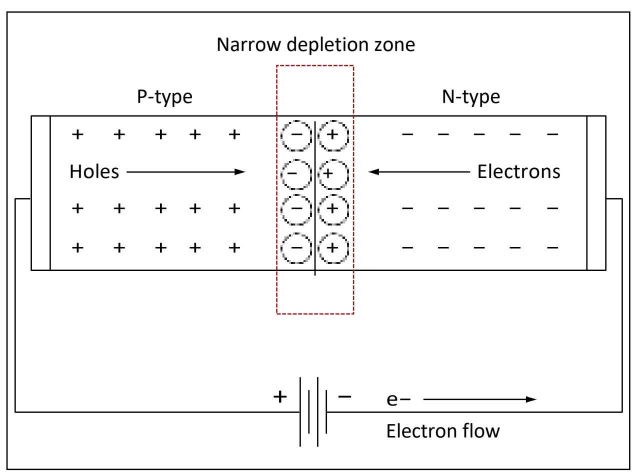

Figure 10-198. Forward biased PN junction.

electrons into the diode from the negative terminal of the battery.

When electrons on the N-type side approach the junction, they recombine with holes. Basically, electrons are flowing into the right end of the diode, while the bulk of the electrons in the N-type material move toward the junctions. The left edge of this moving front of electrons disappears by dropping into holes at the junction. In this way, there is a continuous current of electrons from the battery moving toward the junction.

When the electrons hit the junction, they then become valence electrons. Once a valence electron, they can then move through the holes in the P-type material. When the valence electrons move through the P-type material from the right to the left, a similar movement is occurring with the holes by moving from the left side of the P-type material to the right. Once the valence electron reaches the end of the diode, it will then flow back into the positive terminal of the battery.

In summary:

1. Electron leaves negative terminal of the battery and enters the right end (N-type material) of the diode.
2. Electron then travels through the N-type material.
3. The electron nears the junction and recombines and becomes a valence electron.
4. The electron now travels through the P-type material as a valence electron.
5. The electron then leaves the diode and flows back to the positive terminal of the battery.

Reverse Biased Diode

When the battery is turned around as shown in Figure 10-199, then the diode is reverse biased and current will not flow. The most noticeable effect seen in this illustration is the widened depletion zone.

The applied battery voltage is in the same direction as the depletion zone field. Because of this, holes and electrons tend to move away from the junction. Simply stated, the negative terminal attracts the holes away from the junction, and the positive terminal attracts the electrons away from the barrier. Therefore, the result is a wider depletion zone. This action increases the barrier width because there are more negative ions on the P-side of the junction and more positive ions on the N-side of the junction. This increase in the number of ions at the junction prevents current flow across the barrier by the majority carriers.

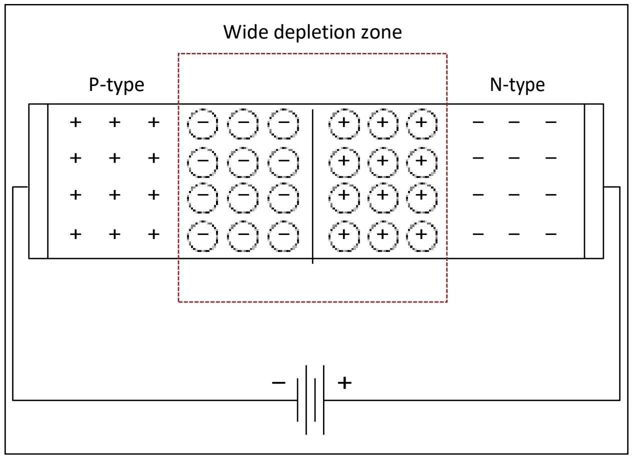

Figure 10-199. Reversed diode.

To summarize, the important thing to remember is that these PN junction diodes will offer very little resistance to current in a forward biased diode. Maximum resistance will happen when the diode is reversed biased. Figure 10-200 shows a graph of the current characteristics of a diode that is biased in both directions.

Rectifiers

Many devices in an aircraft require high amperage, low voltage DC for operation. This power may be furnished by DC engine driven generators, motor generator sets, vacuum tube rectifiers, or dry disk or solid-state rectifiers.

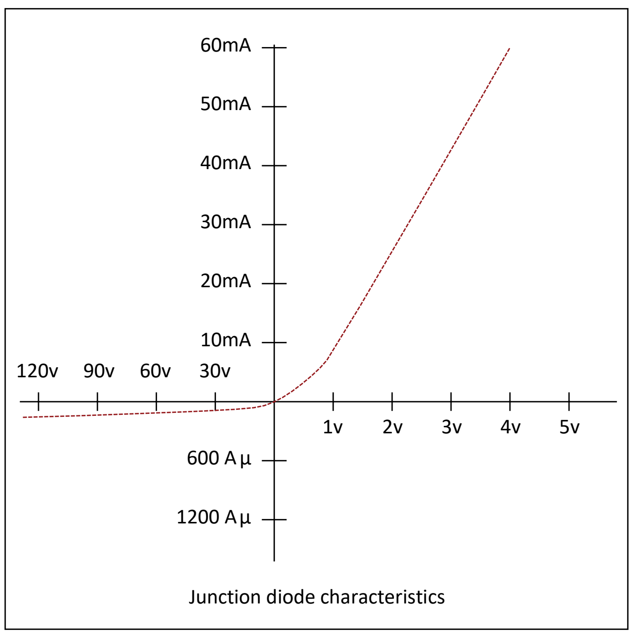

Figure 10-200. Diode biased in both directions.

In aircraft with AC systems, a special DC generator is not desirable since it would be necessary for the engine accessory section to drive an additional piece of equipment. Motor generator sets, consisting of air-cooled AC motors that drive DC generators, eliminate this objection because they operate directly off the AC power system. Vacuum tube or various types of solid-state rectifiers provide a simple and efficient method of obtaining high voltage DC at low amperage. Dry disk and solid-state rectifiers, on the other hand, are an excellent source of high amperage at low voltage.

A rectifier is a device that transforms alternating current into direct current by limiting or regulating the direction of current flow. The principal types of rectifiers are dry disk and solid state. Solid-state, or semiconductor, rectifiers have replaced virtually all other types; and, since dry disk and motor generators are largely limited to older model aircraft, the major part of the study of rectifiers is devoted to solid-state devices used for rectification.

The two methods discussed in this text are the half-wave rectifier and the full-wave rectifier.

Half-Wave Rectifier

Figure 10-201 illustrates the basic concept of a half-wave rectifier. When an AC signal is on a positive swing as shown in illustration A of the input signal, the polarities across the diode and the load resistor will also be positive. In this case, the diode is forward biased and can be replaced with a short circuit as shown in the illustration. The positive portion of the input signal will then appear across the load resistor with no loss in potential across the series diode.

Illustration B now shows the input signal being reversed. Note that the polarities across the diode and the load resistor are also reversed. In this case, the diode is now reverse biased and can be replaced with an equivalent open circuit. The current in the circuit is now 0 amperes and the voltage drop over the load resistor is 0 volts. The resulting waveform for a complete sinusoidal input can be seen at the far right of Figure 10-201. The output waveform is a reproduction of the input waveform minus the negative voltage swing of the wave. For this reason, this type of rectifier is called a half-wave rectifier.

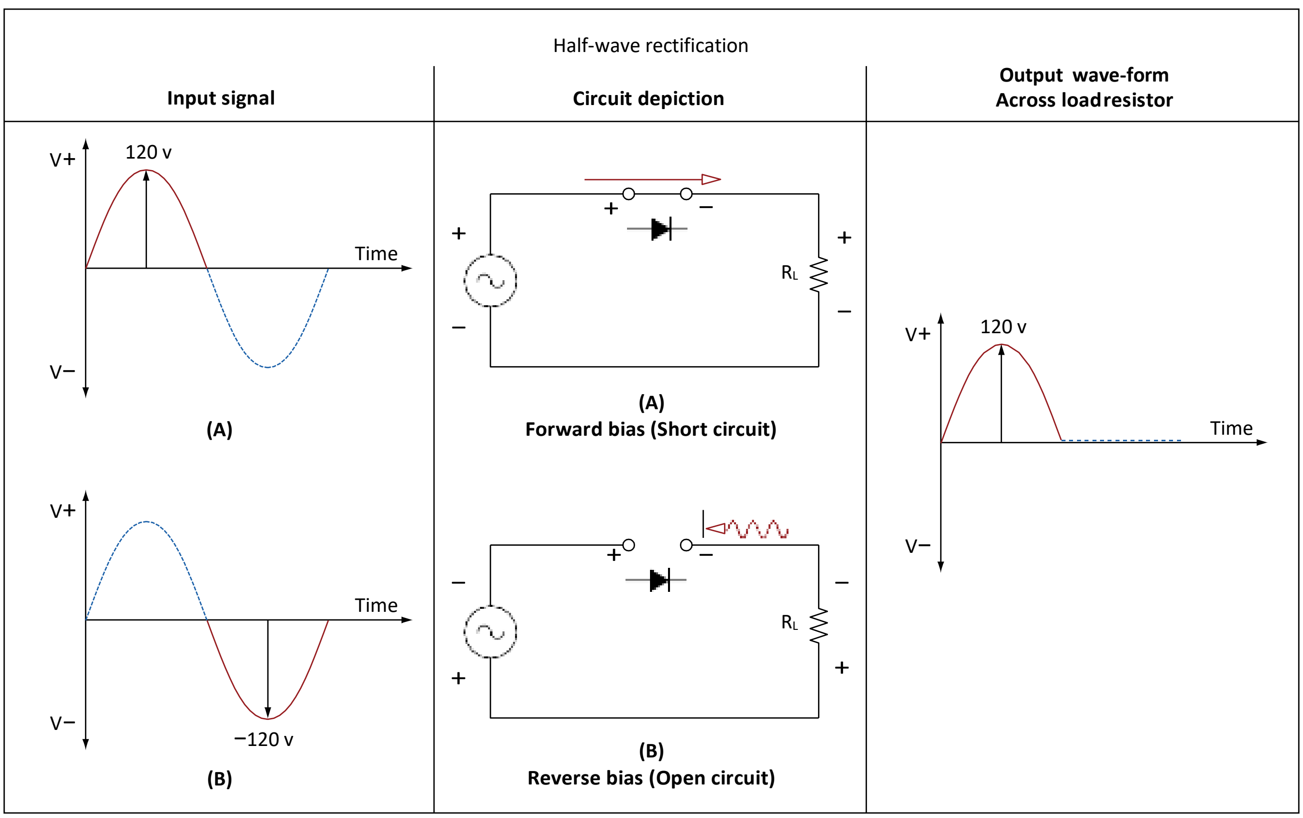

Figure 10-201. Basic concept of half-wave rectifier.

Full-Wave Rectifier

Figure 10-202 illustrates a more common use of the diode as a rectifier. This type of a rectifier is called a full-wave bridge rectifier. The term "full-wave" indicates that the output is a continuous sequence of pulses rather than having gaps that appear in the half-wave rectifier.

Illustration C shows the initial condition, during which, a positive portion of the input signal is applied to the network. Note the polarities across the diodes. Diodes D2 and D4 are reverse biased and can be replaced with an open circuit. Diodes D1 and D3 are forward biased and act as an open circuit. The current path through the diodes is clear to see, and the resulting waveform is developed across the load resistor.

During the negative portion of the applied signal, the diodes will reverse their polarity and bias states. The result is a network shown in illustration D. Current now passes through diodes D4 and D2, which are forward biased, while diodes D1 and D3 are essentially open circuits due to being reverse biased. Note that during both alternations of the input waveform, the current will pass through the load resistor in the same direction. This results in the negative swing of the waveform being flipped up to the positive side of the time line.

Dry Disk

Dry disk rectifiers operate on the principle that electric current flows through a junction of two dissimilar conducting materials more readily in one direction than it does in the opposite direction. This is true because the resistance to current flow in one direction is low, while in the other direction it is high. Depending on the materials used, several amperes may flow in the direction of low resistance but only a few milliamperes in the direction of high resistance.

Three types of dry disk rectifiers may be found in aircraft: the copper oxide rectifier, the selenium rectifier, and the magnesium copper-sulfide rectifier. The copper oxide rectifier consists of a copper disk upon which a layer of copper oxide has been formed by heating. [Figure 10-203] It may also consist of a chemical copper oxide preparation spread evenly over the copper surface. Metal plates, usually lead plates, are pressed against the two opposite faces of the disk to form a good contact. Current flow is from the copper to the copper oxide.

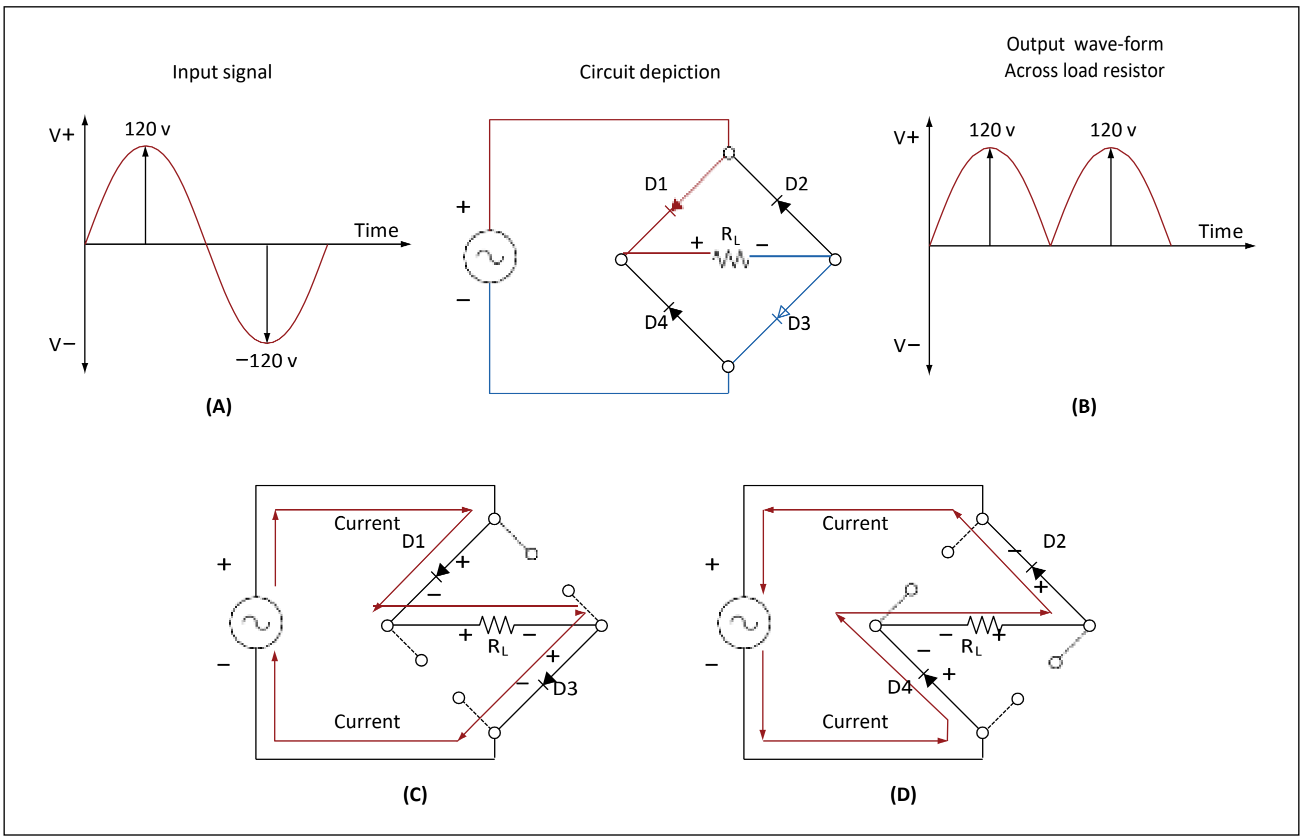

Figure 10-202. Full-wave bridge rectifier.

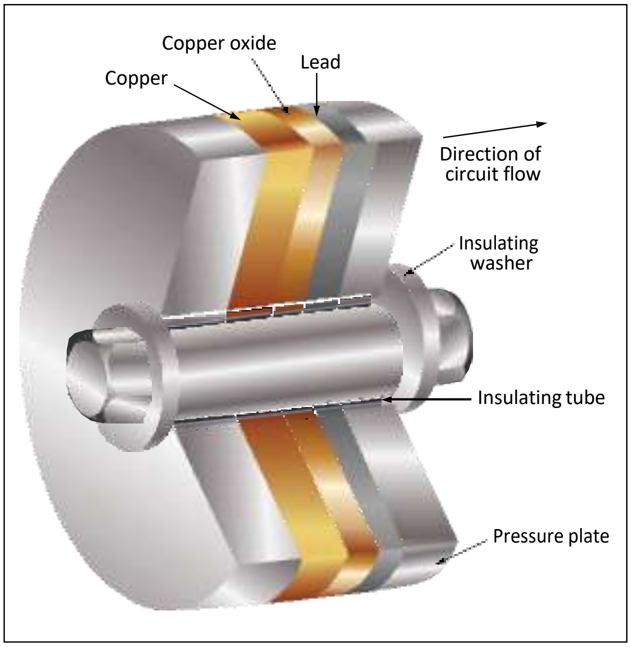

Figure 10-203. Copper oxide dry disk rectifier.

The selenium rectifier consists of an iron disk, similar to a washer, with one side coated with selenium. Its operation is similar to that of the copper oxide rectifier. Current flows from the selenium to the iron.

The magnesium copper-sulfide rectifier is made of washer-shaped magnesium disks coated with a layer of copper sulfide. The disks are arranged similarly to the other types. Current flows from the magnesium to the copper sulfide.

Types of Diodes

Today there are many varieties of diodes, which can be grouped into one of several basic categories.

Power Rectifier Diodes

The rectifier diode is usually used in applications that require high current, such as power supplies. The range in which the diode can handle current can vary anywhere from one ampere to hundreds of amperes. One common example of diodes is the series of diodes, part numbers 1N4001 to 1N4007. The "1N" indicates that there is only one PN junction, or that the device is a diode. The average current carrying range for these rectifier diodes is about one ampere and have a peak inverse voltage between 50 volts to1,000 volts. Larger rectifier diodes can carry currents up to 300 amperes when forward biased and have a peak inverse voltage of 600 volts. A recognizable feature of the larger rectifier diodes is that they are encased in metal in order to provide a heat sink. Figure 10-204 illustrates a line drawing of some general purpose diodes.

Zener Diodes

Zener diodes (sometimes called "breakdown diodes") are designed so that they will break down (allow current to pass) when the circuit potential is equal to or in

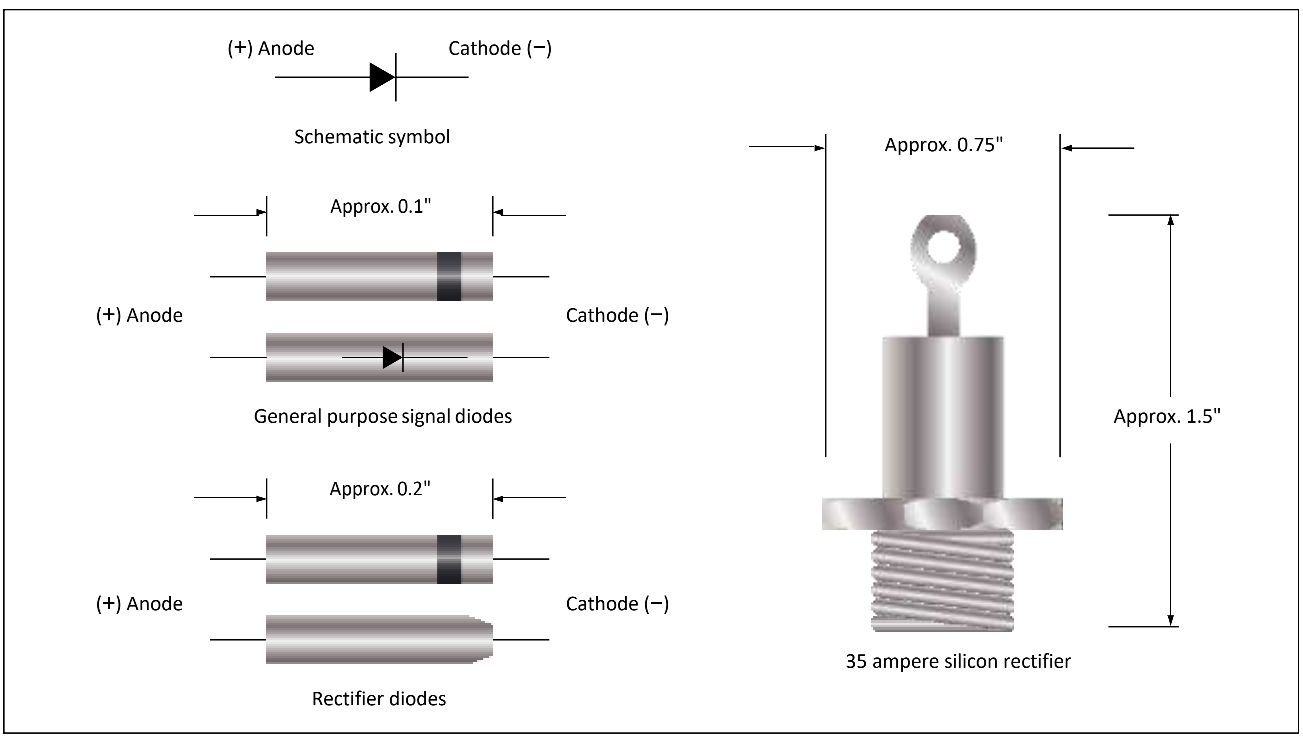

Figure 10-204. General purpose diodes.

excess of the desired reverse bias voltage. The range of reverse bias breakdown-voltages commonly found can range from 2 volts to 200 volts depending on design. Once a specific reverse bias voltage has been reached, the diode will conduct and behave like a constant voltage source. Within the normal operating range, the zener will function as a voltage regulator, waveform clipper, and other related functions. Below the desired voltage, the zener blocks the circuit like any other diode biased in the reverse direction. Because the zener diode allows free flow in one direction when it is used in an AC circuit, two diodes connected in opposite directions must be used. This takes care of both alternations of current. Power ratings of these devices range from about 250 milliwatts to 50 watts.

Special Purpose Diodes

The unique characteristics of semiconductor material have allowed for the development of many specialized types of diodes. A short description of some of the more common diode types is given for general familiarization. Figure 10-205 illustrates the schematic symbols for some of the special purpose diodes.

Light-Emitting Diode (LED)

In a forward biased diode, electrons cross the junction and fall into holes. As the electrons fall into the valence band, they radiate energy. In a rectifier diode, this energy is dissipated as heat. However, in the light-emitting diode (LED), the energy is dissipated as light. By using elements, such as gallium, arsenic, and phosphorous, an LED can be designed to radiate colors, such as red, green, yellow, blue and inferred light. LEDs that are designed for the visible light portion of the spectrum are useful for instruments, indicators, and even cabin lighting. The advantages of the LED over the incandescent lamps are longer life, lower voltage, faster on and off operations, and less heat.

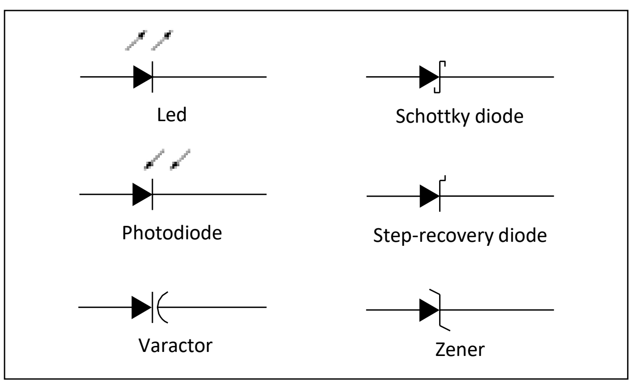

Figure 10-205. Schematic symbols for special purpose diodes.

Liquid Crystal Displays (LCD)

The liquid crystal display (LCD) has an advantage over the LED in that it requires less power to operate. Where LEDs commonly operate in the milliwatt range, the LCD operates in the microwatt range. The liquid crystal is encapsulated between two glass plates. When voltage is not applied to the LCD, the display will be clear. However, when a voltage is applied, the result is a change in the orientation of the atoms of the crystals. The incident light will then be reflected in a different direction. A frosted appearance will result in the regions that have voltage applied and will permit distinguishing of numeric values.

Photodiode

Thermal energy produces minority carriers in a diode. The higher the temperature, the greater the current in a reverse current diode. Light energy can also produce minority carriers. By using a small window to expose the PN junction, a photodiode can be built. When light fall upon the junction of a reverse- biased photodiode, electrons-hole pairs are created inside the depletion layer. The stronger the light, the greater the number of light-produced carriers, which in turn causes a greater magnitude of reverse-current. Because of this characteristic, the photodiode can be used in light detecting circuits.

Varactors

The varactor is simply a variable-capacitance diode. The reverse voltage applied controls the variable-capacitance of the diode. The transitional capacitance will decrease as the reverse voltage is increasingly applied. In many applications, the varactor has replaced the old mechanically tuned capacitors. Varactors can be placed in parallel with an inductor and provide a resonant tank circuit for a tuning circuit. By simply varying the reverse voltage across the varactor, the resonant frequency of the circuit can be adjusted.

Schottky Diodes

Schottky diodes are designed to have a metal, such as gold, silver, or platinum, on one side of the junction and doped silicon, usually an N-type, on the other side of the junction. This type of a diode is considered a unipoler device because free electrons are the majority carrier on both sides of the junction. The Schottky diode has no depletion zone or charge storage, which means that the switching time can be as high as 300 MHz. This characteristic exceeds that of the bipolar diode.

Diode Identification

Figure 10-204 illustrates a number of methods employed for identifying diodes. Typically manufacturers place some form of an identifier on the diode to indicate which end is the anode and which end is the cathode. Dots, bands, colored bands, the letter ‘k’ or unusual shapes indicate the cathode end of the diode.