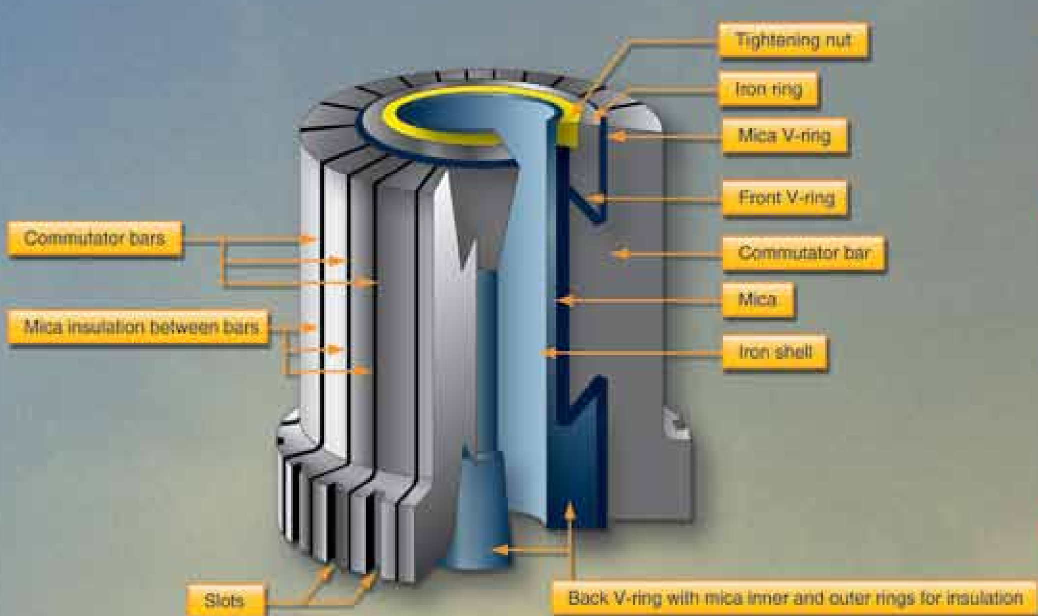
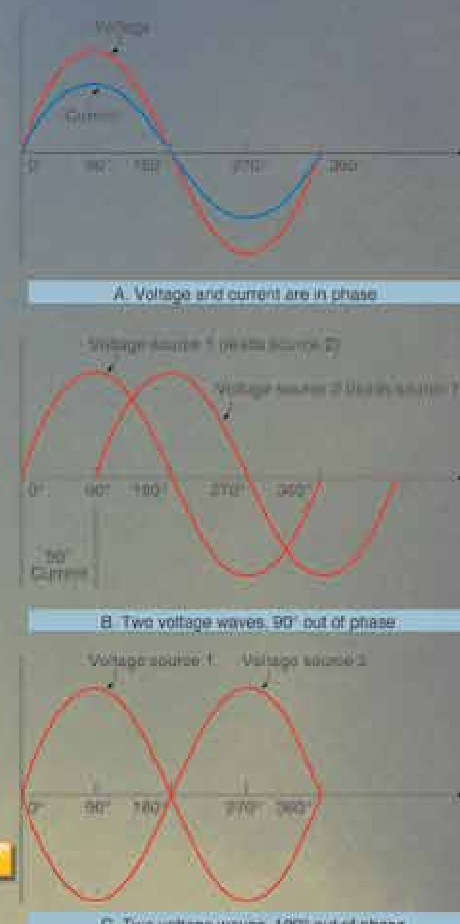
Chapter 9

Aircraft Electrical System

Introduction

The satisfactory performance of any modern aircraft depends to a very great degree on the continuing reliability of electrical systems and subsystems. Improperly or carelessly installed or maintained wiring can be a source of both immediate and potential danger. The continued proper performance of electrical systems depends on the knowledge and technique of the mechanic who installs, inspects, and maintains the electrical system wires and cables.





Ohm's Law

Ohm's Law describes the basic mathematical relationships of electricity. The law was named after German Physicist George Simon Ohm (1789–1854). Basically, Ohm's Law states that the current (electron flow) through a conductor is directly proportional to the voltage (electrical pressure) applied to that conductor and inversely proportional to the resistance of the conductor. The unit used to measure resistance is called the ohm. The symbol for the ohm is the Greek letter omega (Ω). In mathematical formulas, the capital letter R refers to resistance. The resistance of a conductor and the voltage applied to it determine the number of amperes of current flowing through the conductor. Thus, 1 ohm of resistance limits the current flow to 1 ampere in a conductor to which a voltage of 1 volt is applied. The primary formula derived from Ohm's Law is: E = I × R (E = electromotive force measured in volts, I = current flow measured in amps, and R = resistance measured in ohms). This formula can also be written to solve for current or resistance:

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

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

Ohm's Law provides a foundation of mathematical formulas that predict how electricity responds to certain conditions. *[Figure 9-1]* For example, Ohm's Law can be used to calculate that a lamp of 12 Ohms (Ω) passes a current of 2 amps when connected to a 24-volt direct current (DC) power source.

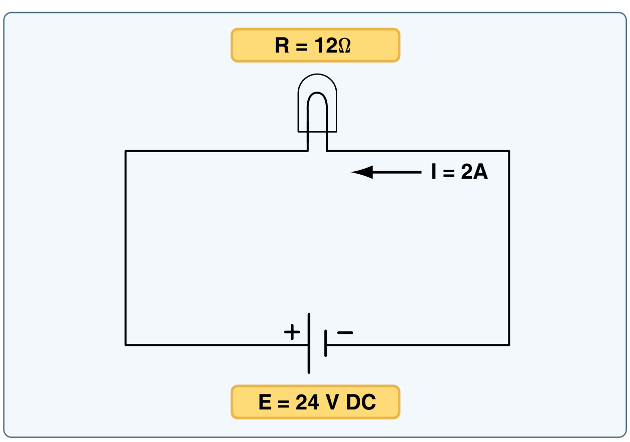


Figure 9-1. *Ohm's Law used to calculate how much current a lamp will pass when connected to a 24-volt DC power source.*

Example 1

A 28-volt landing light circuit has a lamp with 4 ohms of resistance. Calculate the total current of the circuit.

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

$$I = \frac{28 \text{ volts}}{4\Omega}$$

$$I = 7 \text{ amps}$$

Example 2

A 28-volt deice boot circuit has a current of 6.5 amps. Calculate the resistance of the deice boot.

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

$$R = \frac{28 \text{ volts}}{6.5 \text{ amps}}$$

$$R = 4.31\Omega$$

Example 3

A taxi light has a resistance of 4.9 Ω and a total current of 2.85 amps. Calculate the system voltage.

$$E = I \times R$$

$$E = 2.85 \times 4.9\Omega$$

$$E = 14 \text{ volts}$$

Whenever troubleshooting aircraft electrical circuits, it is always valuable to consider Ohm's Law. A good understanding of the relationship between resistance and current flow can help one determine if a circuit contains an open or a short. Remembering that a low resistance means increased current can help explain why circuit breakers pop or fuses blow. In almost all cases, aircraft loads are wired in parallel to each other; therefore, there is a constant voltage supplied to all loads and the current flow through a load is a function of that load's resistance.

Figure 9-2 illustrates several ways of using Ohm's Law for the calculation of current, voltage, and resistance.

Current

Electrical current is the movement of electrons. This electron movement is referred to as current, flow, or current flow. In practical terms, this movement of electrons must take place within a conductor (wire). Current is typically measured in amps. The symbol for current is I and the symbol for amps is A.

The current flow is actually the movement of the free electrons found within conductors. Common conductors

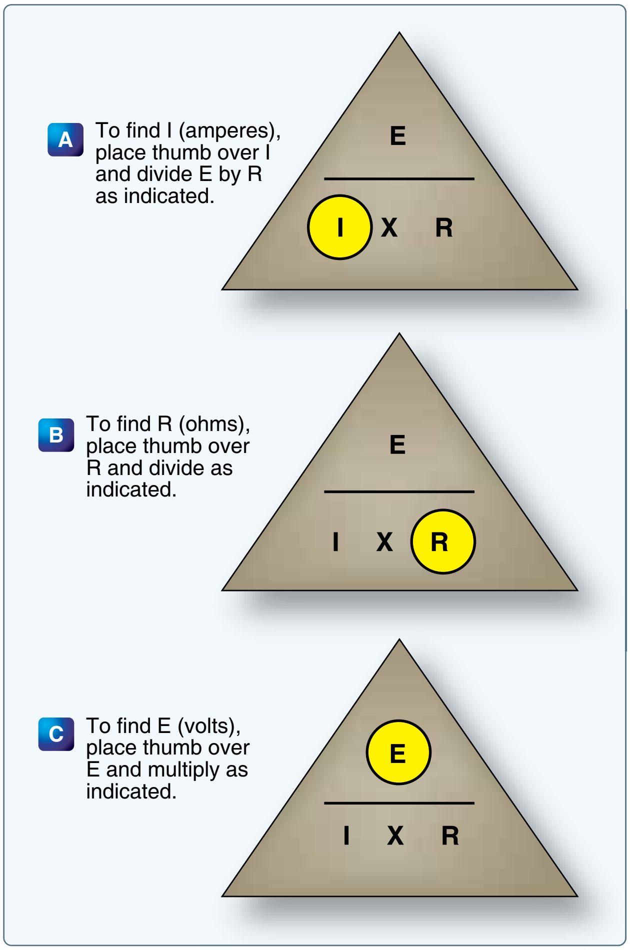


Figure 9-2. *Ohm's Law chart.*

include copper, silver, aluminum, and gold. The term "free electron" describes a condition in some atoms where the outer electrons are loosely bound to their parent atom. These loosely bound electrons are easily motivated to move in a given direction when an external source, such as a battery, is applied to the circuit. These electrons are attracted to the positive terminal of the battery, while the negative terminal is the source of the electrons. So, the measure of current is actually the number of electrons moving through a conductor in a given amount of time.

The internationally accepted unit for current is the ampere (A). One ampere (A) of current is equivalent to 1 coulomb (C) of charge passing through a conductor in 1 second. One coulomb of charge equals 6.28×10^{18} electrons. Obviously, the unit of amperes is a much more convenient term to use than coulombs. The unit of coulombs is simply too small to be practical.

When current flow is in one direction, it is called direct current (DC). Later in the text, the form of current that periodically oscillates back and forth within the circuit is discussed. The present discussion is concerned only with the use of DC. It should be noted that as with the movement of any mass, electron movement (current flow) only occurs when there is a force present to push the electrons. This force is commonly called voltage (described in more detail in the next section). When a voltage is applied across the conductor, an electromotive force creates an electric field within the conductor, and a current is established. The electrons do not move in a straight direction, but undergo repeated collisions with other nearby atoms within a conductor. These collisions usually knock other free electrons from their atoms, and these electrons move on toward the positive end of the conductor with an average velocity called the drift velocity, which is relatively low speed. To understand the nearly instantaneous speed of the effect of the current, it is helpful to visualize a long tube filled with steel balls. *[Figure 9-3]*

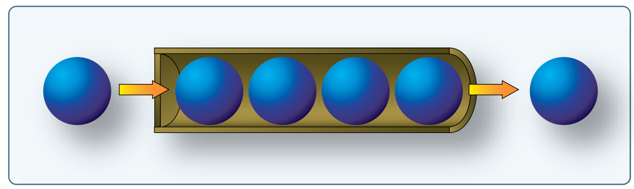


Figure 9-3. *Electron flow.*

It can be seen that a ball introduced in one end of the tube, which represents the conductor, immediately causes a ball to be emitted at the opposite end of the tube. Thus, electric current can be viewed as instantaneous, even though it is the result of a relatively slow drift of electrons.

Conventional Current Theory and Electron Theory

There are two competing schools of thought regarding the flow of electricity. The two explanations are the conventional current theory and the electron theory. Both theories describe the movement of electrons through a conductor. They simply explain the direction current moves. Typically during troubleshooting or the connection of electrical circuits, the use of either theory can be applied as long as it is used consistently. The Federal Aviation Administration (FAA) officially defines current flow using electron theory (negative to positive).

The conventional current theory was initially advanced by Benjamin Franklin, who reasoned that current flowed out of a positive source into a negative source or an area that lacked an abundance of charge. The notation assigned to the electric charges was positive (+) for the abundance of charge and negative (–) for a lack of charge. It then seemed natural to visualize the flow of current as being from the positive (+) to the negative (–). Later discoveries were made that proved that just the opposite is true. Electron theory describes what actually happens in the case of an abundance of electrons flowing out of the negative (–) source to an area that lacks electrons or the positive (+) source. Both conventional flow and electron flow are used in industry.

Electromotive Force (Voltage)

Voltage is most easily described as electrical pressure force. It is the electromotive force (EMF), or the push or pressure from one end of the conductor to the other, that ultimately moves the electrons. The symbol for EMF is the capital letter E. EMF is always measured between two points and voltage is considered a value between two points. For example, across the terminals of the typical aircraft battery, voltage can be measured as the potential difference of 12 volts or 24 volts. That is to say that between the two terminal posts of the battery, there is a voltage available to push current through a circuit. Free electrons in the negative terminal of the battery move toward the excessive number of positive charges in the positive terminal. The net result is a flow or current through a conductor. There cannot be a flow in a conductor unless there is an applied voltage from a battery, generator, or ground power unit. The potential difference, or the voltage across any two points in an electrical system, can be determined by:

$$V_1 - V_2 = V_{Drop}$$

Example

The voltage at one point is 14 volts. The voltage at a second point in the circuit is 12.1 volts. To calculate the voltage drop, use the formula above to get a total voltage drop of 1.9 volts.

Figure 9-4 illustrates the flow of electrons of electric current. Two interconnected water tanks demonstrate that when a difference of pressure exists between the two tanks, water flows until the two tanks are equalized. *Figure 9-4* shows the level of water in tank A to be at a higher level, reading 10 pounds per square inch (psi) (higher potential energy), than the water level in tank B, reading 2 psi (lower potential energy). Between the two tanks, there is 8 psi potential difference. If the valve in the interconnecting line between the tanks is opened, water flows from tank A into tank B until the level of water (potential energy) of both tanks is equalized. It is important to note that it was not the pressure in tank A that caused the water to flow; rather, it was the difference in pressure between tank A and tank B that caused the flow. This comparison illustrates the principle that electrons move, when a path is available, from a point of excess electrons (higher potential energy) to a point deficient in electrons (lower potential energy). The force that causes this movement is the potential difference in electrical energy between the two points. This force is called the electrical pressure (voltage), the potential difference, or the electromotive force (electron moving force).

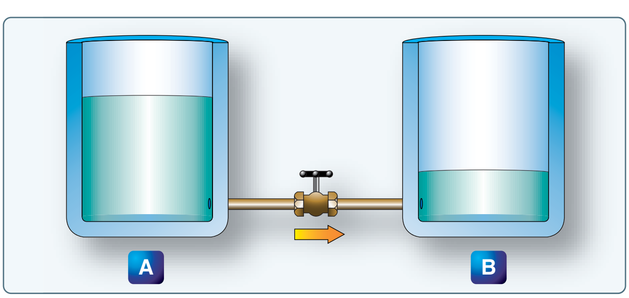


Figure 9-4. *Difference of pressure.*

Resistance

The two fundamental properties of current and voltage are related by a third property known as resistance. In any electrical circuit, when voltage is applied to it, a current results. The resistance of the conductor determines the amount of current that flows under the given voltage. In general, the greater the circuit resistance, the less the current. If the resistance is reduced, then the current will increase. This relation is linear in nature and is known as Ohm's Law. An example would be if the resistance of a circuit is doubled, and the voltage is held constant, then the current through the resistor is cut in half.

There is no distinct dividing line between conductors and insulators; under the proper conditions, all types of material conduct some current. Materials offering a resistance to current flow midway between the best conductors and the poorest conductors (insulators) are sometimes referred to as semiconductors and find their greatest application in the field of transistors.

The best conductors are materials, chiefly metals, that possess a large number of free electrons. Conversely, insulators are materials having few free electrons. The best conductors are silver, copper, gold, and aluminum, but some nonmetals, such as carbon and water, can be used as conductors. Materials such as rubber, glass, ceramics, and plastics are such poor conductors that they are usually used as insulators. The current flow in some of these materials is so low that it is usually considered zero.

Factors Affecting Resistance

The resistance of a metallic conductor is dependent on the type of conductor material. It has been pointed out that certain metals are commonly used as conductors because of the large number of free electrons in their outer orbits. Copper is usually considered the best available conductor material, since a copper wire of a particular diameter offers a lower resistance to current flow than an aluminum wire of the same diameter. However, aluminum is much lighter than copper, and for this reason, as well as cost considerations, aluminum is often used when the weight factor is important.

The resistance of a metallic conductor is directly proportional to its length. The longer the length of a given size of wire, the greater the resistance. *Figure 9-5* shows two wire conductors of different lengths. If 1 volt of electrical pressure is applied across the two ends of the conductor that is 1 foot in length and the resistance to the movement of free electrons is assumed to be 1 ohm, the current flow is limited to 1 ampere. If the same size conductor is doubled in length, the same electrons set in motion by the 1 volt applied now find twice the resistance.

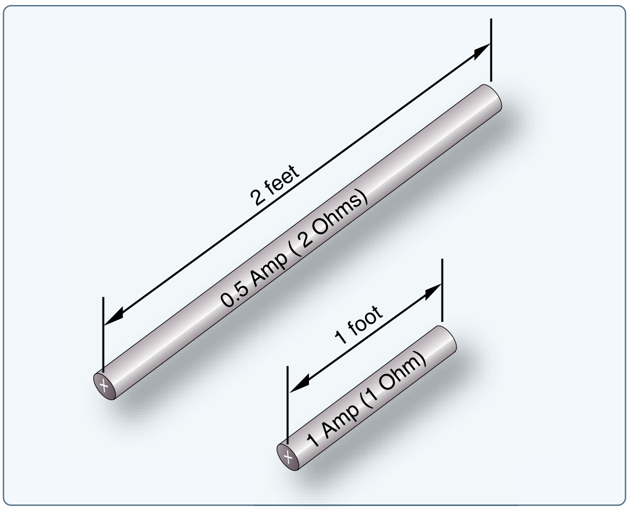


Figure 9-5. *Resistance varies with length of conductor.*

Electromagnetic Generation of Power

Electrical energy can be produced through a number of methods. Common methods include the use of light, pressure, heat, chemical, and electromagnetic induction. Of these processes, electromagnetic induction is most responsible for the generation of the majority of the electrical power used by humans. Virtually all mechanical devices (generators and alternators) that produce electrical power employ the process of electromagnetic induction. The use of light, pressure, heat, and chemical sources for electrical power is found on aircraft but produce a minimal amount of all the electrical power consumed during a typical flight.

In brief, light can produce electricity using a solar cell (photovoltaic cell). These cells contain a certain chemical that converts light energy into voltage/current.

Using pressure to generate electrical power is commonly known as the piezoelectric effect. The piezoelectric effect (piezo or piez taken from Greek: to press; pressure; to squeeze) is a result of the application of mechanical pressure on a dielectric or nonconducting crystal.

Chemical energy can be converted into electricity, most commonly in the form of a battery. A primary battery produces electricity using two different metals in a chemical solution like alkaline electrolyte. A chemical reaction exists between the metals which frees more electrons in one metal than in the other.

Heat used to produce electricity creates the thermoelectric effect. When a device called a thermocouple is subjected to heat, a voltage is produced. A thermocouple is a junction between two different metals that produces a voltage related to a temperature difference. If the thermocouple is connected to a complete circuit, a current also flows. Thermocouples are often found on aircraft as part of a temperature monitoring system, such as a cylinder head temperature gauge.

Electromagnetic induction is the process of producing a voltage (EMF) by moving a magnetic field in relationship to a conductor. As shown in *Figure 9-6,* when a conductor (wire) is moved through a magnetic field, an EMF is produced in the conductor. If a complete circuit is connected to the conductor, the voltage also produces a current flow.

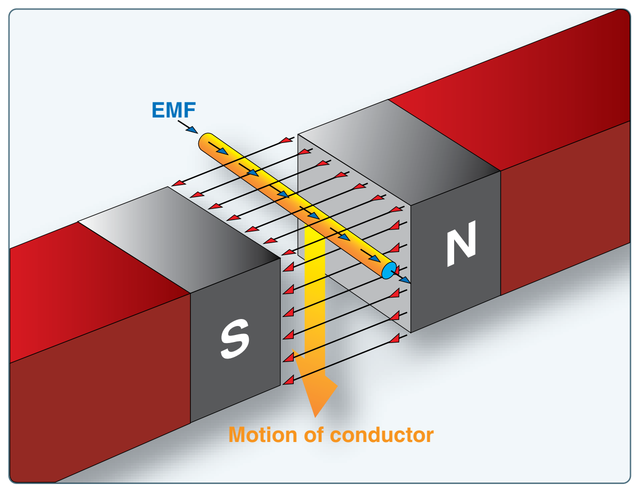


Figure 9-6. *Inducing an EMF in a conductor.*

One single conductor does not produce significant voltage/current via electromagnetic induction. *[Figure 9-6]* In practice, instead of a single wire, a coil of wire is moved through the magnetic field of a strong magnet. This produces a greater electrical output. In many cases, the magnetic field is created by using a powerful electromagnet. This allows for the production of a greater voltage/current due to the stronger magnetic field produced by the electromagnet when compared to an ordinary magnet.

Please note that this text often refers to voltage/current in regards to electrical power. Remember voltage (electrical pressure) must be present to produce a current (electron flow). Hence, the output energy generated through the process of electromagnetic induction always consists of voltage.

Current also results when a complete circuit is connected to that voltage. Electrical power is produced when there is both electrical pressure E (EMF) and current (I). Power = Current × Voltage (P = I × E)

It is the relative motion between a conductor and a magnetic field that causes current to flow in the conductor. Either the conductor or magnet can be moving or stationary. When a magnet and its field are moved through a coiled conductor, as shown in *Figure 9-7*, a DC voltage with a specific polarity is produced. The polarity of this voltage depends on the direction in which the magnet is moved and the position of the north and south poles of the magnetic field. The generator left-hand rule can be used to determine the direction of current flow within the conductor. *[Figure 9-8]* Of course, the direction of current flow is a function of the polarity of the voltage induced in to the conductor.

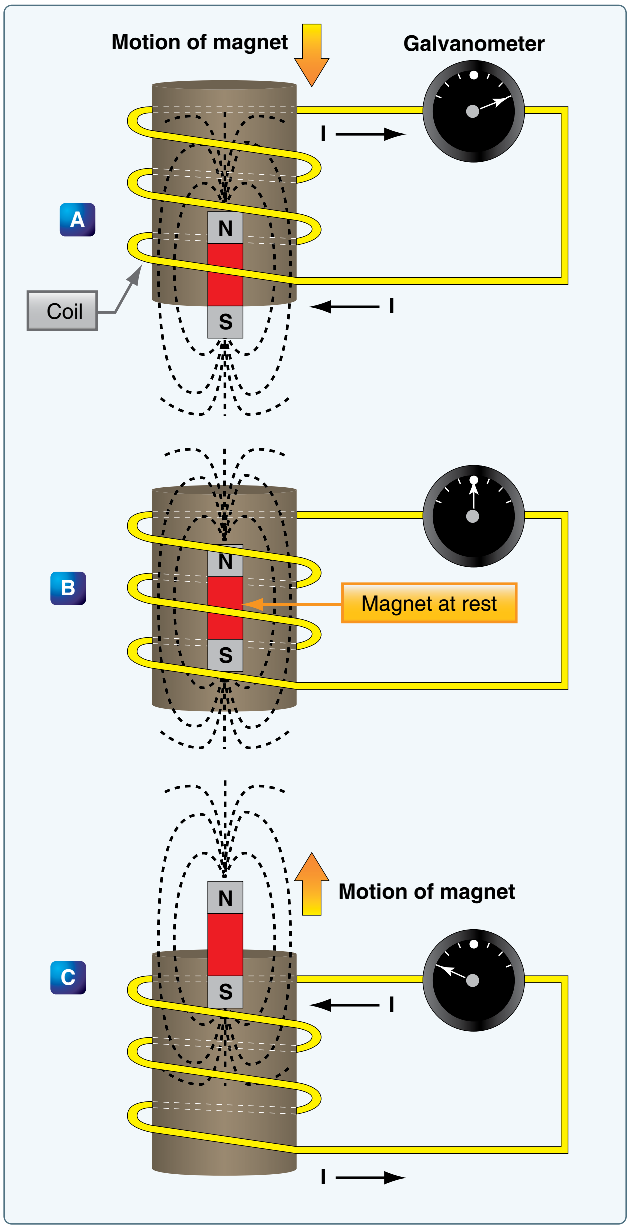


Figure 9-7. *Inducing a current flow.*

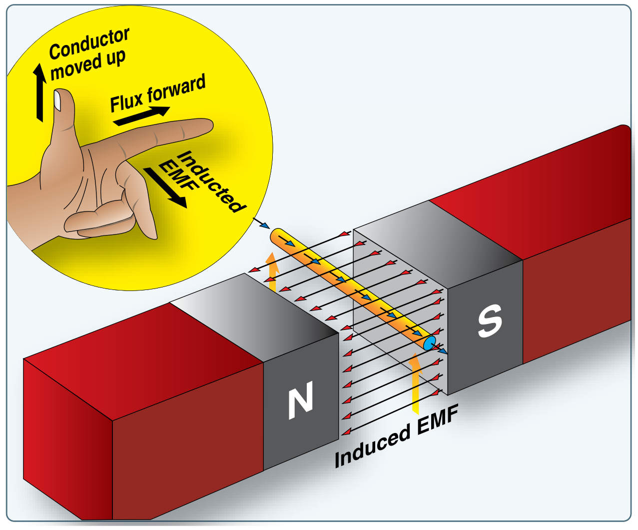


Figure 9-8. *An application of the generator left-hand rule.*

In practice, producing voltage/current using the process of electromagnetic induction requires a rotating machine. Generally speaking, on all aircraft, a generator or alternator employs the principles of electromagnetic induction to create electrical power for the aircraft. Either the magnetic field can rotate or the conductor can rotate. *[Figure 9-9]* The rotating component is driven by a mechanical device, such as an aircraft engine.

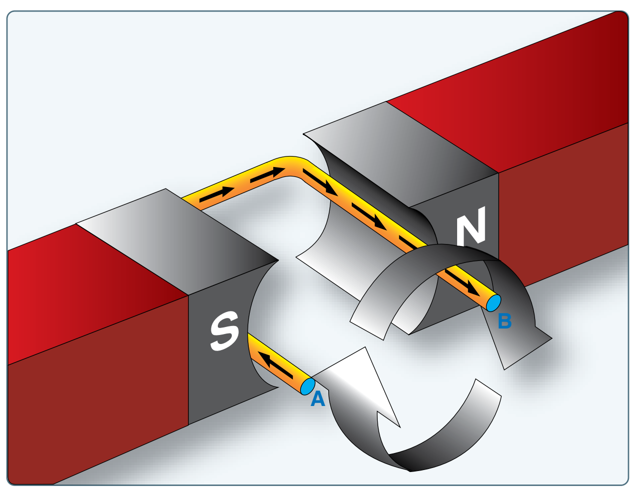


Figure 9-9. *Voltage induced in a loop.*

During the process of electromagnetic induction, the value of the induced voltage/current depends on three basic factors:

1. Number of turns in the conductor coil (more loops equals greater induced voltage)

2. Strength of the electromagnet (the stronger the magnetic field, the greater the induced voltage)
3. Speed of rotation of the conductor or magnet (the faster the rotation, the greater the induced voltage)

Figure 9-10 illustrates the basics of a rotating machine used to produce voltage. The simple generating device 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), C1 and C2. 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 is applied, then it can be observed that as wire B moves up across the field, a voltage is induced that causes the current to flow towards the reader. As wire A moves down across the field, a voltage is induced that causes the current to flow away from the reader. 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 9-11 illustrates the generation of alternating current (AC) with a simple loop conductor rotating in a magnetic field. As it is rotated in a counterclockwise direction, varying voltages are induced in the conductive loop.

Position 1
The 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 induced voltage gradually increases.

Position 2
The conductor is now moving in a direction perpendicular to the flux and cuts a maximum number of lines of force; therefore, a maximum voltage is induced. As the conductor moves beyond position 2, it cuts a decreasing amount of flux, and the induced voltage decreases.

Position 3
At this point, the conductor has made half a revolution 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 now reverses since the A conductor is moving 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 it reaches position 4.

Position 4
Like position 2, the conductor is again moving perpendicular to the flux and generates a maximum negative voltage. From position 4 to position 5, the induced voltage gradually decreases until the voltage is zero, and the conductor and wave are ready to start another cycle.

Position 5
The curve shown at position 5 is called a sine wave. It represents the polarity and the magnitude of the instantaneous

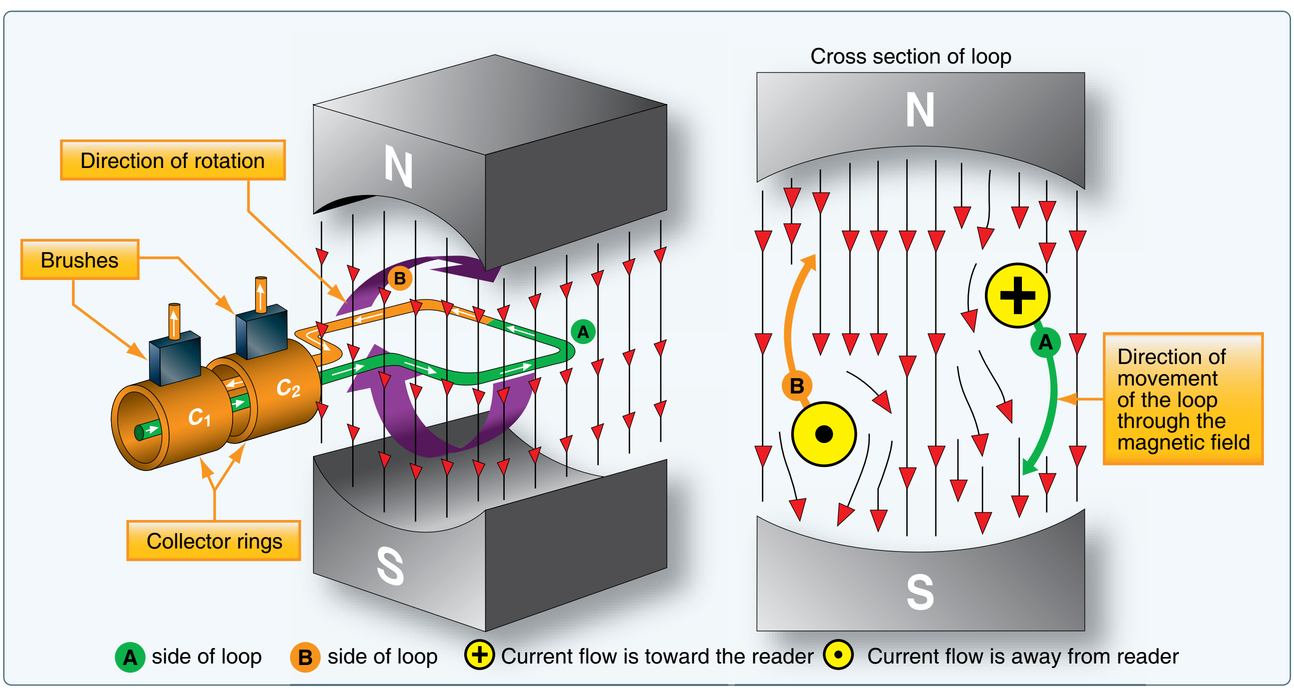


Figure 9-10. *Simple generator.*

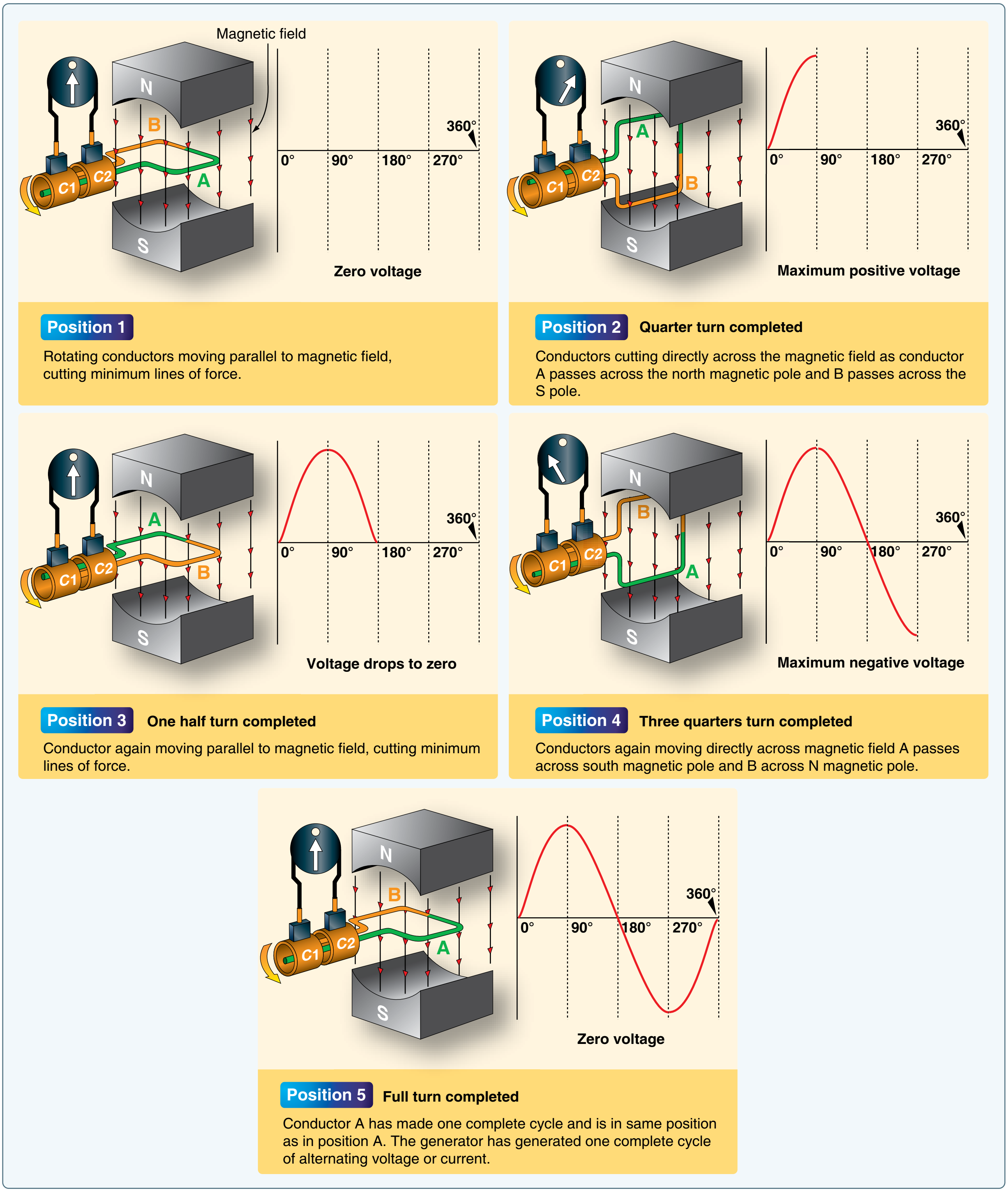


Figure 9-11. *Generation of a sine wave.*

values of the voltages generated. The horizontal baseline is divided into degrees, or time, and the vertical distance above or below the baseline represents the value of voltage at each particular point in the rotation of the loop.

The specific operating principles of both alternators and generators as they apply to aircraft is presented later in this text.

Alternating Current (AC) Introduction

Alternating current (AC) electrical systems are found on most multi-engine, high performance turbine powered aircraft and transport category aircraft. AC is the same type of electricity used in industry and to power our homes. Direct current (DC) is used on systems that must be compatible with battery power, such as on light aircraft and automobiles. There are many benefits of AC power when selected over DC power for aircraft electrical systems.

AC can be transmitted over long distances more readily and more economically than DC, since AC 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 AC (especially with large transport category aircraft). Space and weight can be saved since AC devices, especially motors, are smaller and simpler than DC devices. In most AC motors, no brushes are required, and they require less maintenance than DC motors. Circuit breakers operate satisfactorily under loads at high altitudes in an AC system, whereas arcing is so excessive on DC systems that circuit breakers must be replaced frequently. Finally, most airplanes using a 24-volt DC system have special equipment that requires a certain amount of 400 cycle AC current. For these aircraft, a unit called an inverter is used to change DC to AC. Inverters are discussed later in this book.

AC is constantly changing in value and polarity, or as the name implies, alternating. *Figure 9-12* shows a graphic comparison of DC and AC. The polarity of DC never changes, and the polarity and voltage constantly change in AC. It should also be noted that the AC cycle repeats at given intervals. With AC, both voltage and current start at zero, increase, reach a peak, then decrease and reverse polarity. If one is to graph this concept, it becomes easy to see the alternating wave form. This wave form is typically referred to as a sine wave.

Definitions

Values of AC

There are three values of AC that apply to both voltage and current. These values help to define the sine wave and are called instantaneous, peak, and effective. It should be noted that during the discussion of these terms, the text refers to voltage. But remember, the values apply to voltage and current in all AC circuits.

Instantaneous

An instantaneous voltage is the value at any instant in time along the AC wave. The sine wave represents 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.

Peak

The peak value is the largest instantaneous value, often referred to as the maximum value. The largest single positive value occurs after a certain period of time when the sine wave reaches 90°, and the largest single negative value occurs when the wave reaches 270°. Although important in the understanding of the AC sine wave, peak values are seldom used by aircraft technicians.

Effective

The effective values for voltage are always less than the peak (maximum) values of the sine wave and approximate DC voltage of the same value. For example, an AC circuit of 24 volts and 2 amps should produce the same heat through a resistor as a DC circuit of 24 volts and 2 amps. The effective value is also known as the root mean square, or RMS value, which refers to the mathematical process by which the value is derived.

Most AC meters display the effective value of the AC. In almost all cases, the voltage and current ratings of a system

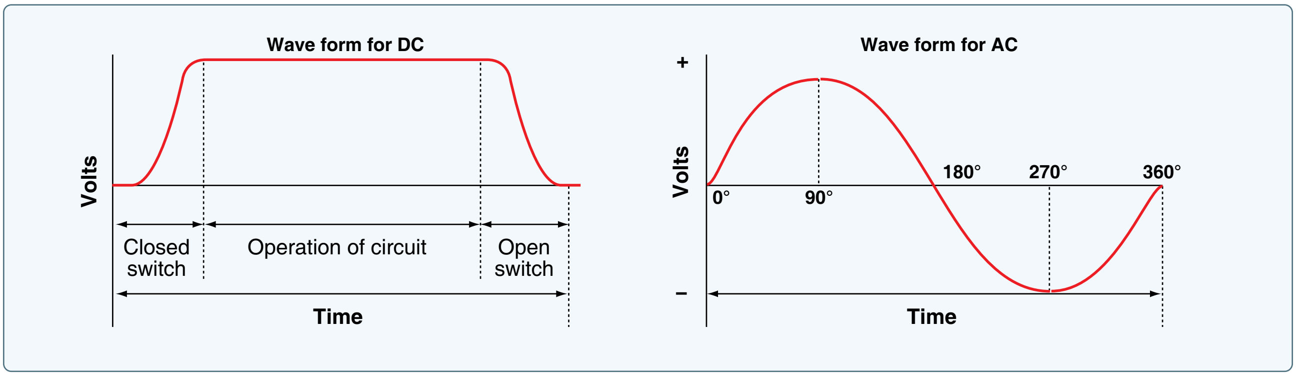


Figure 9-12. *DC and AC voltage curves.*

or component are given in effective values. In other words, the industry ratings are based on effective values. Peak and instantaneous values, used only in very limited situations, would be stated as such. In the study of AC, any values given for current or voltage are assumed to be effective values unless otherwise specified. In practice, only the effective values of voltage and current are used.

The effective value is equal to .707 times the peak (maximum) value. Conversely, the peak value is 1.41 times the effective value. Thus, the 110 volt value given for AC is only 0.707 of the peak voltage of this supply. The maximum voltage is approximately 155 volts (110 × 1.41 = 155 volts maximum).

How often the AC waveform repeats is known as the AC frequency. The frequency is typically measured in cycles per second (CPS) or hertz (Hz). One Hz equals one CPS. The time it takes for the sine wave to complete one cycle is known as period (P). Period is a value or time period and typically measured in seconds, milliseconds, or microseconds. It should be noted that the time period of a cycle can change from one system to another; it is always said that the cycle completes in 360° (related to the 360° of rotation of an AC alternator). *[Figure 9-13]*

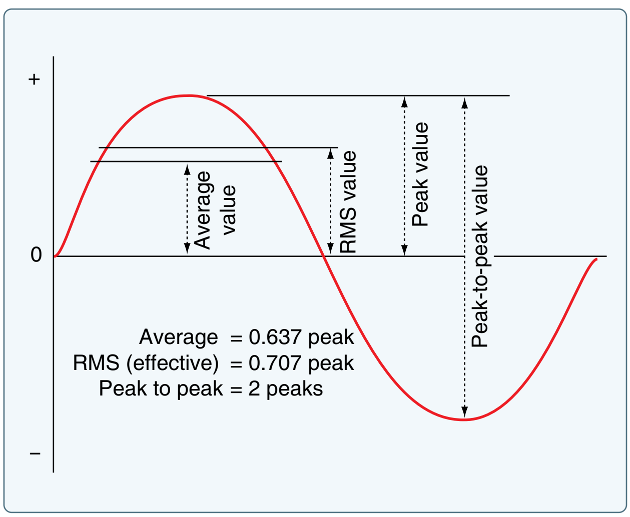


Figure 9-13. *Values of AC.*

Cycle Defined

A cycle is a completion of a pattern. Whenever a voltage or current passes through a series of changes, returns to the starting point, and then repeats the same series of changes, the series is called a cycle. When the voltage values are graphed, as in *Figure 9-14,* the complete AC cycle is displayed. One complete cycle is often referred to as the sine wave and said to be 360°. It is typical to start the sine wave where the voltage is zero. The voltage then increases to a maximum positive value, decreases to a value of zero, then

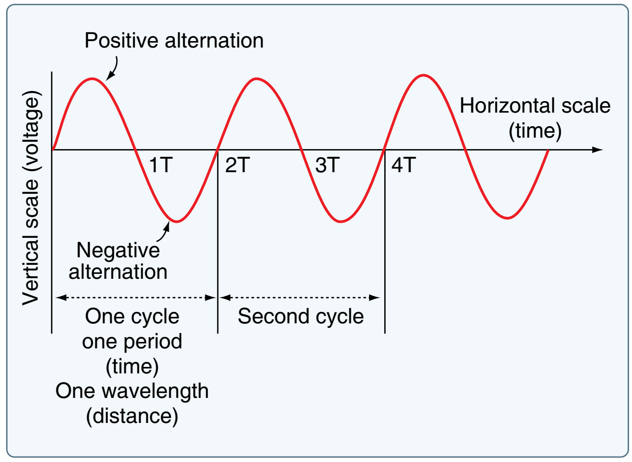


Figure 9-14. *Cycle of voltage.*

increases to a maximum negative value, and again decreases to zero. The cycle repeats until the voltage is no longer available. There are two alternations in a complete cycle: the positive alternation and the negative. It should be noted that the polarity of the voltage reverses for each half cycle. Therefore, during the positive half cycle, the electron flow is considered to be in one direction; during the negative half cycle, the electrons reverse direction and flow the opposite way through the circuit.

Frequency Defined

The frequency is the number of cycles of AC per second (CPS). The standard unit of frequency measurement is the Hz. *[Figure 9-15]* 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.

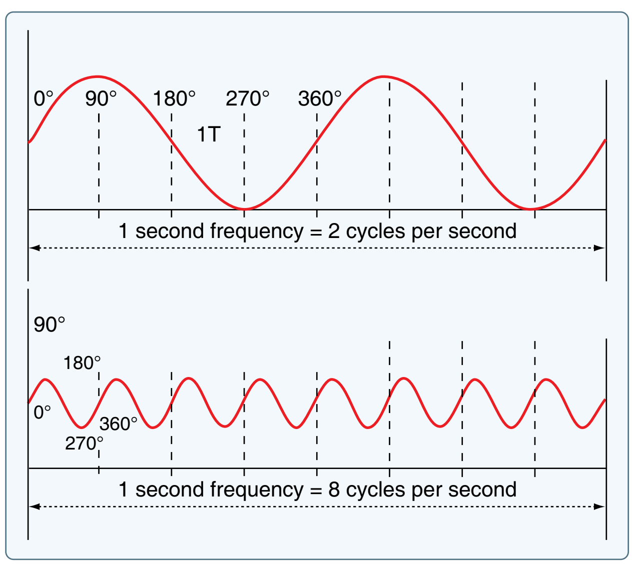


Figure 9-15. *Frequency in cycles per second.*

The frequency, then, is equal to the number of cycles in one revolution multiplied by the number of revolutions per second.

Period Defined

The time required for a sine wave to complete one full cycle is called a period (P). A period is typically measured in seconds, milliseconds, or microseconds. *[Figure 9-14]* The period of a sine wave is inversely proportional to the frequency. That is to say that the higher the frequency, the shorter the period. The mathematical relationship between frequency and period is given as:

Period

$$P = \frac{1}{f}$$

Frequency

$$F = \frac{1}{P}$$

Wavelength Defined

The distance that a waveform travels during a period is commonly referred to as a wavelength and is indicated by the Greek letter lambda (λ). Wavelength is related to frequency by the formula:

$$\frac{\text{wave speed}}{\text{frequency}} = \text{wavelength}$$

The higher the frequency is, the shorter the wavelength is. The measurement of wavelength is taken from one point on the waveform to a corresponding point on the next waveform. *[Figure 9-14]* Since wavelength is a distance, common units of measure include meters, centimeters, millimeters, or nanometers. For example, a sound wave of frequency 20 Hz would have wavelength of 17 meters and a visible red light wave of 4.3 × 10 –12 Hz would have a wavelength of roughly 700 nanometers. Keep in mind that the actual wavelength depends on the media through which the waveform must travel.

Phase Relationships

Phase is the relationship between two sine waves, typically measured in angular degrees. For example, if there are two different alternators producing power, it would be easy to compare their individual sine waves and determine their phase relationship. In *Figure 9-16B*, there is a 90° phase difference between the two voltage waveforms. A phase relationship can be between any two sine waves. The phase relationship can be measured between two voltages of different alternators or the current and voltage produced by the same alternator.

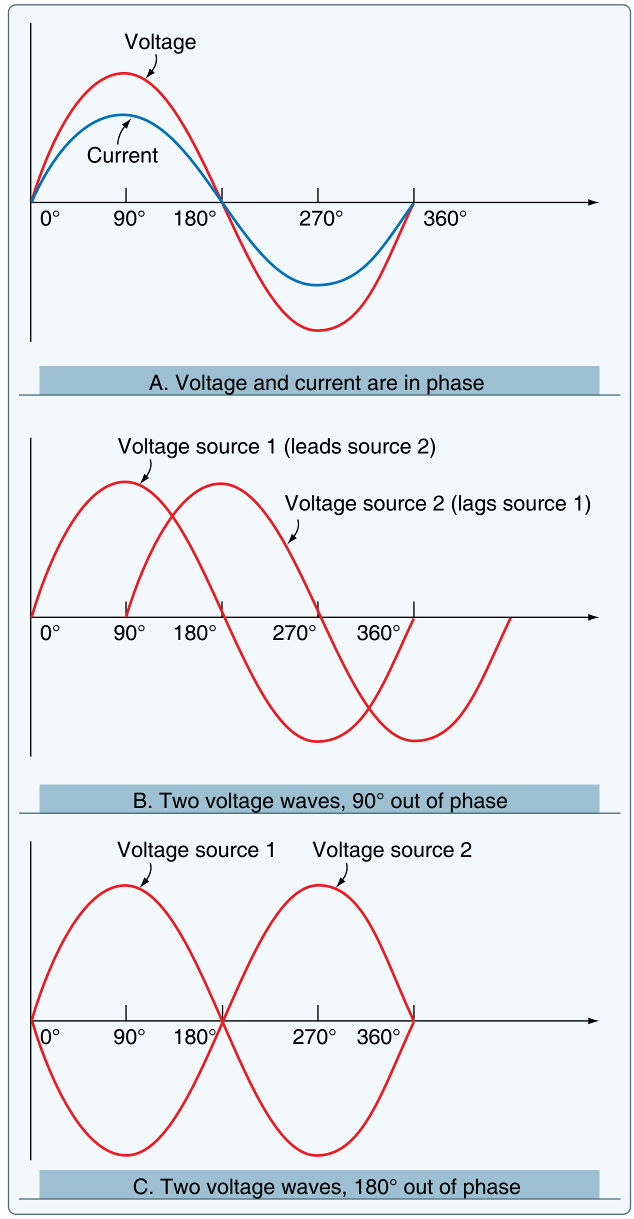


Figure 9-16. *In-phase and out-of-phase conditions.*

Figure 9-16A shows a voltage signal and a current signal superimposed on the same time axis. Notice that when the voltage increases in the positive alternation that the current also increases. When the voltage reaches its peak value, so does the current. Both waveforms then reverse and decrease back to a zero magnitude, then proceed in the same manner in the negative direction as they did in the positive direction. When two waves are exactly in step with each other, they are said to be in phase. To be in phase, the two waveforms must go through their maximum and minimum points at the same time and in the same direction.

When two waveforms go through their maximum and minimum points at different times, a phase difference exists between the two. In this case, the two waveforms are said to be out of phase with each other. The terms lead and lag are often used to describe the phase difference between waveforms. The waveform that reaches its maximum or minimum value first is said to lead the other waveform. *Figure 9-16B* shows this relationship. On the other hand, the second waveform is said to be lagging the first source. When a waveform is said to be leading or lagging, the difference in degrees is usually stated. If the two waveforms differ by 360°, they are said to be in phase with each other. If there is a 180° difference between the two signals, then they are still out of phase even though they are both reaching their minimum and maximum values at the same time. *[Figure 9-16C]*

Opposition to Current Flow of AC

There are three factors that can create an opposition to the flow of electrons (current) in an AC circuit. Resistance, similar to resistance of DC circuits, is measured in ohms and has a direct influence on AC regardless of frequency. Inductive reactance and capacitive reactance, on the other hand, oppose current flow only in AC circuits, not in DC circuits. Since AC constantly changes direction and intensity, inductors and capacitors may also create an opposition to current flow in AC circuits. It should also be noted that inductive reactance and capacitive reactance may create a phase shift between the voltage and current in an AC circuit. Whenever analyzing an AC circuit, it is very important to consider the resistance, inductive reactance, and the capacitive reactance. All three have an effect on the current of that circuit.

Resistance

As mentioned, resistance creates an opposition to current in an AC circuit similar to the resistance of a DC circuit. The current through a resistive portion of an AC circuit is inversely proportional to the resistance and directly proportional to the voltage applied to that circuit or portion of the circuit. The equations $I = E / R$ & $E = I \times R$ show how current is related to both voltage and resistance. It should be noted that resistance in an AC circuit does not create a phase shift between voltage and current.

Figure 9-17 shows how a circuit of 10 ohms allows 11.5 amps of current flow through an AC resistive circuit of 115 volts.

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

$$I = \frac{115V}{10\Omega}$$

$$I = 11.5 \text{ Amps}$$

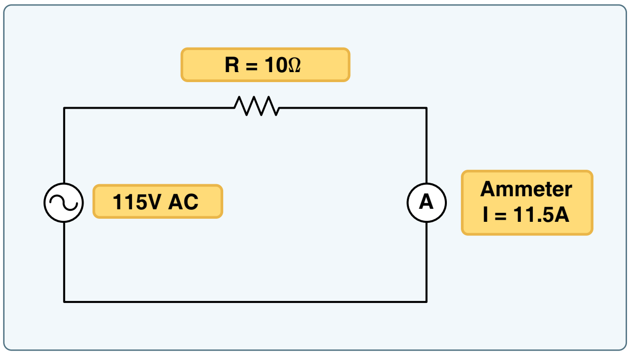


Figure 9-17. *Resistance.*

Inductive Reactance

When moving a magnet through a coil of wire, a voltage is induced across the coil. If a complete circuit is provided, then a current will also be induced. The amount of induced voltage is directly proportional to the rate of change of the magnetic field with respect to the coil. Conversely, current flowing through a coil of wire produces a magnetic field. When this wire is formed into a coil, it then becomes a basic inductor.

The primary effect of a coil is its property to oppose any change in current through it. This property is called inductance. When current flows through any conductor, a magnetic field starts to expand from the center of the wire. As the lines of magnetic force grow outward through the conductor, they induce an EMF in the conductor itself. The induced voltage is always in the direction opposite to the direction of the applied current flow. The effects of this countering EMF are to oppose the applied current. This effect is only a temporary condition. Once the current reaches a steady value in the conductor, the lines of magnetic force are no longer expanding and the countering EMF is no longer present. Since AC is constantly changing in value, the inductance repeats in a cycle always opposite the applied voltage. It should be noted that the unit of measure for inductance is the henry (H).

The physical factors that affect inductance are:

1. Number of turns—doubling the number of turns in a coil produces a field twice as strong if the same current is used. As a general rule, the inductance varies with the square of the number of turns.
2. Cross-sectional area of the coil—the inductance of a coil increases directly as the cross-sectional area of the core increases. Doubling the radius of a coil increases the inductance by a factor of four.
3. Length of a coil—doubling the length of a coil, while keeping the same number of turns, reduces inductance by one-half.

4. Core material around which the coil is formed—coils are wound on either magnetic or nonmagnetic materials. Some nonmagnetic materials include air, copper, plastic, and glass. Magnetic materials include nickel, iron, steel, and cobalt, which have a permeability that provides a better path for the magnetic lines of force and permit a stronger magnetic field.

Since AC is in a constant state of change, the magnetic fields within an inductor are also continuously changing and create an inducted voltage/current. This induced voltage opposes the applied voltage and is known as the counter EMF. This opposition is called inductive reactance, symbolized by XL, and is measured in ohms. This characteristic of the inductor may also create a phase shift between voltage and current of the circuit. The phase shift created by inductive reactance always causes voltage to lead current. That is, the voltage of an inductive circuit reaches its peak values before the current reaches peak values. Additional discussions related to phase shift are presented later in this chapter.

Inductance is the property of a circuit to oppose any change in current and is measured in henries. Inductive reactance is a measure of how much the countering EMF in the circuit opposes the applied current. The inductive reactance of a component is directly proportional to the inductance of the component and the applied frequency to the circuit. By increasing either the inductance or applied frequency, the inductive reactance likewise increases and presents more opposition to current in the circuit. This relationship is given as $XL = 2\pi fL$ Where XL = inductive reactance in ohms, L = inductance in henries, f = frequency in cycles per second, and $\pi = 3.1416$

In *Figure 9-18*, an AC series circuit is shown in which the inductance is 0.146 henry and the voltage is 110 volts at a frequency of 60 cycles per second. Inductive reactance is determined by the following method.

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

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

$$X_L = 55\Omega$$

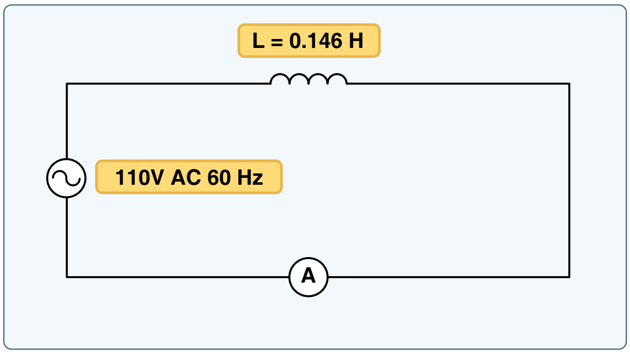


Figure 9-18. *AC circuit containing inductance.*

In AC series circuits, inductive reactance is added like resistances in series in a DC circuit. *[Figure 9-19]* The total reactance in the illustrated circuit equals the sum of the individual reactances.

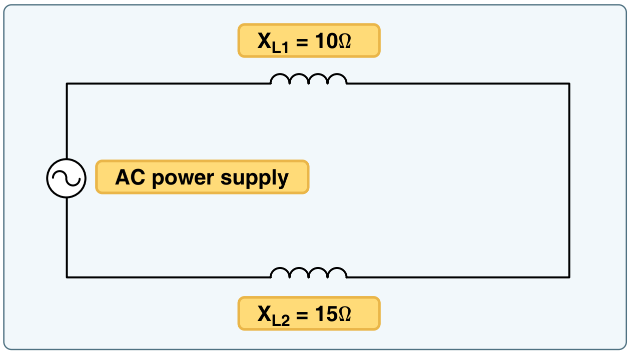


Figure 9-19. *Inductances in series.*

$$X_L = X_{L1} + X_{L2}$$

$$X_L = 10\Omega + 15\Omega$$

$$X_{LT} = 25\Omega$$

The total reactance of inductors connected in parallel is found the same way as the total resistance in a parallel circuit. *[Figure 9-20]* Thus, the total reactance of inductances connected in parallel, as shown, is expressed as:

$$X_{LT} = \frac{1}{\frac{1}{X_{L1}} + \frac{1}{X_{L2}} + \frac{1}{X_{L3}}}$$

$$X_{LT} = \frac{1}{\frac{1}{15} + \frac{1}{15} + \frac{1}{15}}$$

$$X_{LT} = 5\Omega$$

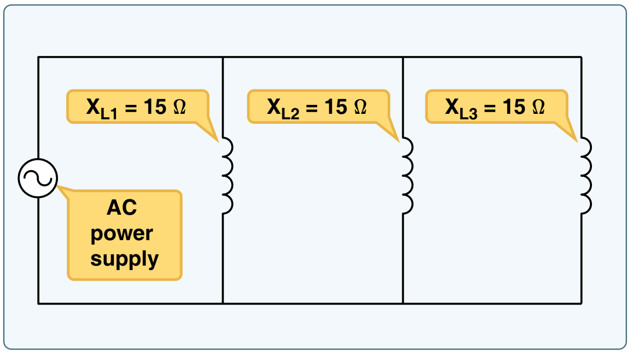


Figure 9-20. *Inductances in parallel.*

Capacitive Reactance

Capacitance is the ability of a body to hold an electric charge. In general, a capacitor is constructed of two parallel plates separated by an insulator. The insulator is commonly called the dielectric. The capacitor's plates have the ability to store electrons when charged by a voltage source. The capacitor discharges when the applied voltage is no longer present and the capacitor is connected to a current path. In an electrical circuit, a capacitor serves as a reservoir or storehouse for electricity.

The basic unit of capacitance is the farad and is given by the letter F. By definition, one farad is one coulomb of charge stored with one volt across the plates of the capacitor. In practical terms, one farad is a large amount of capacitance. Typically, in electronics, much smaller units are used. The two more common smaller units are the microfarad (μF), which is 10^{-6} farad and the picofarad (pF), which is 10^{-12} farad.

Capacitance is a function of the physical properties of the capacitor:

1. The capacitance of parallel plates is directly proportional to their area. A larger plate area produces a larger capacitance, and a smaller area produces less capacitance. If we double the area of the plates, there is room for twice as much charge.
2. The capacitance of parallel plates is inversely proportional to the distance between the plates.
3. The dielectric material effects the capacitance of parallel plates. The dielectric constant of a vacuum is defined as 1, and that of air is very close to 1. These values are used as a reference, and all other materials have values relative to that of air (vacuum).

When an AC is applied in the circuit, the charge on the plates constantly changes. *[Figure 9-21]* This means that electricity must flow first from Y clockwise around to X, then from X counterclockwise around to Y, then from Y clockwise around to X, and so on. Although no current flows through the insulator between the plates of the capacitor, it constantly flows in the remainder of the circuit between X and Y. As this current alternates to and from the capacitor, a certain time lag is created. When a capacitor charges or discharges through a resistance, a certain amount of time is required for a full charge or discharge. The voltage across the capacitor does not change instantaneously. The rate of charging or discharging is determined by the time constant of the circuit. This rate of charge and discharge creates an opposition to current flow in AC circuits known as capacitive reactance. Capacitive reactance is symbolized by X_C and is measured in ohms. This characteristic of a capacitor may also create a phase shift between voltage and current of the circuit. The phase shift created by capacitive reactance always causes current to lead voltage. That is, the current of a capacitive circuit reaches its peak values before the voltage reaches peak values.

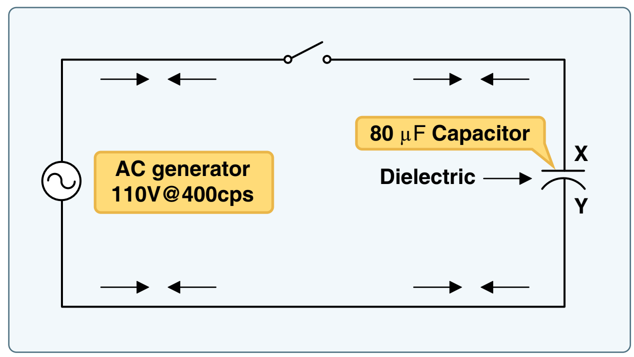


Figure 9-21. *Capacitor in an AC circuit.*

Capacitive reactance is a measure of how much the capacitive circuit opposes the applied current flow. Capacitive reactance is measured in ohms. The capacitive reactance of a circuit is indirectly proportional to the capacitance of the circuit and the applied frequency to the circuit. By increasing either the capacitance or applied frequency, the capacitive reactance decreases, and vice versa. This relationship is given as:

$$X_C = \frac{1}{2\pi fC}$$

Where: X_C = capacitive reactance in ohms, C = capacitance in farads, f = frequency in cycles per second, and $\pi = 3.1416$.

In *Figure 9-21,* a series circuit is shown in which the applied voltage is 110 volts at 400 cps, and the capacitance of a condenser is 80 mf. Find the capacitive reactance and the current flow.

To find the capacitive reactance, the following equation:

$$X_C = \frac{1}{2\pi fC}$$

First, the capacitance, 80 µf, is changed to farads by dividing 80 by 1,000,000, since 1 million microfarads is equal to 1 farad. This quotient equals 0.000080 farad. This is substituted in the equation:

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{1}{2\pi(400)(0.000080)}$$

$$X_C = 4.97\Omega$$

Impedance

The total opposition to current flow in an AC circuit is known as impedance and is represented by the letter Z. The combined effects of resistance, inductive reactance, and capacitive reactance make up impedance (the total opposition to current flow in an AC circuit). In order to accurately calculate voltage and current in AC circuits, the effect of inductance and capacitance along with resistance must be considered. Impedance is measured in ohms.

The rules and equations for DC circuits apply to AC circuits only when that circuit contains resistance alone and no inductance or capacitance. In both series and parallel circuits, if an AC circuit consists of resistance only, the value of the impedance is the same as the resistance, and Ohm's law for an AC circuit, I = E/Z, is exactly the same as for a DC circuit. *Figure 9-22* illustrates a series circuit containing a heater element with 11 ohms resistance connected across a 110-volt source. To find how much current flows if 110 volts AC is applied, the following example is solved:

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

$$I = \frac{110V}{11\Omega}$$

$$I = 10 \text{ Amps}$$

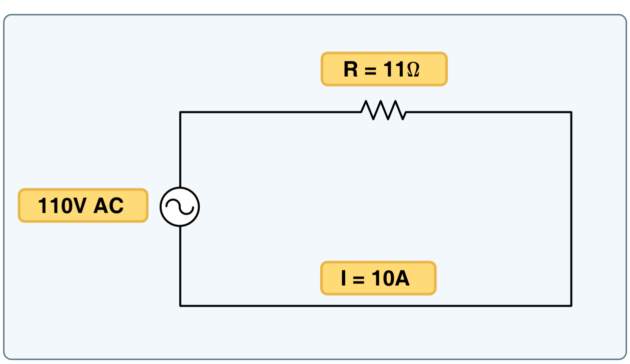


Figure 9-22. *Applying DC and AC to a circuit.*

If there are two resistance values in parallel connected to an AC voltage, as seen in *Figure 9-23,* impedance is equal to the total resistance of the circuit. Once again, the calculations would be handled the same as if it were a DC circuit and the following would apply:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}}$$

$$R_T = \frac{1}{\frac{1}{20} + \frac{1}{20}}$$

$$R_T = 10\Omega$$

Since this is a pure resistive circuit R_T = Z (resistance = Impedance)

$$Z_T = R_T$$

$$Z_T = 10\Omega$$

To determine the current flow in the circuit use the equation:

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

$$I = \frac{50V}{10\Omega}$$

$$I = 5 \text{ Amps}$$

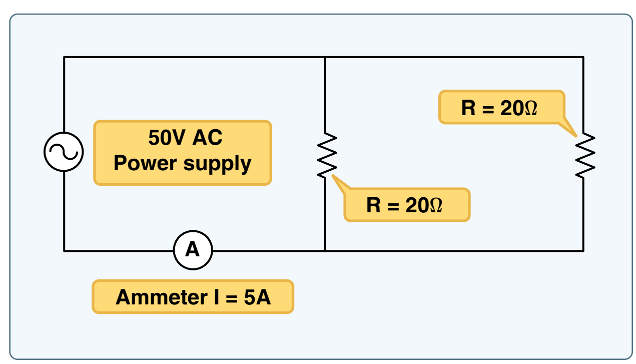


Figure 9-23. *Two resistance values in parallel connected to an AC voltage. Impedance is equal to the total resistance of the circuit.*

Impedance is the total opposition to current flow in an AC circuit. If a circuit has inductance or capacitance, one must take into consideration resistance (R), inductive reactance (X_L), and/or capacitive reactance (X_C) to determine impedance (Z). In this case, Z does not equal R_T. Resistance and reactance (inductive or capacitive) cannot be added directly, but they can be considered as two forces acting at right angles to each other. Thus, the relation between resistance, reactance, and impedance may be illustrated by a right triangle. *[Figure 9-24]* Since these quantities may be related to the sides of a right triangle, the formula for finding the impedance can be found using the Pythagorean Theorem. It states that the square of the hypotenuse is equal to the sum of the squares of the other two sides. Thus, the value of any side of a right triangle can be found if the other two sides are known.

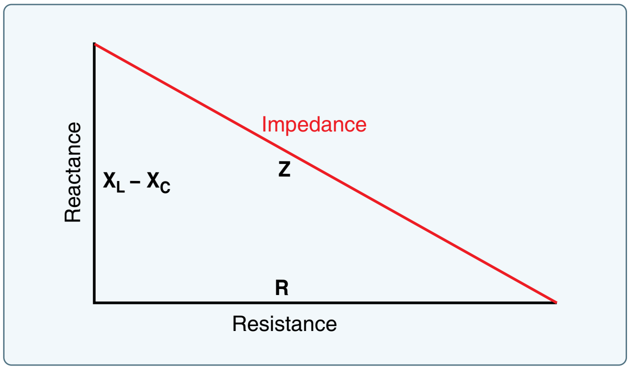


Figure 9-24. *Impedance triangle.*

In practical terms, if a series AC circuit contains resistance and inductance, as shown in *Figure 9-25*, the relation between the sides can be stated as:

$$Z^2 = R^2 + (X_L - X_C)^2$$

The square root of both sides of the equation gives:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

This formula can be used to determine the impedance when the values of inductive reactance and resistance are known. It can be modified to solve for impedance in circuits containing capacitive reactance and resistance by substituting X_C in the formula in place of X_L. In circuits containing resistance with both inductive and capacitive reactance, the reactances can be combined; but because their effects in the circuit are exactly opposite, they are combined by subtraction (the smaller number is always subtracted from the larger):

$$Z = X_L - X_C$$

or

$$X = X_C - X_L$$

Figure 9-25 shows example 1. Here, a series circuit containing a resistor and an inductor are connected to a source of 110 volts at 60 cycles per second. The resistive element is a simple measuring 6 ohms, and the inductive element is a coil with an inductance of 0.021 henry. What is the value of the impedance and the current through the circuit?

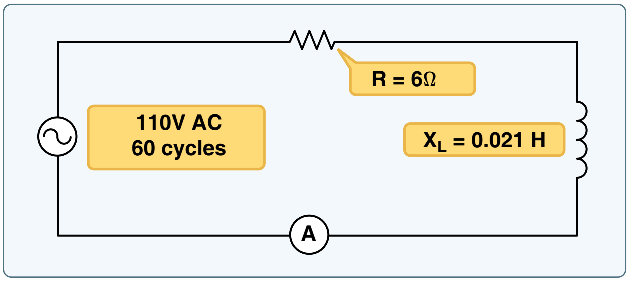


Figure 9-25. *A circuit containing resistance and inductance.*

Solution:
First, the inductive reactance of the coil is computed:

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

$$X_L = 6.28 \times 60 \times 0.021$$

$$X_L = 8 \text{ ohms inductive reactance}$$

Next, the total impedance is computed:

$$Z = \sqrt{R^2 + X_L^2}$$

$$Z = \sqrt{6^2 + 8^2}$$

$$Z = \sqrt{36 + 64}$$

$$Z = \sqrt{100}$$

$$Z = 10\Omega$$

Remember when making calculations for Z always use inductive reactance not inductance, and use capacitive reactance, not capacitance.

Once impedance is found, the total current can be calculated.

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

$$I = \frac{110V}{10\Omega}$$

$$I = 11 \text{ Amps}$$

Since this circuit is resistive and inductive, there is a phase shift where voltage leads current.

Example 2 is a series circuit illustrated in which a capacitor of 200 μf is connected in series with a 10 ohm resistor. *[Figure 9-26]* What is the value of the impedance, the current flow, and the voltage drop across the resistor?

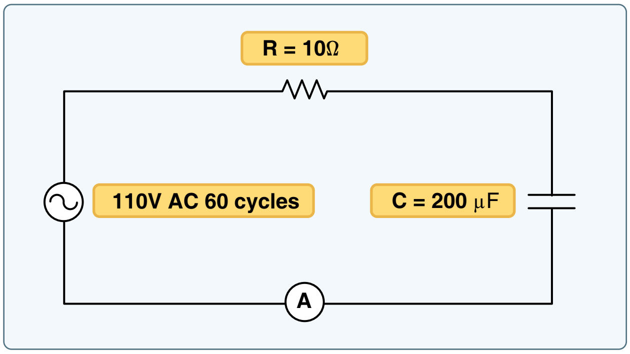


Figure 9-26. *A circuit containing resistance and capacitance.*

Solution:
First, the capacitance is changed from microfarads to farads. Since 1 million microfarads equal 1 farad, then 200 μf = 0.000200 farads

Next solve for capacitive reactance:

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{1}{2\pi(60)(.00020)}$$

$$X_C = \frac{1}{0.07536}$$

$$X_C = 13\Omega$$

To find the impedance,

$$Z = \sqrt{R^2 + X_C^2}$$

$$Z = \sqrt{10^2 + 13^2}$$

$$Z = 16.4\Omega$$

Since this circuit is resistive and capacitive, there is a phase shift where current leads voltage:

To find the current:

$$I_T = \frac{E}{Z}$$

$$I_T = \frac{110V}{6.4\Omega}$$

$$I_T = 6.7 \text{ Amps}$$

To find the voltage drop across the resistor (E_R):

$$E_R = I \times R$$

$$E_R = 6.7A \times 10\Omega$$

$$E_R = 67 \text{ Volts}$$

To find the voltage drop over the capacitor (E_C):

$$E_C = I \times X_C$$

$$E_C = 6.7A \times 13\Omega$$

$$E_C = 86.1 \text{ Volts}$$

The sum of these two voltages does not equal the applied voltage, since the current leads the voltage. Use the following formula to find the applied voltage:

$$E = \sqrt{(E_R)^2 + (E_C)2}$$

$$E = \sqrt{67^2 + 86.1^2}$$

$$E = \sqrt{4{,}489 + 7{,}413}$$

$$E = \sqrt{11{,}902}$$

$$E = 110 \text{ Volts}$$

When the circuit contains resistance, inductance, and capacitance, the following equation is used to find the impedance.

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

Example 3: What is the impedance of a series circuit consisting of a capacitor with a capacitive reactance of 7 ohms, an inductor with an inductive reactance of 10 ohms, and a resistor with a resistance of 4 ohms? *[Figure 9-27]*

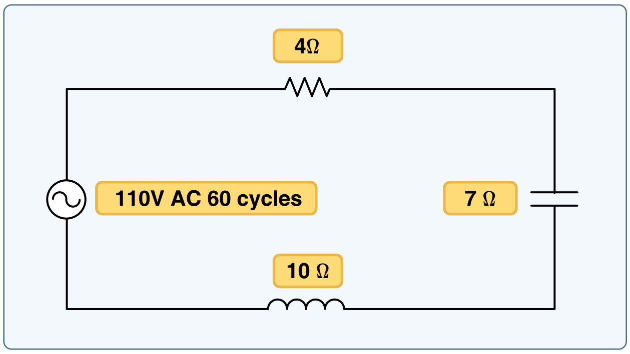


Figure 9-27. *A circuit containing resistance, inductance, and capacitance.*

Solution:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Z = \sqrt{4^2 + (10 - 7)^2}$$

$$Z = \sqrt{25}$$

$$Z = 5\Omega$$

To find total current:

$$I_T = \frac{E_T}{Z}$$

$$I_T = \frac{110V}{5\Omega}$$

$$I_T = 22 \text{ Amps}$$

Remember that inductive and capacitive reactances can cause a phase shift between voltage and current. In this example, inductive reactance is larger than capacitive reactance, so the voltage leads current.

It should be noted that since inductive reactance, capacitive reactance, and resistance affect each other at right angles, the voltage drops of any series AC circuit should be added using vector addition. *Figure 9-28* shows the voltage drops over the series AC circuit described in example 3 above.

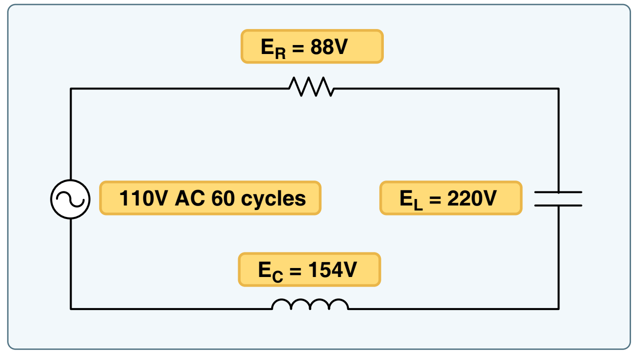


Figure 9-28. *Voltage drops.*

To calculate the individual voltage drops, simply use the equations:

$$E_R = I \times R$$

$$E_{X_L} = I \times X_L$$

$$E_{X_C} = I \times X_C$$

To determine the total applied voltage for the circuit, each individual voltage drop must be added using vector addition.

$$E_T = \sqrt{E_R^2 + (E_L - E_C)^2}$$

$$E_T = \sqrt{88^2 + (220 - 154)^2}$$

$$E_T = \sqrt{88^2 + 66^2}$$

$$E_T = \sqrt{12{,}100}$$

$$E_T = 110 \text{ Volts}$$

Parallel AC Circuits

When solving parallel AC circuits, one must also use a derivative of the Pythagorean Theorem. The equation for finding impedance in an AC circuit is as follows:

$$Z = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2}$$

To determine the total impedance of the parallel circuit shown in *Figure 9-29*, one would first determine the capacitive and inductive reactances. (Remember to convert microfarads to farads.)

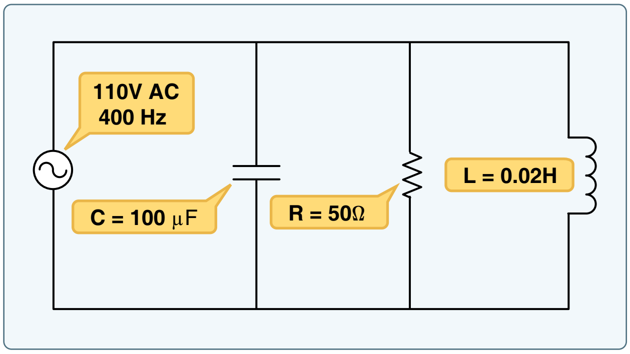


Figure 9-29. *Total impedance of parallel circuit.*

$X_L = 2\pi FL$

$X_L = 2\pi(400)(0.02)$

$X_L = 50\Omega$

$X_C = \frac{1}{2\pi FC}$

100µf = 0.0001F

$X_C = \frac{1}{2\pi(400)(0.0001)}$

$X_C = 4\Omega$

Next, the impedance can be found:

$$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2}}$$

$$Z = \frac{1}{\sqrt{\left(\frac{1}{50}\right)^2 + \left(\frac{1}{50} - \frac{1}{4}\right)^2}}$$

$$Z = \frac{1}{\sqrt{(.02)^2 + (.02 - .25)^2}}$$

$$Z = \frac{1}{\sqrt{.0004 + .0529}}$$

$$Z = \frac{1}{.23}$$

$Z = 4.33\Omega$

To determine the current flow in the circuit:

$I_T = \frac{E_T}{Z}$

$I_T = \frac{100V}{4.33\Omega}$

$I_T = 23.09$ Amps

To determine the current flow through each parallel path of the circuit, calculate I_R, I_L, and I_C.

$I_R = \frac{E}{R}$

$I_R = \frac{100V}{50\Omega}$

$I_R = 2$ Amps

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

$I_L = \frac{100V}{50\Omega}$

$I_L = 2$ Amps

$I_C = \frac{E}{X_C}$

$I_C = \frac{100V}{4\Omega}$

$I_C = 25$ Amps

It should be noted that the total current flow of parallel circuits is found by using vector addition of the individual current flows as follows:

$I_T = \sqrt{I_R^2 + (I_L - I_C)^2}$

$I_T = \sqrt{2^2 + (2 - 25)^2}$

$I_T = \sqrt{2^2 + 23^2}$

$I_T = \sqrt{4 + 529}$

$I_T = \sqrt{533}$

$I_T = 23$ Amps

Power in AC Circuits

Since voltage and current determine power, there are similarities in the power consumed by both AC and DC circuits. In AC however, current is a function of both the resistance and the reactance of the circuit. The power consumed by any AC circuit is a function of the applied voltage and both circuit's resistance and reactance. AC circuits have two distinct types of power, one created by the resistance of the circuit and one created by the reactance of the circuit.

True Power

True power of any AC circuit is commonly referred to as the working power of the circuit. True power is the power consumed by the resistance portion of the circuit and is measured in watts (W). True power is symbolized by the letter P and is indicated by any wattmeter in the circuit. True power is calculated by the formula:

$$P = I^2 \times Z$$

Apparent Power

Apparent power in an AC circuit is sometimes referred to as the reactive power of a circuit. Apparent power is the power consumed by the entire circuit, including both the resistance and the reactance. Apparent power is symbolized by the letter S and is measured in volt-amps (VA). Apparent power is a product of the effective voltage multiplied by the effective current. Apparent power is calculated by the formula:

$$S = I^2 \times Z$$

Power Factor

As seen in *Figure 9-30,* the resistive power and the reactive power effect the circuit at right angles to each other. The power factor in an AC circuit is created by this right angle effect.

Power factor can be defined as the mathematical difference between true power and apparent power. Power factor (PF) is a ratio and always a measurement between 0 and 100. The power factor is directly related to the phase shift of a circuit. The greater the phase shift of a circuit the lower the power factor. For example, an AC circuit that is purely inductive (contains reactance only and no resistance) has a phase shift of 90° and a power factor of 0.0. An AC circuit that is purely resistive (has no reactance) has a phase shift of 0 and a power factor of 100. Power factor is calculated by using the following formula:

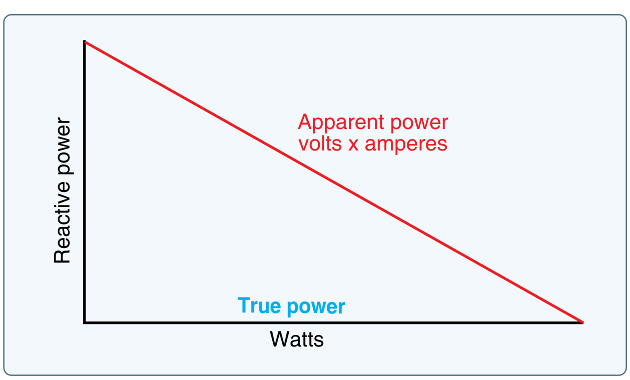


Figure 9-30. *Power relations in AC circuit.*

$$PF = \frac{\text{True Power (Watts)}}{\text{Apparent Power (VA)}} \times 100$$

Example of calculating PF: *Figure 9-31* shows an AC load connected to a 50 volt power supply. The current draw of the circuit is 5 amps and the total resistance of the circuit is 8 ohms. Determine the true power, the apparent power, and the power factor for this circuit.

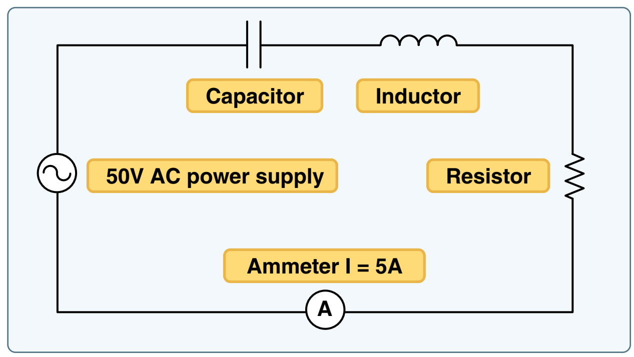


Figure 9-31. *AC load connected to a 50-volt power supply.*

Solution:

$$P = I^2 \times R$$

$$P = 5^2 \times 8$$

$$P = 200 \text{ Watts}$$

$$S = E \times I$$

$$S = 50 \times 5$$

$$S = 250\text{VA}$$

$$PF = \frac{TP}{S} \times 100$$

$$PF = \frac{200}{250} \times 100$$

$$PF = 80$$

Power factor can also be represented as a percentage. Using a percentage to show power factor, the circuit in the previous example would have a power factor of 80 percent.

It should be noted that a low power factor is undesirable. Circuits with a lower power factor create excess load on the power supply and produce inefficiency in the system. Aircraft AC alternators must typically operate with a power factor between 90 percent and 100 percent. It is therefore very important to carefully consider power factor when designing the aircraft electrical system.

Aircraft Batteries

Aircraft batteries are used for many functions (e.g., ground power, emergency power, improving DC bus stability, and fault clearing). Most small private aircraft use lead-acid batteries. Most commercial and corporate aircraft use nickel-cadmium (NiCd) batteries. However, other lead acid types of batteries are becoming available, such as the valve-regulated lead-acid (VRLA) batteries. The battery best suited for a particular application depends on the relative importance of several characteristics, such as weight, cost, volume, service or shelf life, discharge rate, maintenance, and charging rate. Any change of battery type may be considered a major alteration.

Type of Batteries

Aircraft batteries are usually identified by the material used for the plates. The two most common types of battery used are lead-acid and NiCd batteries.

Lead-Acid Batteries

Dry Charged Cell Lead Acid Batteries

Dry charged cell lead-acid batteries, also known as flooded or wet batteries, are assembled with electrodes (plates) that have been fully charged and dried. The electrolyte is added to the battery when it is placed in service, and battery life begins when the electrolyte is added. An aircraft storage battery consists of 6 or 12 lead-acid cells connected in series. The open circuit voltage of the 6 cell battery is approximately 12 volts, and the open circuit voltage of the 12-cell battery is approximately 24 volts. Open circuit voltage is the voltage of the battery when it is not connected to a load. When flooded (vented) batteries are on charge, the oxygen generated at the positive plates escapes from the cell. Concurrently, at the negative plates, hydrogen is generated from water and escapes from the cell. The overall result is the gassing of the cells and water loss. Therefore, flooded cells require periodic water replenishment. *[Figure 9-32]*

Figure 9-32. *Lead acid battery installation.*

Valve-Regulated Lead-Acid Batteries (VRLA)

VRLA batteries contain all electrolyte absorbed in glass-mat separators with no free electrolyte and are sometimes referred to as sealed batteries. *[Figure 9-33]* The electrochemical reactions for VRLA batteries are the same as flooded batteries, except for the gas recombination mechanism that is predominant in VRLA batteries. These types of battery are used in general aviation and turbine powered aircraft and are sometimes authorized replacements for NiCd batteries.

Figure 9-33. *Valve-regulated lead-acid battery (sealed battery).*

When VRLA batteries are on charge, oxygen combines chemically with the lead at the negative plates in the presence of H_2SO_4 to form lead sulfate and water. This oxygen recombination suppresses the generation of hydrogen at the negative plates. Overall, there is no water loss during charging. A very small quantity of water may be lost as a result of self-discharge reactions; however, such loss is so small that no provisions are made for water replenishment. The battery cells have a pressure relief safety valve that may vent if the battery is overcharged.

NiCd Batteries

A NiCd battery consists of a metallic box, usually stainless steel, plastic-coated steel, painted steel, or titanium containing a number of individual cells. *[Figure 9-34]* These cells are connected in series to obtain 12 volts or 24 volts. The cells are connected by highly conductive nickel copper links. Inside the battery box, the cells are held in place by partitions, liners, spacers, and a cover assembly. The battery has a ventilation system to allow the escape of the gases produced during an overcharge condition and provide cooling during normal operation.

Figure 9-34. *NiCd battery installation.*

NiCd cells installed in an aircraft battery are typical of the vented cell type. The vented cells have a vent or low pressure release valve that releases any generated oxygen and hydrogen gases when overcharged or discharged rapidly. This also means the battery is not normally damaged by excessive rates of overcharge, discharge, or even negative charge. The cells are rechargeable and deliver a voltage of 1.2 volts during discharge.

Aircraft that are outfitted with NiCd batteries typically have a fault protection system that monitors the condition of the battery. The battery charger is the unit that monitors the condition of the battery and the following conditions are monitored.

1. Overheat condition
2. Low temperature condition (below –40 °F)
3. Cell imbalance
4. Open circuit
5. Shorted circuit

If the battery charger finds a fault, it turns off and sends a fault signal to the Electrical Load Management System (ELMS).

NiCd batteries are capable of performing to its rated capacity when the ambient temperature of the battery is in the range of approximately 60–90 °F. An increase or decrease in temperature from this range results in reduced capacity. NiCd batteries have a ventilation system to control the temperature of the battery. A combination of high battery temperature (in excess of 160 °F) and overcharging can lead to a condition called thermal runaway. *[Figure 9-35]* The temperature of the battery has to be constantly monitored to ensure safe operation. Thermal runaway can result in a NiCd chemical fire and/or explosion of the NiCd battery under recharge by a constant-voltage source and is due to cyclical, ever-increasing temperature and charging current. One or more shorted cells or an existing high temperature and low charge can produce the following cyclical sequence of events:

1. Excessive current,
2. Increased temperature,
3. Decreased cell(s) resistance,
4. Further increased current, and
5. Further increased temperature.

Figure 9-35. *Thermal runaway damage.*

This does not become a self-sustaining thermal-chemical action if the constant-voltage charging source is removed before the battery temperature is in excess of 160 °F.

Capacity

Capacity is measured quantitatively in ampere-hours delivered at a specified discharge rate to a specified cut-off voltage at room temperature. The cut-off voltage is 1.0 volt per cell. Battery available capacity depends upon several factors including such items as:

1. Cell design (cell geometry, plate thickness, hardware, and terminal design govern performance under specific usage conditions of temperature, discharge rate, etc.).

2. Discharge rate (high current rates yield less capacity than low rates).
3. Temperature (capacity and voltage levels decrease as battery temperature moves away from the 60 °F (16 °C) to 90 °F (32 °C) range toward the high and low extremes).
4. Charge rate (higher charge rates generally yield greater capacity).

Aircraft Battery Ratings by Specification

The one-hour rate is the rate of discharge a battery can endure for 1 hour with the battery voltage at or above 1.67 volts per cell, or 20 volts for a 24-volt lead-acid battery, or 10 volts for a 12-volt lead-acid battery. The one-hour capacity, measured in ampere hours (Ah), is the product of the discharge rate and time (in hours) to the specified end voltage.

The emergency rate is the total essential load, measured in amperes, required to support the essential bus for 30 minutes. This is the rate of discharge a battery can endure for 30 minutes with the battery voltage at or above 1.67 volts per cell, or 20 volts for a 24 volt lead-acid battery, or 10 volts for a 12 volt lead-acid battery.

Storing and Servicing Facilities

Separate facilities for storing and/or servicing flooded electrolyte lead-acid and NiCd batteries must be maintained. Introduction of acid electrolyte into alkaline electrolyte causes permanent damage to vented (flooded electrolyte) NiCd batteries and vice versa. However, batteries that are sealed can be charged and capacity checked in the same area. Because the electrolyte in a valve-regulated lead-acid battery is absorbed in the separators and porous plates, it cannot contaminate a NiCd battery even when they are serviced in the same area.

WARNING: It is extremely dangerous to store or service lead-acid and NiCd batteries in the same area. Introduction of acid electrolytes into alkaline electrolyte destroys the NiCd, and vice versa.

Battery Freezing

Discharged lead-acid batteries exposed to cold temperatures are subject to plate damage due to freezing of the electrolyte. To prevent freezing damage, maintain each cell's specific gravity at 1.275 or, for sealed lead-acid batteries, check open circuit voltage. *[Figure 9-36]* NiCd battery electrolyte is not as susceptible to freezing because no appreciable chemical change takes place between the charged and discharged states. However, the electrolyte freezes at approximately –75 °F.

Specific Gravity	Freezing Point		State of Charge (SOC) for Sealed Lead-Acid Batteries at 70°		
	°C	°F	SOC	12 volt	24 volt
1.300	–70	–95	100%	12.9	25.8
1.275	–62	–80	75%	12.7	25.4
1.250	–52	–62	50%	12.4	24.8
1.225	–37	–35	25%	12.0	24.0
1.200	–26	–16			
1.175	–20	–04			
1.150	–15	+05			
1.125	–10	+13			
1.100	–08	+19			

Figure 9-36. *Lead-acid battery electrolyte freezing points.*

NOTE: Only a load check determines overall battery condition.

Temperature Correction

U.S.-manufactured lead-acid batteries are considered fully charged when the specific gravity reading is between 1.275 and 1.300. A ⅓ discharged battery reads about 1.240 and a ⅔ discharged battery shows a specific gravity reading of about 1.200 when tested by a hydrometer at an electrolyte temperature of 80 °F. However, to determine precise specific gravity readings, a temperature correction should be applied to the hydrometer indication. *[Figure 9-37]* As an example, for a hydrometer reading of 1.260 and electrolyte temperature of 40 °F, the corrected specific gravity reading of the electrolyte is 1.244.

Electrolyte Temperature		Points to Subtract From or Add to Specific Gravity Readings
°C	°F	12 volt
+60	+140	+0.024
+55	+130	+0.020
+49	+120	+0.016
+43	+110	+0.012
+38	+100	+0.008
+33	+90	+0.004
+27	+80	0
+23	+70	–0.004
+15	+60	–0.008
+10	+50	–0.012
+05	+40	–0.016
–02	+30	–0.020
–07	+20	–0.024
–13	+10	–0.028
–18	0	–0.032
–23	–10	–0.036
–28	–20	–0.040
–35	–30	–0.044

Figure 9-37. *Sulfuric acid temperature correction.*

Battery Charging

Operation of aircraft batteries beyond their ambient temperature or charging voltage limits can result in excessive cell temperatures leading to electrolyte boiling, rapid deterioration of the cells, and battery failure. The relationship between maximum charging voltage and the number of cells in the battery is also significant. This determines (for a given ambient temperature and state of charge) the rate at which energy is absorbed as heat within the battery. For lead-acid batteries, the voltage per cell must not exceed 2.35 volts. In the case of NiCd batteries, the charging voltage limit varies with design and construction. Values of 1.4 and 1.5 volts per cell are generally used. In all cases, follow the recommendations of the battery manufacturer.

Constant Voltage Charging (CP)

The battery charging system in an airplane is of the constant voltage type. An engine-driven generator, capable of supplying the required voltage, is connected through the aircraft electrical system directly to the battery. A battery switch is incorporated in the system so that the battery may be disconnected when the airplane is not in operation.

The voltage of the generator is accurately controlled by means of a voltage regulator connected in the field circuit of the generator. For a 12-volt system, the voltage of the generator is adjusted to approximately 14.25. On 24-volt systems, the adjustment should be between 28 and 28.5 volts. When these conditions exist, the initial charging current through the battery is high. As the state of charge increases, the battery voltage also increases, causing the current to taper down. When the battery is fully charged, its voltage is almost equal to the generator voltage, and very little current flows into the battery. When the charging current is low, the battery may remain connected to the generator without damage.

When using a constant-voltage system in a battery shop, a voltage regulator that automatically maintains a constant voltage is incorporated in the system. A higher capacity battery (e.g., 42 Ah) has a lower resistance than a lower capacity battery (e.g., 33 Ah). Hence, a high-capacity battery draws a higher charging current than a low-capacity battery when both are in the same state of charge and when the charging voltages are equal. The constant voltage method is the preferred charging method for lead-acid batteries.

Constant Current Charging

Constant current charging is the most convenient for charging batteries outside the airplane because several batteries of varying voltages may be charged at once on the same system. A constant current charging system usually consists of a rectifier to change the normal AC supply to DC. A transformer is used to reduce the available 110-volt or 220-volt AC supply to the desired level before it is passed through the rectifier. If a constant current charging system is used, multiple batteries may be connected in series, provided that the charging current is kept at such a level that the battery does not overheat or gas excessively.

The constant current charging method is the preferred method for charging NiCd batteries. Typically, a NiCd battery is constant current charged at a rate of 1CA until all the cells have reached at least 1.55V. Another charge cycle follows at 0.1CA, again until all cells have reached 1.55V. The charge is finished with an overcharge or top-up charge, typically for not less than 4 hours at a rate of 0.1CA. The purpose of the overcharge is to expel as much, if not all the gases collected on the electrodes, hydrogen on the anode, and oxygen on the cathode; some of these gases recombine to form water that, in turn, raises the electrolyte level to its highest level after which it is safe to adjust the electrolyte levels. During the overcharge or top-up charge, the cell voltages go beyond 1.6V and then slowly start to drop. No cell should rise above 1.71V (dry cell) or drop below 1.55V (gas barrier broken).

Charging is done with vent caps loosened or open. A stuck vent might increase the pressure in the cell. It also allows for refilling of water to correct levels before the end of the top-up charge while the charge current is still on. However, cells should be closed again as soon as the vents have been cleaned and checked since carbon dioxide dissolved from outside air carbonates the cells and ages the battery.

Battery Maintenance

Battery inspection and maintenance procedures vary with the type of chemical technology and the type of physical construction. Always follow the battery manufacturer's approved procedures. Battery performance at any time in a given application depends upon the battery's age, state of health, state of charge, and mechanical integrity, which you can determine according to the following:

- To determine the life and age of the battery, record the install date of the battery on the battery. During normal battery maintenance, battery age must be documented either in the aircraft maintenance log or in the shop maintenance log.
- Lead-acid battery state of health may be determined by duration of service interval (in the case of vented batteries), by environmental factors (such as excessive heat or cold), and by observed electrolyte leakage (as evidenced by corrosion of wiring and connectors or accumulation of powdered salts). If the battery needs to be refilled often, with no evidence of external leakage, this may indicate a poor state of the battery, the battery charging system, or an overcharge condition.

- Use a hydrometer to determine the specific gravity of the lead-acid battery electrolyte, which is the weight of the electrolyte compared to the weight of pure water. Take care to ensure the electrolyte is returned to the cell from which it was extracted. When a specific gravity difference of 0.050 or more exists between cells of a battery, the battery is approaching the end of its useful life and replacement should be considered. Electrolyte level may be adjusted by the addition of distilled water. Do not add electrolyte.
- Battery state of charge is determined by the cumulative effect of charging and discharging the battery. In a normal electrical charging system, the aircraft generator or alternator restores a battery to full charge during a flight of 1 hour to 90 minutes.
- Proper mechanical integrity involves the absence of any physical damage, as well as assurance that hardware is correctly installed and the battery is properly connected. Battery and battery compartment venting system tubes, nipples, and attachments, when required, provide a means of avoiding the potential buildup of explosive gases, and should be checked periodically to ensure that they are securely connected and oriented in accordance with the maintenance manual's installation procedures. Always follow procedures approved for the specific aircraft and battery system to ensure that the battery system is capable of delivering specified performance.

Battery and Charger Characteristics

The following information is provided to acquaint the user with characteristics of the more common aircraft battery and battery charger types. *[Figure 9-38]* Products may vary from these descriptions due to different applications of available technology. Consult the manufacturer for specific performance data.

Figure 9-38. *Battery charger.*

NOTE: Never connect a lead-acid battery to a charger, unless properly serviced.

Lead-Acid Batteries

Lead-acid vented batteries have a two volt nominal cell voltage. Batteries are constructed so that individual cells cannot be removed. Occasional addition of water is required to replace water loss due to overcharging in normal service. Batteries that become fully discharged may not accept recharge. Lead-acid sealed batteries are similar in most respects to lead-acid vented batteries, but do not require the addition of water.

The lead-acid battery is economical and has extensive application but is heavier than an equivalent performance battery of another type. The battery is capable of a high rate of discharge and low-temperature performance. However, maintaining a high rate of discharge for a period of time usually warps the cell plates, shorting out the battery. Its electrolyte has a moderate specific gravity, and state of charge can be checked with a hydrometer.

Lead-acid batteries are usually charged by regulated DC voltage sources. This allows maximum accumulation of charge in the early part of recharging.

NiCd Batteries

NiCd vented batteries have a 1.2-volt nominal cell voltage. Occasional addition of distilled water is required to replace water loss due to overcharging in normal service. Cause of failure is usually shorting or weakening of a cell. After replacing the bad cell with a good cell, the battery's life can be extended for 5 or more years. Full discharge is not harmful to this type of battery.

NiCd sealed batteries are similar in most respects to NiCd vented batteries, but do not normally require the addition of water. Fully discharging the battery (to zero volts) may cause irreversible damage to one or more cells, leading to eventual battery failure due to low capacity.

The state of charge of a NiCd battery cannot be determined by measuring the specific gravity of the potassium hydroxide electrolyte. The electrolyte specific gravity does not change with the state of charge. The only accurate way to determine the state of charge of a NiCd battery is by a measured discharge with a NiCd battery charger and following the manufacturer's instructions. After the battery has been fully charged and allowed to stand for at least 2 hours, the fluid level may be adjusted, if necessary, using distilled or demineralized water. Because the fluid level varies with the state of charge, water should never be added while the battery is installed in the aircraft. Overfilling the battery results in electrolyte spewage during charging. This causes corrosive effects on the cell links, self-discharge of the battery, dilution of the electrolyte density, possible blockage of the cell vents, and eventual cell rupture.

Constant current battery chargers are usually provided for NiCd batteries because the NiCd cell voltage has a negative temperature coefficient. With a constant voltage charging source, a NiCd battery having a shorted cell might overheat due to excessive overcharge and undergo a thermal runaway, destroying the battery and creating a possible safety hazard to the aircraft. Pulsed-current battery chargers are sometimes provided for NiCd batteries.

CAUTION: It is important to use the proper charging procedures for batteries under test and maintenance. These charging regimes for reconditioning and charging cycles are defined by the aircraft manufacturer and should be closely followed.

Aircraft Battery Inspection

Aircraft battery inspection consists of the following items:

1. Inspect battery sump jar and lines for condition and security.
2. Inspect battery terminals and quickly disconnect plugs and pins for evidence of corrosion, pitting, arcing, and burns. Clean as required.
3. Inspect battery drain and vent lines for restriction, deterioration, and security.
4. Routine preflight and postflight inspection procedures should include observation for evidence of physical damage, loose connections, and electrolyte loss.

Ventilation Systems

Modern airplanes are equipped with battery ventilating systems. The ventilating system removes gasses and acid fumes from the battery in order to reduce fire hazards and to eliminate damage to airframe parts. Air is carried from a scoop outside the airplane through a vent tube to the interior of the battery case. After passing over the top of the battery, air, battery gasses, and acid fumes are carried through another tube to the battery sump. This sump is a glass or plastic jar of at least one pint capacity. In the jar is a felt pad about 1 inch thick saturated with a 5-percent solution of bicarbonate of soda and water. The tube carrying fumes to the sump extends into the jar to within about ¼ inch of the felt pad. An overboard discharge tube leads from the top of the sump jar to a point outside the airplane. The outlet for this tube is designed so there is negative pressure on the tube whenever the airplane is in flight. This helps to ensure a continuous flow of air across the top of the battery through the sump and outside the airplane. The acid fumes going into the sump are neutralized by the action of the soda solution, thus preventing corrosion of the aircraft's metal skin or damage to a fabric surface.

Installation Practices

- External surface—Clean the external surface of the battery prior to installation in the aircraft.
- Replacing lead-acid batteries—When replacing lead-acid batteries with NiCd batteries, a battery temperature or current monitoring system must be installed. Neutralize the battery box or compartment and thoroughly flush with water and dry. A flight manual supplement must also be provided for the NiCd battery installation. Acid residue can be detrimental to the proper functioning of a NiCd battery, as alkaline is to a lead-acid battery.
- Battery venting—Battery fumes and gases may cause an explosive mixture or contaminated compartments and should be dispersed by adequate ventilation. Venting systems often use ram pressure to flush fresh air through the battery case or enclosure to a safe overboard discharge point. The venting system pressure differential should always be positive and remain between recommended minimum and maximum values. Line runs should not permit battery overflow fluids or condensation to be trapped and prevent free airflow.
- Battery sump jars—A battery sump jar installation may be incorporated in the venting system to dispose of battery electrolyte overflow. The sump jar should be of adequate design and the proper neutralizing agent used. The sump jar must be located only on the discharge side of the battery venting system.
- Installing batteries—When installing batteries in an aircraft, exercise care to prevent inadvertent shorting of the battery terminals. Serious damage to the aircraft structure (frame, skin and other subsystems, avionics, wire, fuel, etc.) can be sustained by the resultant high discharge of electrical energy. This condition may normally be avoided by insulating the terminal posts during the installation process. Remove the grounding lead first for battery removal, then the positive lead. Connect the grounding lead of the battery last to minimize the risk of shorting the hot terminal of the battery during installation.

- Battery hold down devices—Ensure that the battery hold down devices are secure, but not so tight as to exert excessive pressure that may cause the battery to buckle causing internal shorting of the battery.
- Quick-disconnect type battery—If a quick-disconnect type of battery connector that prohibits crossing the battery lead is not employed, ensure that the aircraft wiring is connected to the proper battery terminal. Reverse polarity in an electrical system can seriously damage a battery and other electrical components. Ensure that the battery cable connections are tight to prevent arcing or a high resistance connection.

Troubleshooting

See *Figure 9-39* for a troubleshooting chart.

DC Generators and Controls

DC generators transform mechanical energy into electrical energy. As the name implies, DC generators produce direct current and are typically found on light aircraft. In many cases, DC generators have been replaced with DC alternators. Both devices produce electrical energy to power the aircraft's electrical loads and charge the aircraft's battery. Even though they share the same purpose, the DC alternator and DC generator are very different. DC generators require a control circuit in order to ensure the generator maintains the correct voltage and current for the current electrical conditions of the aircraft. Typically, aircraft generators maintain a nominal output voltage of approximately 14 volts or 28 volts.

Generators

The principles of electromagnetic induction were discussed earlier in this chapter. These principles show that voltage is induced in the armature of a generator throughout the entire 360° rotation of the conductor. The armature is the rotating portion of a DC generator. As shown, the voltage being induced is AC. *[Figure 9-40]*

Since the conductor loop is constantly rotating, some means must be provided to connect this loop of wire to the electrical loads. As shown in *Figure 9-41,* slip rings and brushes can be used to transfer the electrical energy from the rotating loop to the stationary aircraft loads. The slip rings are connected to the loop and rotate; the brushes are stationary and allow a current path to the electrical loads. The slip rings are typically a copper material and the brushes are a soft carbon substance.

It is important to remember that the voltage being produced by this basic generator is AC, and AC voltage is supplied to the slip rings. Since the goal is to supply DC loads, some means must be provided to change the AC voltage to a DC voltage. Generators use a modified slip ring arrangement, known as a commutator, to change the AC produced in the generator loop into a DC voltage. The action of the commutator allows the generator to produce a DC output.

By replacing the slip rings of the basic AC generator with two half cylinders (the commutator), a basic DC generator is obtained. In *Figure 9-42*, the red side of the coil is connected to the red segment and the amber side of the coil to the amber segment. The segments are insulated from each other. The two stationary brushes are placed on opposite sides of the commutator and are so mounted that each brush contacts each segment of the commutator as the commutator revolves simultaneously with the loop. The rotating parts of a DC generator (coil and commutator) are called an armature.

As seen in the very simple generator of *Figure 9-42*, as the loop rotates the brushes make contact with different segments of the commutator. In positions A, C, and E, the brushes touch the insulation between the brushes; when the loop is in these positions, no voltage is being produced. In position B, the positive brush touches the red side of the conductor loop. In position D, the positive brush touches the amber side of the armature conductor. This type of connection reversal changes the AC produced in the conductor coil into DC to power the aircraft. An actual DC generator is more complex, having several loops of wire and commutator segments.

Because of this switching of commutator elements, the red brush is always in contact with the coil side moving downward, and the amber brush is always in contact with the coil side moving upward. Though the current actually reverses its direction in the loop in exactly the same way as in the AC generator, commutator action causes the current to flow always in the same direction through the external circuit or meter.

The voltage generated by the basic DC generator in *Figure 9-42* varies from zero to its maximum value twice for each revolution of the loop. This variation of DC voltage is called ripple and may be reduced by using more loops, or coils, as shown in *Figure 9-43*.

As the number of loops is increased, the variation between maximum and minimum values of voltage is reduced *[Figure 9-43]*, and the output voltage of the generator approaches a steady DC value. For each additional loop in the rotor, another two commutator segments is required. A photo of a typical DC generator commutator is shown in *Figure 9-44*.

Trouble	Probable Cause	Corrective Action
Apparent loss of capacity	Very common when recharging on a constant potential bus, as in aircraft	Reconditioning will alleviate this condition.
	Usually indicates imbalance between cells because of difference in temperature, charge efficiency, self-discharge rate, etc., in the cells	
	Electrolyte level too low Battery not fully charged	Charge. Adjust electrolyte level. Check aircraft voltage regulator. If OK, reduce maintenance interval.
Complete failure to operate	Defective connection in equipment circuitry in which battery is installed, such as broken lead, inoperative relay, or improper receptacle installation	Check and correct external circuitry.
	End terminal connector loose or diengaged Poor intercell connections	Clean and retighten hardware using proper torque values.
	Open circuit or dry cell	Replace defective cell.
Excessive spewage of electrolyte	High charge voltage High temperature during charge Electrolyte level too high	Clean battery, charge, and adjust electrolyte level.
	Loose or damaged vent cap	Clean battery, tighten or replace cap, charge and adjust electrolyte level.
	Damaged cell and seal	Short out all cells to 0 volts, clean battery, replace defective cell, charge, and adjust electrolyte level.
Failure of one or more cells to rise to the required 1.55 volts at the end of charge	Negative electrode not fully charged Cellophane separator damage	Discharge battery and recharge. If the cell still fails to rise to 1.55 volts or if the cell's voltage rises to 1.55 volts or above and then drops, remove cell and replace.
Distortion of cell case to cover	Overcharged, overdischarged, or overheated cell with internal short	Discharge battery and disassemble. Replace defective cell. Recondition battery.
	Plugged vent cap	Replace vent cap.
	Overheated battery	Check voltage regulator: treat battery as above, replacing battery case and cover and all other defective parts.
Foreign material within the cell case	Introduced into cell through addition of impure water or water contaminated with acid	Discharge battery and disassemble, remove cell and replace, recondition battery.
Frequent addition of water	Cell out of balance	Recondition battery.
	Damaged "O" ring, vent cap	Replace damaged parts.
	Leaking cell	Discharge battery and disassemble. Replace defective cell, recondition battery.
	Charge voltage too high	Adjust voltage regulator.
Corrosion of top hardware	Acid flumes or spray or other corrosive atmosphere	Replace parts. Battery should be kept clean and kept away from such environments.

Figure 9-39. *Battery troubleshooting guide.*

Trouble	Probable Cause	Corrective Action
Discolored or burned end connectors or intercell connectors	Dirty connections Loose connection Improper mating of parts	Clean parts: replace if necessary. Retighten hardware using proper torque values. Check to see that parts are properly mated.
Distortion of battery case and/or cover	Explosion caused by: Dry cells Charger failure High charge voltage Plugged vent caps Loose intercell connectors	Discharge battery and disassemble. Replace damaged parts and recondition.

Figure 9-39. *Battery troubleshooting guide (continued).*

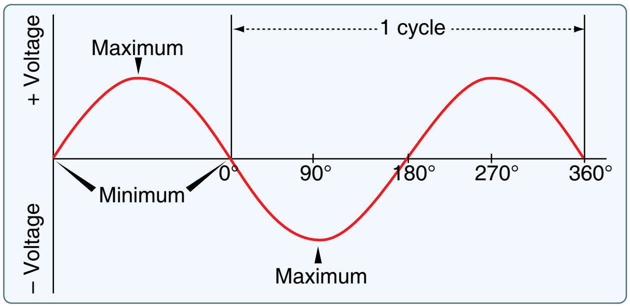


Figure 9-40. *Output of an elementary generator.*

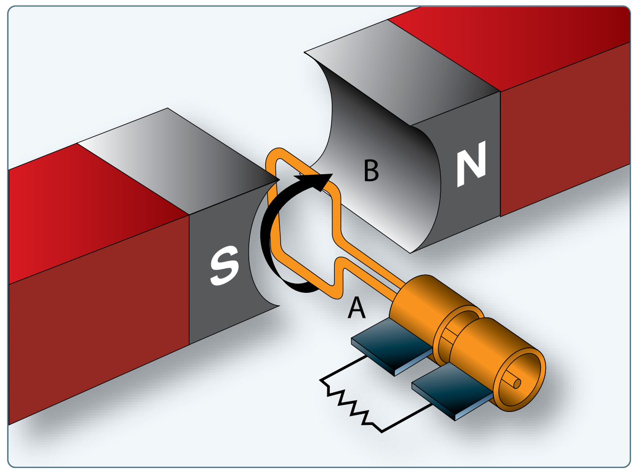


Figure 9-41. *Generator slip rings and loop rotate; brushes are stationary.*

Construction Features of DC Generators

The major parts, or assemblies, of a DC generator are a field frame, a rotating armature, and a brush assembly. The parts of a typical aircraft generator are shown in *Figure 9-45*.

Field Frame

The frame has two functions: to hold the windings needed to produce a magnetic field, and to act as a mechanical support for the other parts of the generator. The actual electromagnet conductor is wrapped around pieces of laminated metal called field poles. The poles are typically bolted to the inside of the frame and laminated to reduce eddy current losses and serve the same purpose as the iron core of an electromagnet; they concentrate the lines of force produced by the field coils. The field coils are made up of many turns of insulated wire and are usually wound on a form that fits over the iron core of the pole to which it is securely fastened. *[Figure 9-46]*

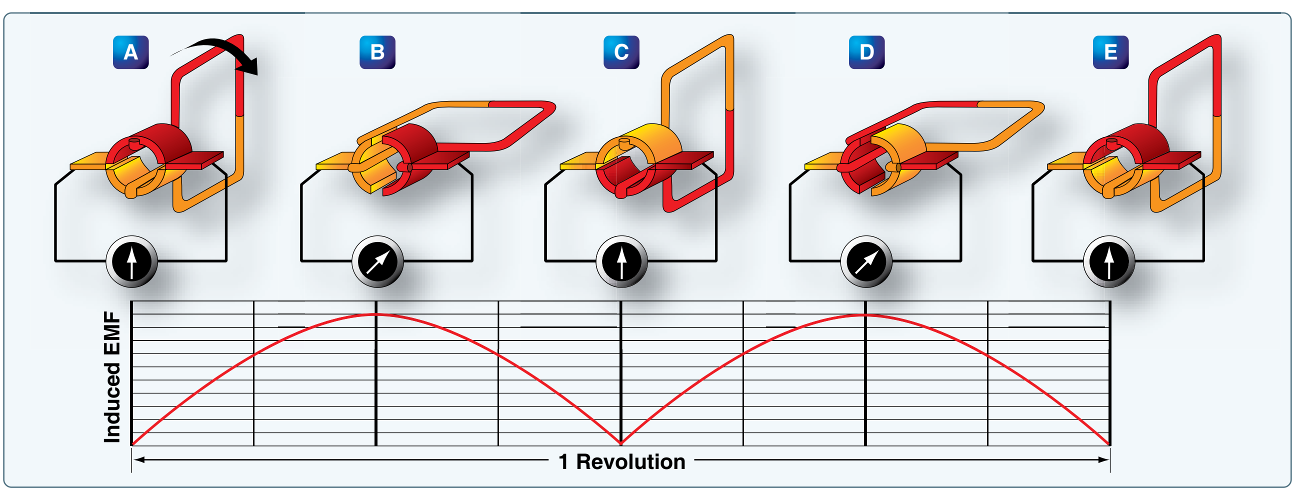


Figure 9-42. *A two-piece slip ring, or commutator, allows brushes to transfer current that flows in a single direction (DC).*

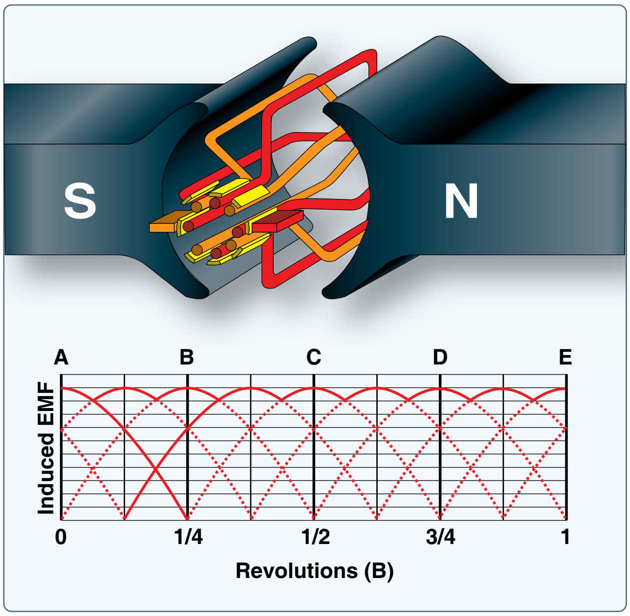


Figure 9-43. *Increasing the number of coils reduces the ripple in the voltage.*

A DC current is fed to the field coils to produce an electromagnetic field. This current is typically obtained from an external source that provides voltage and current regulation for the generator system. Generator control systems are discussed later in this chapter.

Figure 9-44. *Typical DC generator commutator.*

Armature

The armature assembly of a generator consists of two primary elements: the wire coils (called windings) wound around an iron core and the commutator assembly. The armature windings are evenly spaced around the armature and mounted on a steel shaft. The armature rotates inside the magnetic field produced by the field coils. The core of the armature acts as an iron conductor in the magnetic field and, for this reason, is laminated to prevent the circulation of eddy currents. A typical armature assembly is shown in *Figure 9-47*.

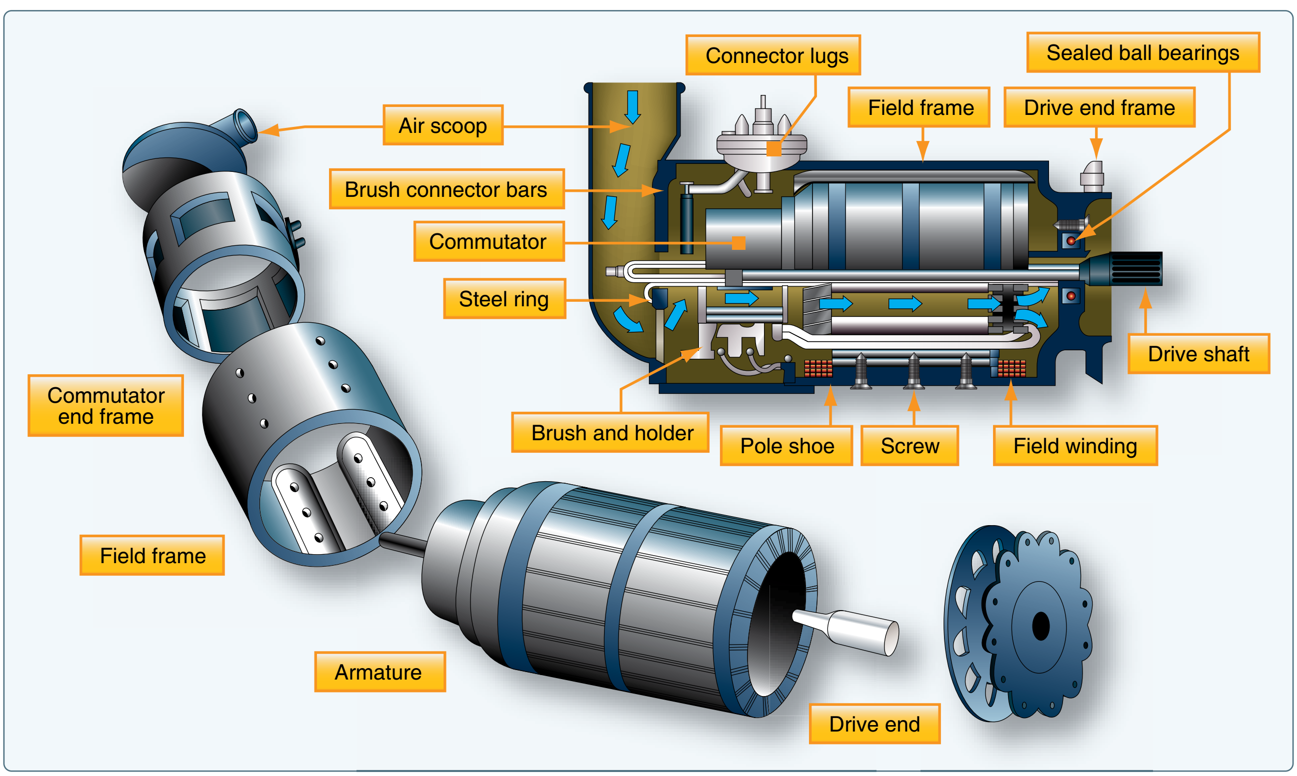


Figure 9-45. *Typical 24-volt aircraft generator.*

Figure 9-46. *Generator field frame.*

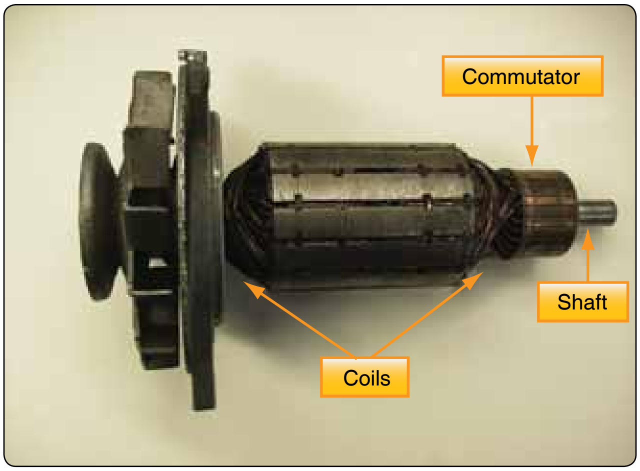


Figure 9-47. *A drum-type armature.*

Commutators

Figure 9-48 shows a cross-sectional view of a typical commutator. The commutator is located at the end of an armature and consists of copper segments divided by a thin insulator. The insulator is often made from the mineral mica. The brushes ride on the surface of the commutator forming the electrical contact between the armature coils and the external circuit. A flexible, braided copper conductor, commonly called a pigtail, connects each brush to the external circuit. The brushes are free to slide up and down in their holders in order to follow any irregularities in the surface of the commutator. The constant making and breaking of electrical connections between the brushes and the commutator segments, along with the friction between the commutator and the brush, causes brushes to wear out and need regular attention or replacement. For these reasons, the material commonly used for brushes is high-grade carbon. The carbon must be soft enough to prevent undue wear of the commutator and yet hard enough to provide reasonable brush life. Since the contact resistance of carbon is fairly high, the brush must be quite large to provide a current path for the armature windings.

The commutator surface is highly polished to reduce friction as much as possible. Oil or grease must never be used on a

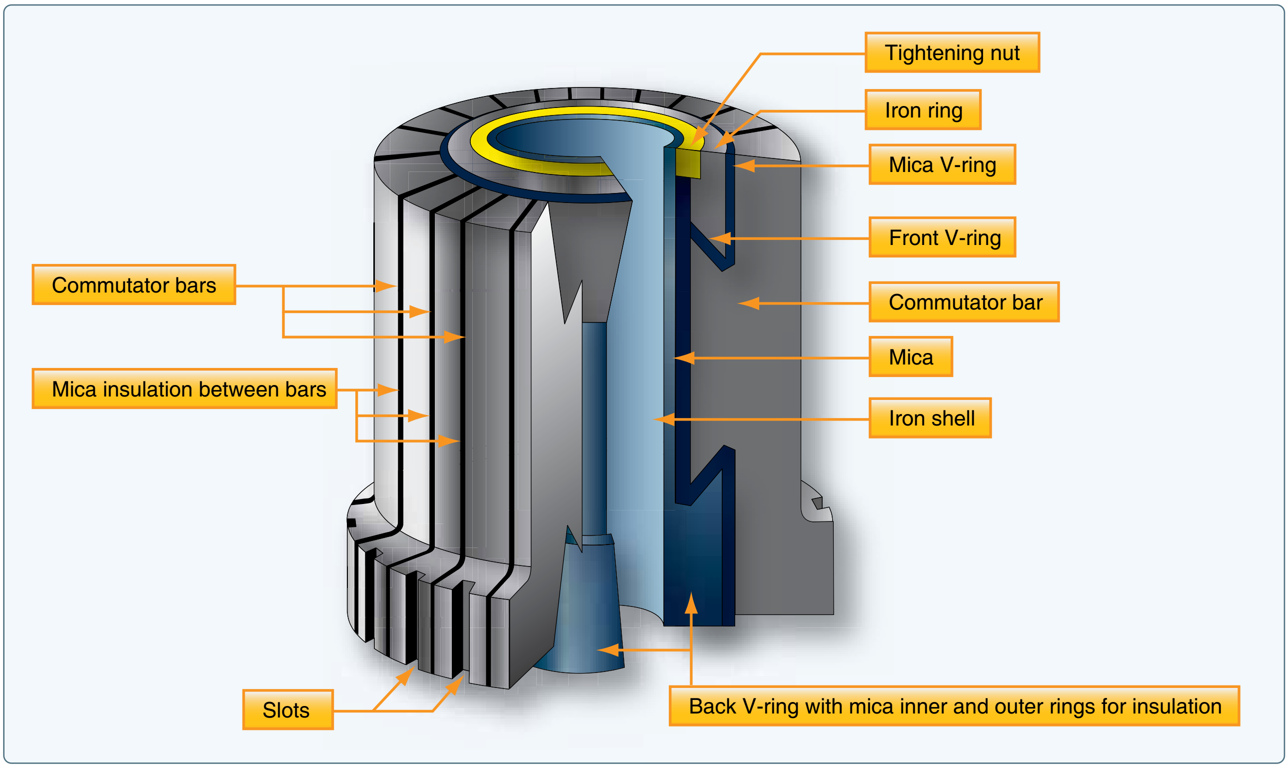


Figure 9-48. *Commutator with portion removed to show construction.*

commutator, and extreme care must be used when cleaning it to avoid marring or scratching the surface.

Types of DC Generators

There are three types of DC generator: series wound, parallel (shunt) wound, and series-parallel (or compound wound). The appropriate generator is determined by the connections to the armature and field circuits with respect to the external circuit. The external circuit is the electrical load powered by the generator. In general, the external circuit is used for charging the aircraft battery and supplying power to all electrical equipment being used by the aircraft. As their names imply, windings in series have characteristics different from windings in parallel.

Series Wound DC Generators

The series generator contains a field winding connected in series with the external circuit. *[Figure 9-49]* Series generators have very poor voltage regulation under changing load, since the greater the current is through the field coils to the external circuit, the greater the induced EMF's and the greater the output voltage is. When the aircraft electrical load is increased, the voltage increases; when the load is decreased, the voltage decreases.

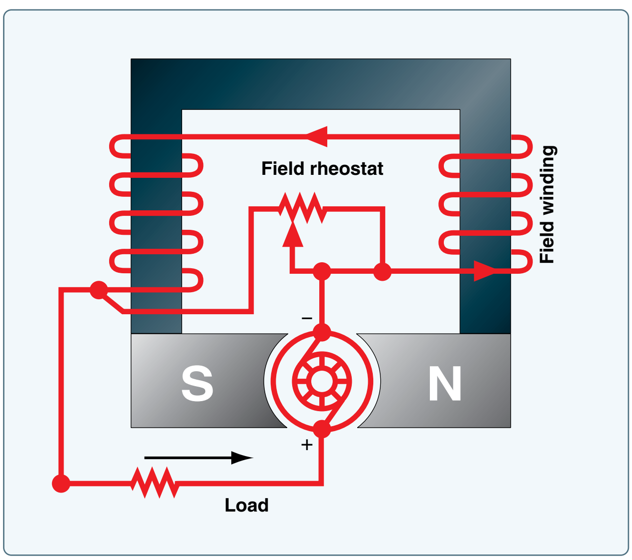


Figure 9-49. *Diagram of a series wound generator.*

Since the series wound generator has such poor voltage and current regulation, it is never employed as an airplane generator. Generators in airplanes have field windings, that are connected either in shunt or in compound formats.

Parallel (Shunt) Wound DC Generators

A generator having a field winding connected in parallel with the external circuit is called a shunt generator. *[Figure 9-50]* It should be noted that, in electrical terms, shunt means parallel. Therefore, this type of generator could be called either a shunt generator or a parallel generator.

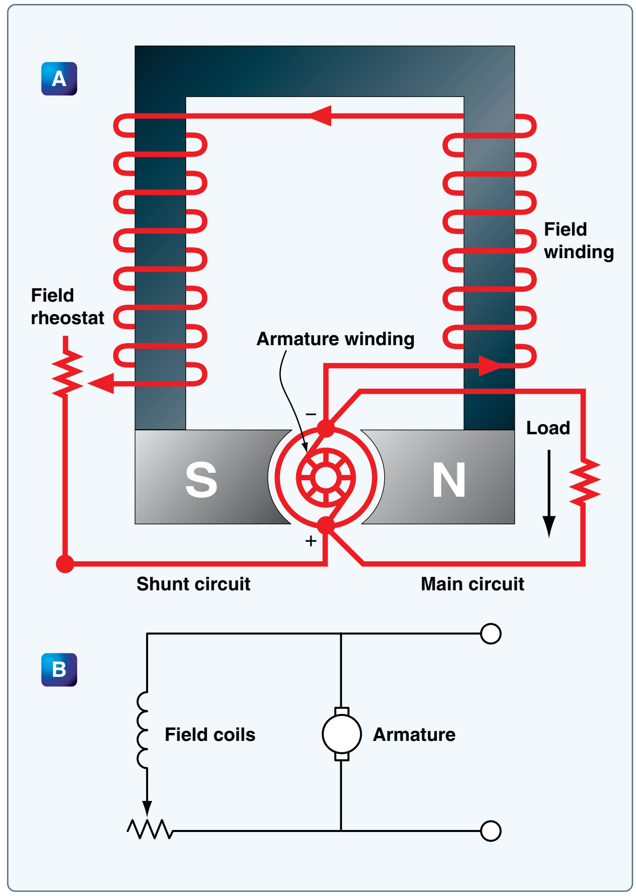


Figure 9-50. *Shunt wound generator.*

In a shunt generator, any increase in load causes a decrease in the output voltage, and any decrease in load causes an increase output voltage. This occurs since the field winding is connected in parallel to the load and armature, and all the current flowing in the external circuit passes only through the armature winding (not the field).

As shown in *Figure 9-50A*, the output voltage of a shunt generator can be controlled by means of a rheostat inserted in series with the field windings. As the resistance of the field circuit is increased, the field current is reduced; consequently, the generated voltage is also reduced. As the field resistance is decreased, the field current increases and the generator output increases. In the actual aircraft, the field rheostat would be replaced with an automatic control device, such as a voltage regulator.

Compound Wound DC Generators

A compound wound generator employs two field windings one in series and another in parallel with the load. *[Figure 9-51]* This arrangement takes advantage of both the series and

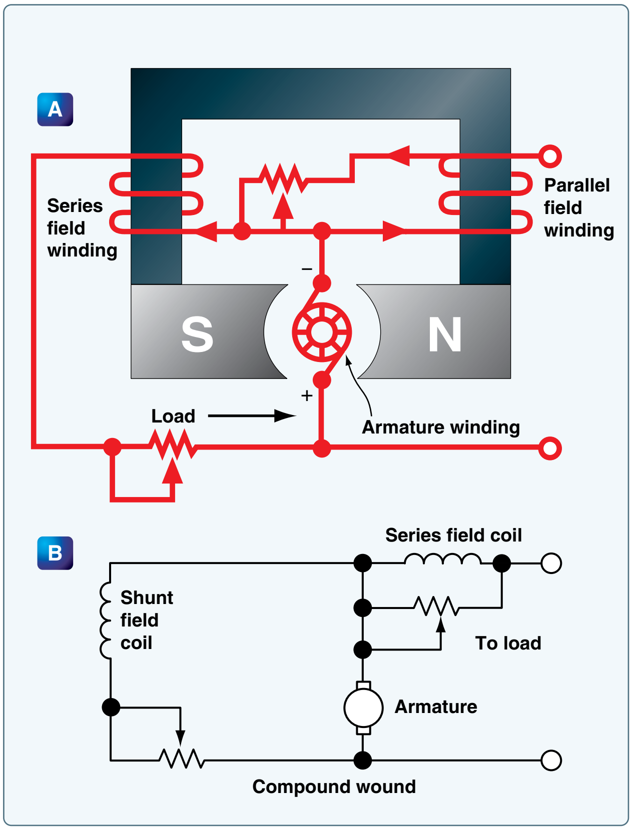


Figure 9-51. *Compound wound generator.*

parallel characteristics described earlier. The output of a compound wound generator is relatively constant, even with changes in the load.

Generator Ratings

A DC generator is typically rated for its voltage and power output. Each generator is designed to operate at a specified voltage, approximately 14 or 28 volts. It should be noted that aircraft electrical systems are designed to operate at one of these two voltage values. The aircraft's voltage depends on which battery is selected for that aircraft. Batteries are either 12 or 24 volts when fully charged. The generator selected must have a voltage output slightly higher than the battery voltage. Hence, the 14-or 28-volt rating is required for aircraft DC generators.

The power output of any generator is given as the maximum number of amperes the generator can safely supply. Generator rating and performance data are stamped on the nameplate attached to the generator. When replacing a generator, it is important to choose one of the proper ratings.

The rotation of generators is termed either clockwise or counterclockwise, as viewed from the driven end. The direction of rotation may also be stamped on the data plate. It is important that a generator with the correct rotation be used; otherwise, the polarity of the output voltage is reversed. The speed of an aircraft engine varies from idle rpm to takeoff rpm; however, during the major portion of a flight, it is at a constant cruising speed. The generator drive is usually geared to turn the generator between 1⅛ and 1½ times the engine crankshaft speed. Most aircraft generators have a speed at which they begin to produce their normal voltage. Called the "coming in" speed, it is usually about 1,500 rpm.

DC Generator Maintenance

The following information about the inspection and maintenance of DC generator systems is general in nature because of the large number of differing aircraft generator systems. These procedures are for familiarization only. Always follow the applicable manufacturer's instructions for a given generator system. In general, the inspection of the generator installed in the aircraft should include the following items:

1. Security of generator mounting.
2. Condition of electrical connections.
3. Dirt and oil in the generator. If oil is present, check engine oil seals. Blow out any dirt with compressed air.
4. Condition of generator brushes.
5. Generator operation.
6. Voltage regulator operation.

Sparking of brushes quickly reduces the effective brush area in contact with the commutator bars. The degree of such sparking should be determined. Excessive wear warrants a detailed inspection and possible replacement of various components. *[Figure 9-52]*

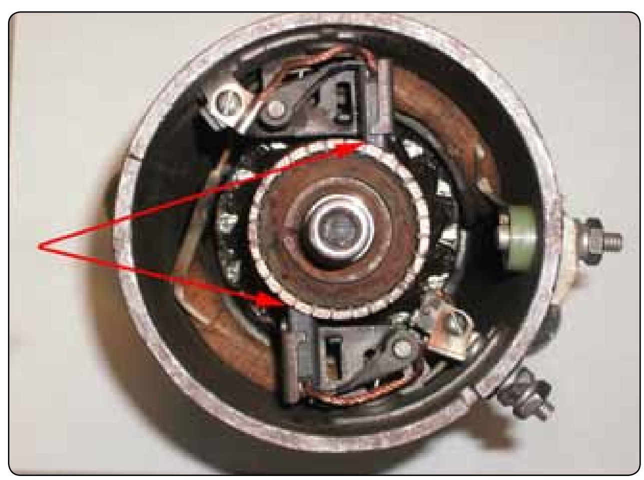


Figure 9-52. *Wear areas of commutator and brushes.*

Manufacturers usually recommend the following procedures to seat brushes that do not make good contact with slip rings or commutators. Lift the brush sufficiently to permit the insertion of a strip of extra-fine 000 (triple aught) grit, or finer, sandpaper under the brush, rough side towards the carbon brush. *[Figure 9-53]*

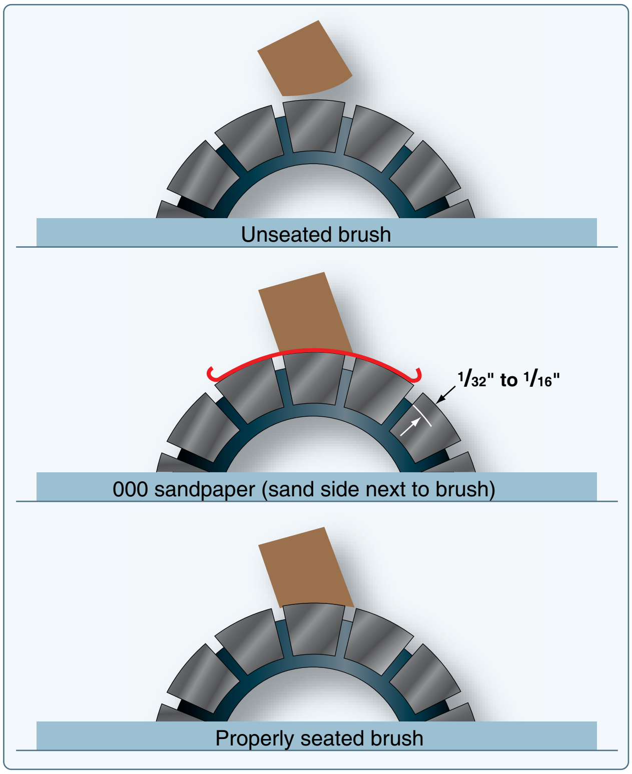


Figure 9-53. *Seating brushes with sandpaper.*

Pull the sandpaper in the direction of armature rotation, being careful to keep the ends of the sandpaper as close to the slip ring or commutator surface as possible in order to avoid rounding the edges of the brush. When pulling the sandpaper back to the starting point, raise the brush so it does not ride on the sandpaper. Sand the brush only in the direction of rotation. Carbon dust resulting from brush sanding should be thoroughly cleaned from all parts of the generators after a sanding operation.

After the generator has run for a short period, brushes should be inspected to make sure that pieces of sand have not become embedded in the brush. Under no circumstances should emery cloth or similar abrasives be used for seating brushes (or smoothing commutators), since they contain conductive materials that cause arcing between brushes and commutator bars. It is important that the brush spring pressure be correct. Excessive pressure causes rapid wear of brushes. Too little pressure, however, allows bouncing of the brushes, resulting in burned and pitted surfaces. The pressure recommended by the manufacturer should be checked by the use of a spring scale graduated in ounces. Brush spring tension on some generators can be adjusted. A spring scale is used to measure the pressure that a brush exerts on the commutator.

Flexible low-resistance pigtails are provided on most heavy current carrying brushes, and their connections should be securely made and checked at frequent intervals. The pigtails should never be permitted to alter or restrict the free motion of the brush. The purpose of the pigtail is to conduct the current from the armature, through the brushes, to the external circuit of the generator.

Generator Controls

Theory of Generator Control

All aircraft are designed to operate within a specific voltage range (for example 13.5–14.5 volts). And since aircraft operate at a variety of engine speeds (remember, the engine drives the generator) and with a variety of electrical demands, all generators must be regulated by some control system. The generator control system is designed to keep the generator output within limits for all flight variables. Generator control systems are often referred to as voltage regulators or generator control units (GCU).

Aircraft generator output can easily be adjusted through control of the generator's magnetic field strength. Remember, the strength of the magnetic field has a direct effect on generator output. More field current means more generator output and vice versa. *Figure 9-54* shows a simple generator control used to adjust field current. When field current is controlled, generator output is controlled. Keep in mind, this system is manually adjusted and would not be suitable for aircraft. Aircraft systems must be automatic and are therefore a bit more complex.

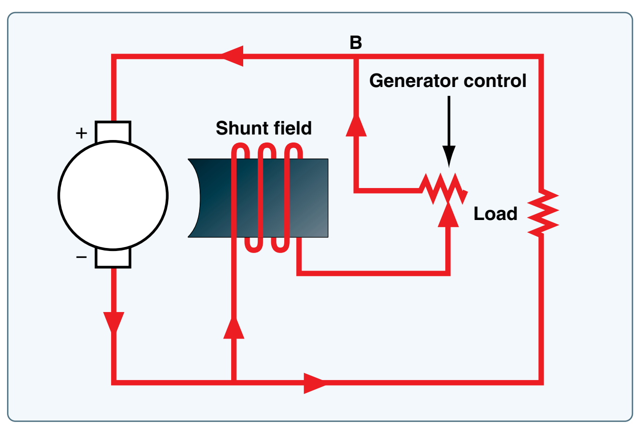


Figure 9-54. *Regulation of generator voltage by field rheostat.*

There are two basic types of generator controls: electro-mechanical and solid-state (transistorized). The electromechanical type controls are found on older aircraft and tend to require regular inspection and maintenance. Solid-state systems are more modern and typically considered to have better reliability and more accurate generator output control.

Functions of Generator Control Systems

Most generator control systems perform a number of functions related to the regulation, sensing, and protection of the DC generation system. Light aircraft typically require a less complex generator control system than larger multiengine aircraft. Some of the functions listed below are not found on light aircraft.

Voltage Regulation

The most basic of the GCU functions is that of voltage regulation. Regulation of any kind requires the regulation unit to take a sample of a generator output and compare that sample to a known reference. If the generator's output voltage falls outside of the set limits, then the regulation unit must provide an adjustment to the generator field current. Adjusting field current controls generator output.

Overvoltage Protection

The overvoltage protection system compares the sampled voltage to a reference voltage. The overvoltage protection circuit is used to open the relay that controls the field excitation current. It is typically found on more complex generator control systems.

Parallel Generator Operations

On multiengine aircraft, a paralleling feature must be employed to ensure all generators operate within limits. In general, paralleling systems compare the voltages between two or more generators and adjust the voltage regulation circuit accordingly.

Overexcitation Protection

When one generator in a paralleled system fails, one of the generators can become overexcited and tends to carry more than its share of the load, if not all of the loads. Basically, this condition causes the generator to produce too much current. If this condition is sensed, the overexcited generator must be brought back within limits, or damage occurs. The overexcitation circuit often works in conjunction with the overvoltage circuit to control the generator.

Differential Voltage

This function of a control system is designed to ensure all generator voltage values are within a close tolerance before being connected to the load bus. If the output is not within the specified tolerance, then the generator contactor is not allowed to connect the generator to the load bus.

Reverse Current Sensing

If the generator cannot maintain the required voltage level, it eventually begins to draw current instead of providing it. This situation occurs, for example, if a generator fails. When a generator fails, it becomes a load to the other operating generators or the battery. The defective generator must be removed from the bus. The reverse current sensing function monitors the system for a reverse current. Reverse current indicates that current is flowing to the generator not from the generator. If this occurs, the system opens the generator relay and disconnects the generator from the bus.

Generator Controls for High Output Generators

Most modern high output generators are found on turbine powered corporate-type aircraft. These small business jets and turboprop aircraft employ a generator and starter combined into one unit. This unit is referred to as a starter-generator. A starter-generator has the advantage of combining two units into one housing, saving space and weight. Since the starter-generator performs two tasks, engine starting and generation of electrical power, the control system for this unit is relatively complex.

A simple explanation of a starter-generator shows that the unit contains two sets of field windings. One field is used to start the engine and one used for the generation of electrical power. *[Figure 9-55]*

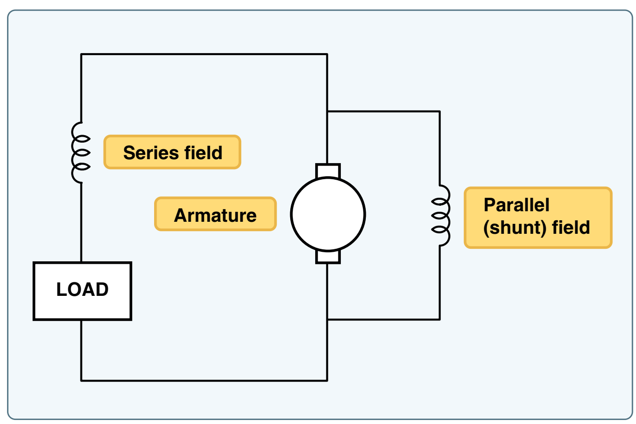


Figure 9-55. *Starter-generator.*

During the start function, the GCU must energize the series field and the armature causes the unit to act like a motor. During the generating mode, the GCU must disconnect the series field, energize the parallel field, and control the current produced by the armature. At this time, the starter-generator acts like a typical generator. Of course, the GCU must perform all the functions described earlier to control voltage and protect the system. These functions include voltage regulation, reverse current sensing, differential voltage, overexcitation protection, overvoltage protection, and parallel generator operations. A typical GCU is shown in *Figure 9-56*.

Figure 9-56. *Generator control unit (GCU).*

In general, modern GCUs for high-output generators employ solid-state electronic circuits to sense the operations of the generator or starter-generator. The circuitry then controls a series of relays and/or solenoids to connect and disconnect the unit to various distribution busses. One unit found in almost all voltage regulation circuitry is the zener diode. The zener diode is a voltage sensitive device that is used to monitor system voltage. The zener diode, connected in conjunction to the GCU circuitry, then controls the field current, which in turn controls the generator output.

Generator Controls for Low-Output Generators

A typical generator control circuit for low-output generators modifies current flow to the generator field to control generator output power. As flight variables and electrical loads change, the GCU must monitor the electrical system and make the appropriate adjustments to ensure proper system voltage and current. The typical generator control is referred to as a voltage regulator or a GCU.

Since most low-output generators are found on older aircraft, the control systems for these systems are electromechanical devices. (Solid-state units are found on more modern aircraft that employ DC alternators and not DC generators.) The two most common types of voltage regulator are the carbon pile regulator and the three-unit regulator. Each of these units controls field current using a type of variable resistor. Controlling field current then controls generator output. A simplified generator control circuit is shown in *Figure 9-57*.

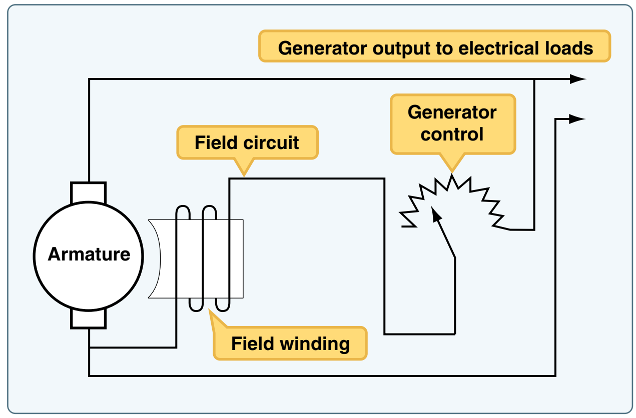


Figure 9-57. *Voltage regulator for low-output generator.*

Carbon Pile Regulators

The carbon pile regulator controls DC generator output by sending the field current through a stack of carbon disks (the carbon pile). The carbon disks are in series with the generator field. If the resistance of the disks increases, the field current decreases and the generator output goes down. If the resistance of the disks decreases, the field current increases and generator output goes up. As seen in *Figure 9-58*, a voltage coil is installed in parallel with the generator output leads. The voltage coil acts like an electromagnet that increases or decrease strength as generator output voltage changes. The magnetism of the voltage coil controls the pressure on the carbon stack. The pressure on the carbon stack controls the resistance of the carbon; the resistance of the carbon controls field current and the field current controls generator output.

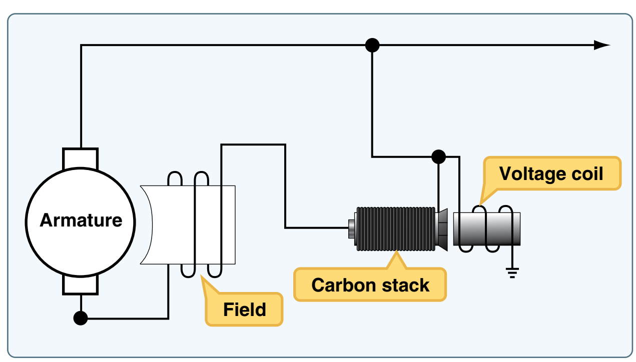


Figure 9-58. *Carbon pile regulator.*

Carbon pile regulators require regular maintenance to ensure accurate voltage regulation; therefore, most have been replaced on aircraft with more modern systems.

Three-Unit Regulators

The three-unit regulator used with DC generator systems is made of three distinct units. Each of these units performs a specific function vital to correct electrical system operation. A typical three-unit regulator consists of three relays mounted in a single housing. Each of the three relays monitors generator outputs and opens or closes the relay contact points according to system needs. A typical three-unit regulator is shown in *Figure 9-59*.

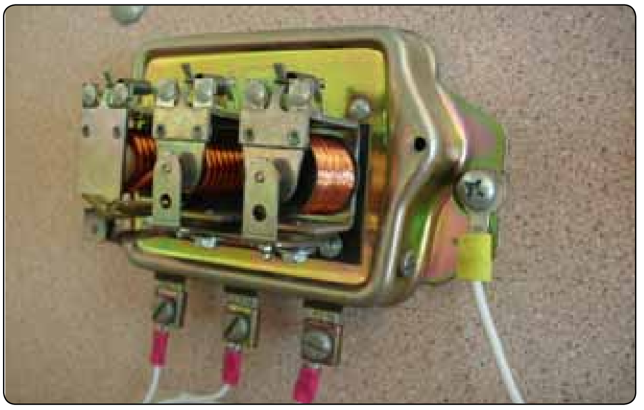


Figure 9-59. *The three relays found on this regulator are used to regulate voltage, limit current, and prevent reverse current flow.*

Voltage Regulator

The voltage regulator section of the three-unit regulator is used to control generator output voltage. The voltage regulator monitors generator output and controls the generator field current as needed. If the regulator senses that system voltage is too high, the relay points open and the current in the field circuit must travel through a resistor. This resistor lowers field current and therefore lowers generator output. Remember, generator output goes down whenever generator field current goes down.

As seen in *Figure 9-60*, the voltage coil is connected in parallel with the generator output, and it therefore measures the voltage of the system. If voltage gets beyond a predetermined limit, the voltage coil becomes a strong magnet and opens the contact points. If the contact points are open, field current must travel through a resistor and therefore field current goes down. The dotted arrow shows the current flow through the voltage regulator when the relay points are open.

Since this voltage regulator has only two positions (points open and points closed), the unit must constantly be in adjustment to maintain accurate voltage control. During normal system operation, the points are opening and closing at regular intervals. The points are in effect vibrating. This type of regulator is sometimes referred to as a vibrating-type regulator. As the points vibrate, the field current raises and lowers and the field magnetism averages to a level that

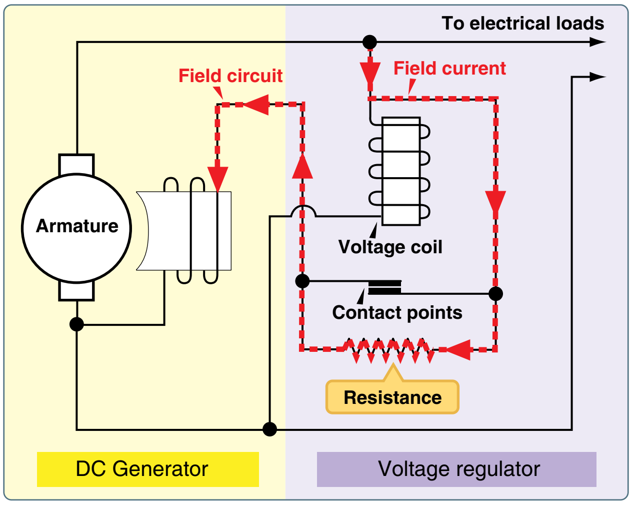


Figure 9-60. *Voltage regulator.*

maintains the correct generator output voltage. If the system requires more generator output, the points remain closed longer and vice versa.

Current Limiter

The current limiter section of the three-unit regulator is designed to limit generator output current. This unit contains a relay with a coil wired in series with respect to the generator output. As seen in *Figure 9-61,* all the generator output current must travel through the current coil of the relay. This creates a relay that is sensitive to the current output of the generator. That is, if generator output current increases, the relay points open and vice versa. The dotted line shows the current flow to the generator field when the current limiter points are open. It should be noted that, unlike the voltage regulator relay, the current limiter is typically closed during normal flight. Only during extreme current loads must the current limiter points open; at that time, field current is lowered and generator output is kept within limits.

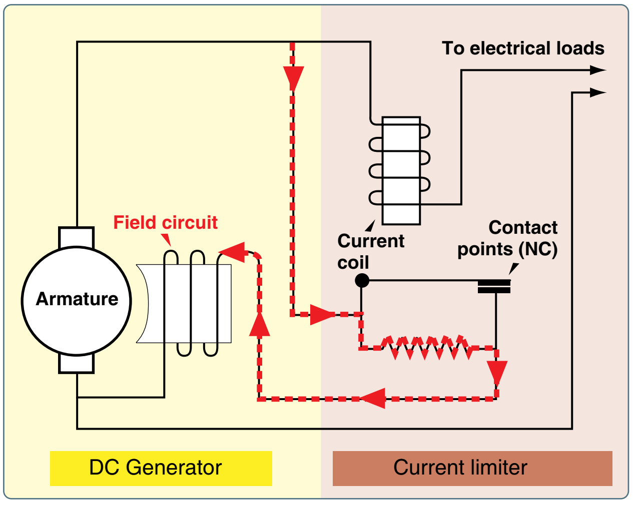


Figure 9-61. *Current limiter.*

Reverse-Current Relay

The third unit of a three-unit regulator is used to prevent current from leaving the battery and feeding the generator. This type of current flow would discharge the battery and is opposite of normal operation. It can be thought of as a reverse current situation and is known as reverse current relay. The simple reverse current relay shown in *Figure 9-62* contains both a voltage coil and a current coil.

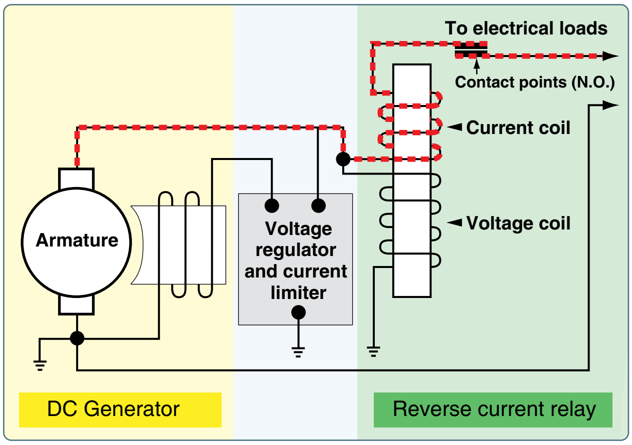


Figure 9-62. *Reverse-current relay.*

The voltage coil is wired in parallel to the generator output and is energized any time the generator output reaches its operational voltage. As the voltage coil is energized, the contact points close and the current is then allowed to flow to the aircraft electrical loads, as shown by the dotted lines. The diagram shows the reverse current relay in its normal operating position; the points are closed and current is flowing from the generator to the aircraft electrical loads. As current flows to the loads, the current coil is energized and the points remain closed. If there is no generator output due to a system failure, the contact points open because magnetism in the relay is lost. With the contact points open, the generator is automatically disconnected from the aircraft electrical system, which prevents reverse flow from the load bus to the generator. A typical three-unit regulator for aircraft generators is shown in *Figure 9-63*.

As seen in *Figure 9-63*, all three units of the regulator work together to control generator output. The regulator monitors generator output and controls power to the aircraft loads as needed for flight variables. Note that the vibrating regulator just described was simplified for explanation purposes. A typical vibrating regulator found on an aircraft would probably be more complex.

DC Alternators and Controls

DC alternators (like generators) change mechanical energy into electrical energy by the process of electromagnetic induction. In general, DC alternators are lighter and more efficient than DC generators. DC alternators and their related controls are found on modern, light, piston-engine aircraft. The alternator is mounted in the engine compartment driven by a v-belt, or drive gear mechanism, which receives power from the aircraft engine. *[Figure 9-64]* The control system of a DC alternator is used to automatically regulate alternator output power and ensure the correct system voltage for various flight parameters.

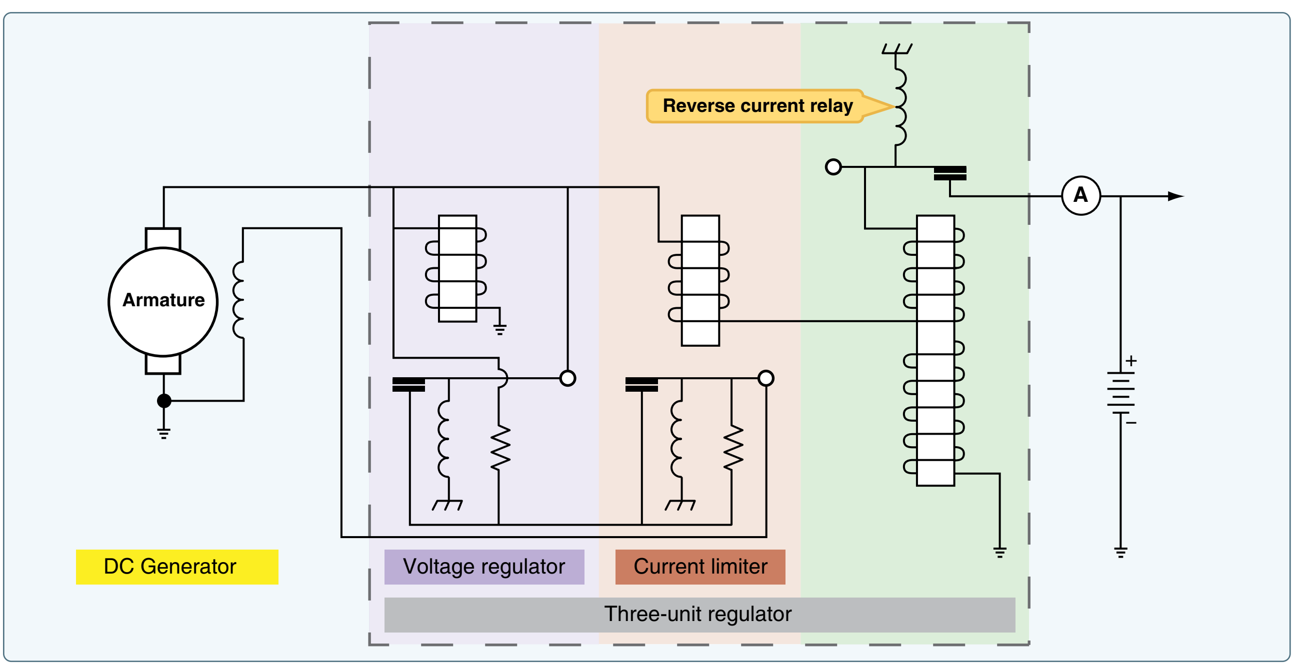


Figure 9-63. *Three-unit regulator for variable speed generators.*

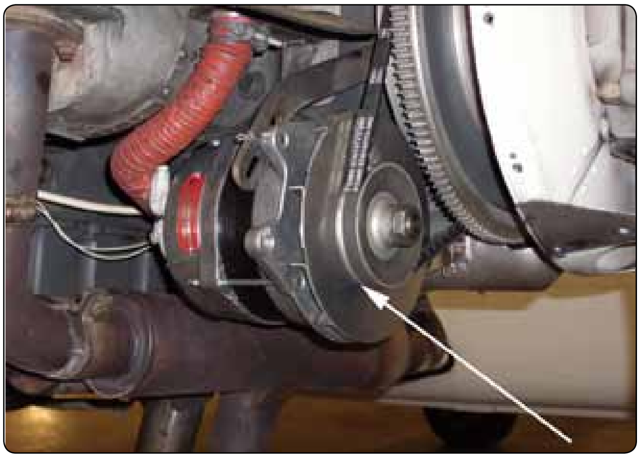


Figure 9-64. *DC alternator installation.*

DC Alternators

DC alternators contain two major components: the armature winding and the field winding. The field winding (which produces a magnetic field) rotates inside the armature and, using the process of electromagnetic induction, the armature produces a voltage. This voltage produced by the armature is fed to the aircraft electrical bus and produces a current to power the electrical loads. *Figure 9-65* shows a basic diagram of a typical alternator.

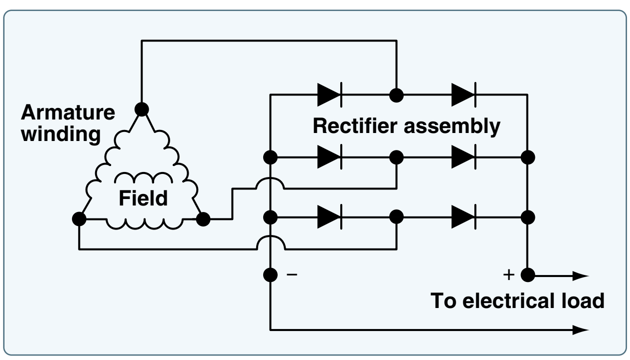


Figure 9-65. *Diagram of a typical alternator.*

The armature used in DC alternators actually contains three coils of wire. Each coil receives current as the magnetic field rotates inside the armature. The resulting output voltage consists of three distinct AC sine waves, as shown in *Figure 9-66*. The armature winding is known as a three-phase armature, named after the three different voltage waveforms produced.

Figure 9-67 shows the two common methods used to connect the three phase armature windings: the delta winding and the Y winding. For all practical purposes, the two windings produce the same results in aircraft DC alternators.

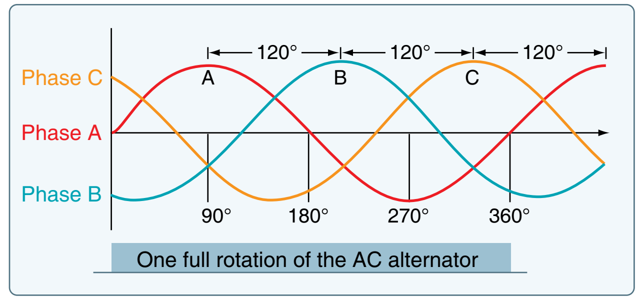


Figure 9-66. *Sine waves.*

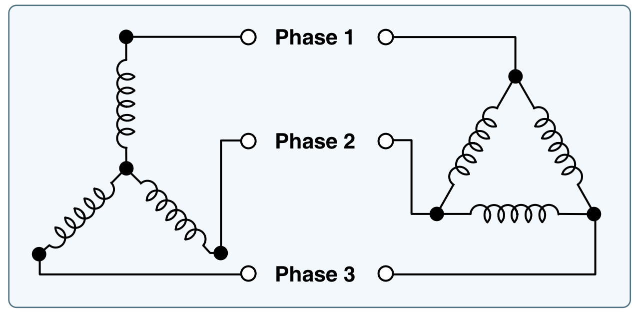


Figure 9-67. *Three-phase armature windings: Y on the left and delta winding on the right.*

Since the three-phase voltage produced by the alternators armature is AC, it is not compatible with typical DC electrical loads and must be rectified (changed to DC). Therefore, the armature output current is sent through a rectifier assembly that changes the three-phase AC to DC. *[Figure 9-67]* Each phase of the three-phase armature overlaps when rectified, and the output becomes a relatively smooth ripple DC. *[Figure 9-68]*

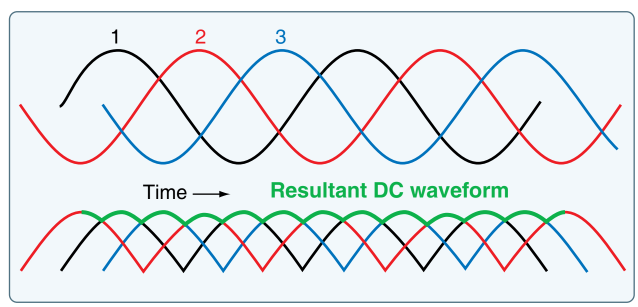


Figure 9-68. *Relatively smooth ripple DC.*

The invention of the diode has made the development of the alternator possible. The rectifier assembly is comprised of six diodes. This rectifier assembly replaces the commutator and brushes found on DC generators and helps to make the alternator more efficient. *Figure 9-69* shows the inside of a typical alternator; the armature assembly is located on the outer edges of the alternator and the diodes are mounted to the case.

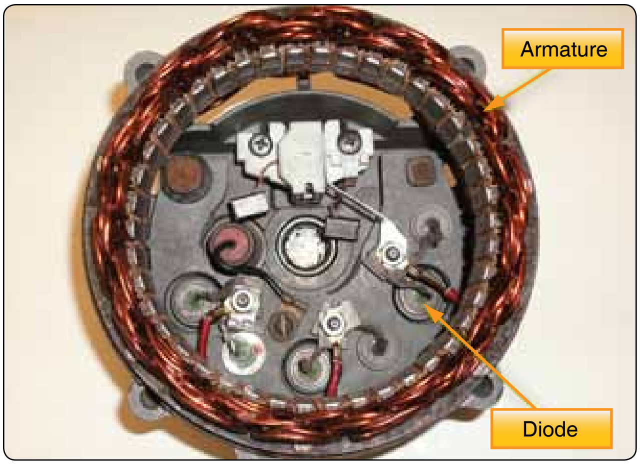


Figure 9-69. *Diode assembly.*

The field winding, shown in *Figure 9-70*, is mounted to a rotor shaft so it can spin inside of the armature assembly.

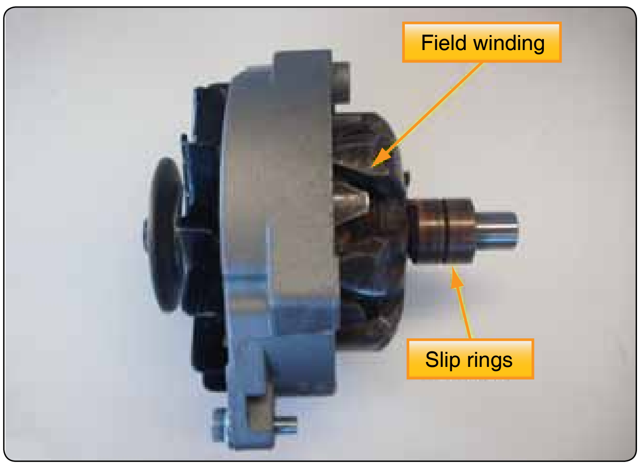


Figure 9-70. *Alternator field winding.*

The field winding must receive current from an aircraft battery in order to produce an electromagnet. Since the field rotates, a set of brushes must be used to send power to the rotating field. Two slip rings are mounted to the rotor and connect the field winding to electrical contacts called brushes. Since the brushes carry relatively low current, the brushes of an alternator are typically smaller than those found inside a DC generator. *[Figure 9-71]* DC alternator brushes last longer and require less maintenance than those found in a DC generator.

The alternator case holds the alternator components inside a compact housing that mounts to the engine. Aircraft alternators either produce a nominal 14-volt output or a 26-volt output. The physical size of the alternator is typically a function of the alternator's amperage output. Common alternators for light aircraft range in output form 60–120 amps.

Figure 9-71. *Alternator brushes.*

Alternator Voltage Regulators

Voltage regulators for DC alternators are similar to those found on DC generators. The general concepts are the same in that adjusting alternator field current controls alternator output. Regulators for most DC alternators are either the vibrating-relay type or solid-state regulators, which are found on most modern aircraft. Vibrating-relay regulators are similar to those discussed in the section on generator regulators. As the points of the relay open, the field current is lowered and alternator output is lowered and vice versa.

Solid-State Regulators

Solid-state regulators for modern light aircraft are often referred to as alternator control units (ACUs). These units contain no moving parts and are generally considered to be more reliable and provide better system regulation than vibrating-type regulators. Solid-state regulators rely on transistor circuitry to control alternator field current and alternator output. The regulator monitors alternator output voltage/current and controls alternator field current accordingly. Solid-state regulators typically provide additional protection circuitry not found in vibrating-type regulators. Protection may include over- or under-voltage protection, overcurrent protection, as well as monitoring the alternator for internal defects, such as a defective diode. In many cases, the ACU also provides a warning indication to the pilot if a system malfunction occurs.

A key component of any solid-state voltage regulator is known as the zener diode. *Figure 9-72* shows the schematic diagram symbol of a zener diode, as well as one installed in an ACU.

The operation of a zener diode is similar to a common diode in that the zener only permits current flow in one direction. This is true until the voltage applied to the zener reaches a certain level. At that predetermined voltage level, the zener then permits current flow with either polarity. This is known as the breakdown or zener voltage.

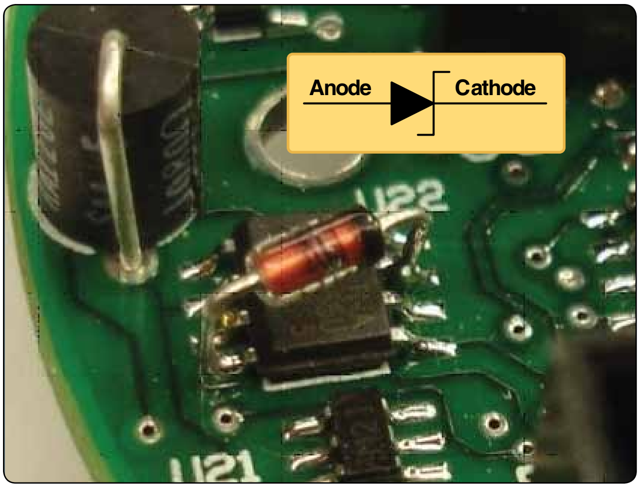


Figure 9-72. *Zener diode.*

As an ACU monitors alternator output, the zener diode is connected to system voltage. When the alternator output reaches the specific zener voltage, the diode controls a transistor in the circuit, which in turn controls the alternator field current. This is a simplified explanation of the complete circuitry of an ACU. *[Figure 9-73]* However, it is easy to see how the zener diode and transistor circuit are used in place of an electromechanical relay in a vibrating-type regulator. The use of solid-state components creates a more accurate regulator that requires very little maintenance. The solid-state ACU is, therefore, the control unit of choice for modern aircraft with DC alternators.

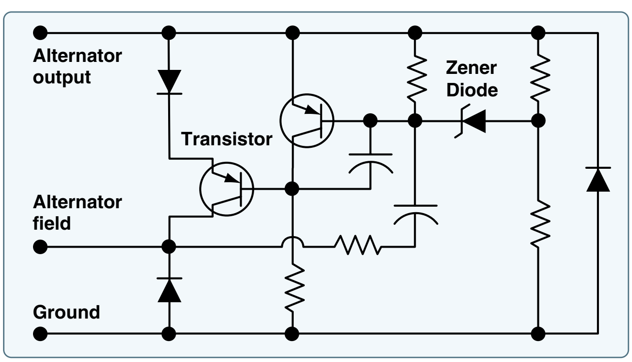


Figure 9-73. *ACU circuitry.*

Power Systems

Since certain electrical systems operate only on AC, many aircraft employ a completely AC electrical system, as well as a DC system. The typical AC system would include an AC alternator (generator), a regulating system for that alternator, AC power distribution busses, and related fuses and wiring. Note that when referring to AC systems, the terms "alternator" and "generator" are often used interchangeably. This chapter uses the term "AC alternator."

AC power systems are becoming more popular on modern aircraft. Light aircraft tend to operate most electrical systems using DC, therefore the DC battery can easily act as a backup power source. Some modern light aircraft also employ a small AC system. In this case, the light aircraft probably uses an AC inverter to produce the AC needed for this system.

Inverters are commonly used when only a small amount of AC is required for certain systems. Inverters may also be used as a backup AC power source on aircraft that employ an AC alternator. *Figure 9-74* shows a typical inverter that might be found on modern aircraft.

Figure 9-74. *Inverter.*

A modern inverter is a solid-state device that converts DC power into AC power. The electronic circuitry within an inverter is quite complex; however, for an aircraft technician's purposes, the inverter is simply a device that uses DC power, then feeds power to an AC distribution bus. Many inverters supply both 26-volt AC, as well as 115-volt AC. The aircraft can be designed to use either voltage or both simultaneously. If both voltages are used, the power must be distributed on separate 26-and 115-volt AC busses.

AC Alternators

AC alternators are found only on aircraft that use a large amount of electrical power. Virtually all transport category aircraft, such as the Boeing 757 or the Airbus A-380, employ one AC alternator driven by each engine. These aircraft also have an auxiliary AC alternator driven by the auxiliary power unit. In most cases, transport category aircraft also have at least one more AC backup power source, such as an AC inverter or a small AC alternator driven by a ram-air turbine (RAT).

AC alternators produce a three-phase AC output. For each revolution of the alternator, the unit produces three separate voltages. The sine waves for these voltages are separated by 120°. *[Figure 9-75]* This wave pattern is similar to those produced internally by a DC alternator; however, in this case, the AC alternator does not rectify the voltage and the output of the unit is AC.

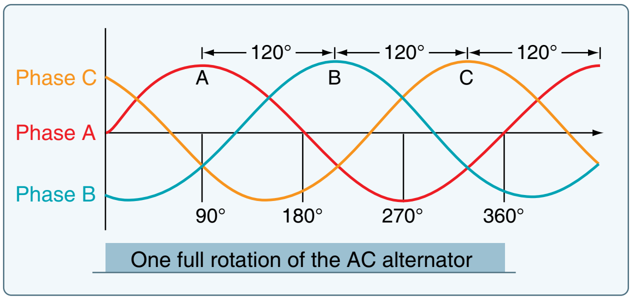


Figure 9-75. *AC alternator sine waves.*

The modern AC alternator does not utilize brushes or slip rings and is often referred to as a brushless AC alternator. This brushless design is extremely reliable and requires very little maintenance. In a brushless alternator, energy to or from the alternator's rotor is transferred using magnetic energy. In other words, energy from the stator to the rotor is transferred using magnetic flux energy and the process of electromagnetic induction. A typical large aircraft AC alternator is shown in *Figure 9-76*.

Figure 9-76. *Large aircraft AC alternator.*

As seen in *Figure 9-77*, the brushless alternator actually contains three generators: the Exciter generator (armature and permanent magnet field), the Pilot exciter generator (armature and fields windings), and the main AC alternator (armature winding and field windings. The need for brushes is eliminated by using a combination of these three distinct generators.

The exciter is a small AC generator with a stationary field made of a permanent magnet and two electromagnets. The exciter armature is three phase and mounted on the rotor shaft. The exciter armature output is rectified and sent to the pilot exciter field and the main generator field.

The pilot exciter field is mounted on the rotor shaft and is connected in series with the main generator field. The pilot exciter armature is mounted on the stationary part of the assembly. The AC output of the pilot exciter armature is supplied to the generator control circuitry where it is rectified, regulated, and then sent to the exciter field windings. The current sent to the exciter field provides the voltage regulation for the main AC alternator. If greater AC alternator output is needed, there is more current sent to the exciter field and vice versa.

In short, the exciter permanent magnet and armature starts the generation process, and the output of the exciter armature is rectified and sent to the pilot exciter field. The pilot exciter field creates a magnetic field and induces power in the pilot exciter armature through electromagnetic induction. The output of the pilot exciter armature is sent to the main alternator control unit and then sent back to the exciter field. As the rotor continues to turn, the main AC alternator field generates power into the main AC alternator armature, also using electromagnetic induction. The output of the main AC armature is three-phase AC and used to power the various electrical loads.

Some alternators are cooled by circulating oil through the internal components of the alternator. The oil used for cooling is supplied from the constant speed drive assembly and often cooled by an external oil cooler assembly. Located in the flange connecting the generator and drive assemblies, ports make oil flow between the constant speed drive and the generator possible. This oil level is critical and typically checked on a routine basis.

Alternator Drive

The unit shown in *Figure 9-78* contains an alternator assembly combined with an automatic drive mechanism. The automatic drive controls the alternator's rotational speed which allows the alternator to maintain a constant 400-Hz AC output.

All AC alternators must rotate at a specific rpm to keep the frequency of the AC voltage within limits. Aircraft AC alternators should produce a frequency of approximately 400 Hz. If the frequency strays more than 10 percent from this value, the electrical systems do not operate correctly. A unit called a constant-speed drive (CSD) is used to ensure the alternator rotates at the correct speed to ensure a 400-

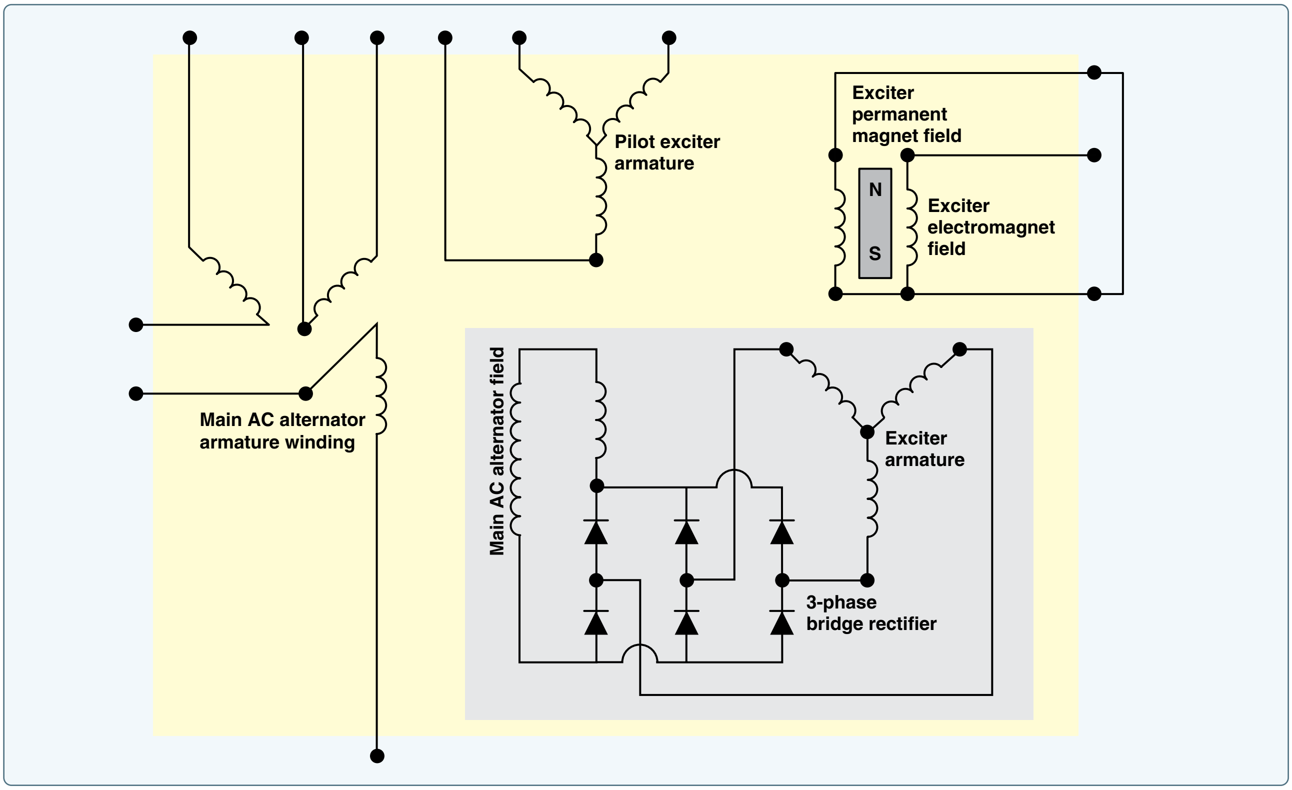


Figure 9-77. *Schematic of an AC alternator.*

Hz frequency. The CSD can be an independent unit or mounted within the alternator housing. When the CSD and the alternator are contained within one unit, the assembly is known as an integrated drive generator (IDG).

The CSD is a hydraulic unit similar to an automatic transmission found in a modern automobile. The engine of the automobile can change rpm while the speed of the car remains constant. This is the same process that occurs for an aircraft AC alternator. If the aircraft engine changes speed, the alternator speed remains constant. A typical hydraulic-type drive is shown in *Figure 9-79*. This unit can be controlled either electrically or mechanically. Modern aircraft employ an electronic system. The constant-speed drive enables the alternator to produce the same frequency at slightly above engine idle rpm as it does at maximum engine rpm.

The hydraulic transmission is mounted between the AC alternator and the aircraft engine. Hydraulic oil or engine oil is used to operate the hydraulic transmission, which creates a constant output speed to drive the alternator. In some cases, this same oil is used to cool the alternator as shown in the CSD cutaway view of *Figure 9-79*. The input drive shaft is powered by the aircraft engine gear case. The output drive shaft, on the opposite end of the transmission, engages the drive shaft of the alternator. The CSD employs a hydraulic pump assembly, a mechanical speed control, and a hydraulic drive. Engine rpm drives the hydraulic pump, the hydraulic drive turns the alternator. The speed control unit is made up of a wobble plate that adjusts hydraulic pressure to control output speed.

Figure 9-80 shows a typical electrical circuit used to control alternator speed. The circuit controls the hydraulic assembly found in a typical CSD. As shown, the alternator input speed is monitored by a tachometer (tach) generator. The tach generator signal is rectified and sent to the valve assembly. The valve assembly contains three electromagnetic coils that operate the valve. The AC alternator output is sent through a control circuit that also feeds the hydraulic valve assembly. By balancing the force created by the three electromagnets, the valve assembly controls the flow of fluid through the automatic transmission and controls the speed of the AC alternator.

It should be noted that an AC alternator also produces a constant 400 Hz if that alternator is driven directly by an engine that rotates at a constant speed. On many aircraft, the auxiliary power unit operates at a constant rpm. AC alternators driven by these APUs are typically driven directly by the engine, and there is no CSD required. For these units, the APU engine controls monitor the alternator output frequency. If the alternator output frequency varies from 400 Hz, the APU speed control adjusts the engine rpm accordingly to keep the alternator output within limits.

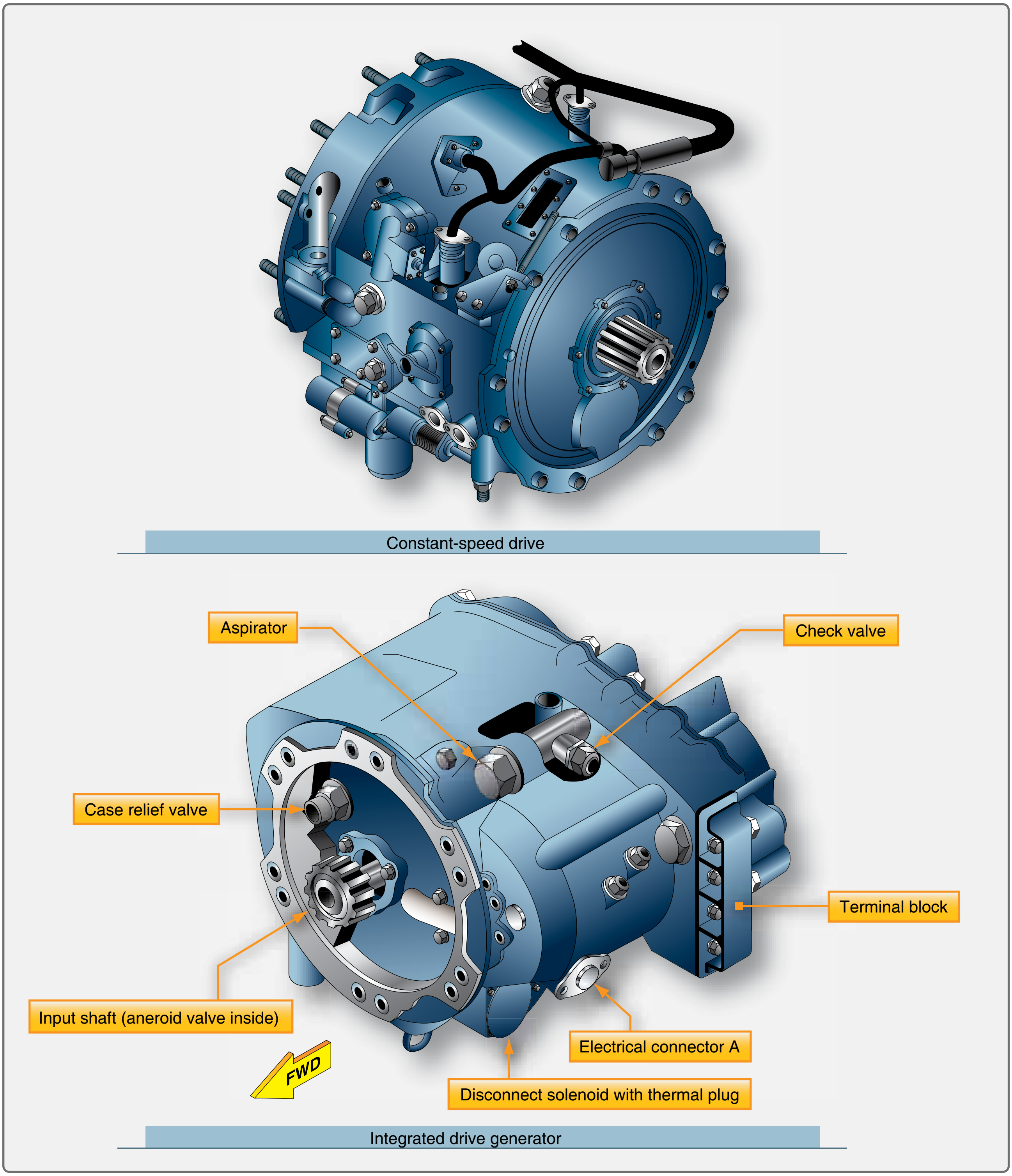


Figure 9-78. *Constant-speed drive (top) and integrated drive generator (bottom).*

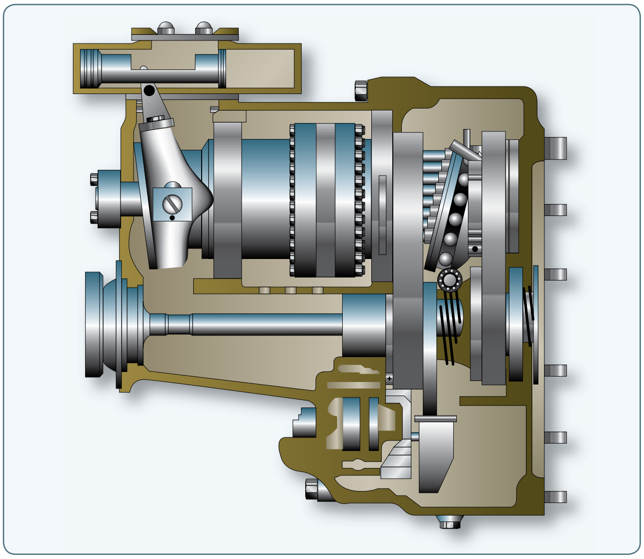


Figure 9-79. *A hydraulic constant speed drive for an AC alternator.*

AC Alternators Control Systems

Modern aircraft that employ AC alternators use several computerized control units, typically located in the aircraft's equipment bay for the regulation of AC power throughout the aircraft. *Figure 9-81* shows a photo of a typical equipment bay and computerized control units.

Since AC alternators are found on large transport category aircraft designed to carry hundreds of passengers, their control systems always have redundant computers that provide safety in the event of a system failure. Unlike DC systems, AC systems must ensure that the output frequency of the alternator stays within limits. If the frequency of an alternator varies from 400 Hz, or if two or more alternators connected to the same bus are out of phase, damage occurs to the system. All AC alternator control units contain circuitry that regulates both voltage and frequency. These control units also monitor a variety of factors to detect any system

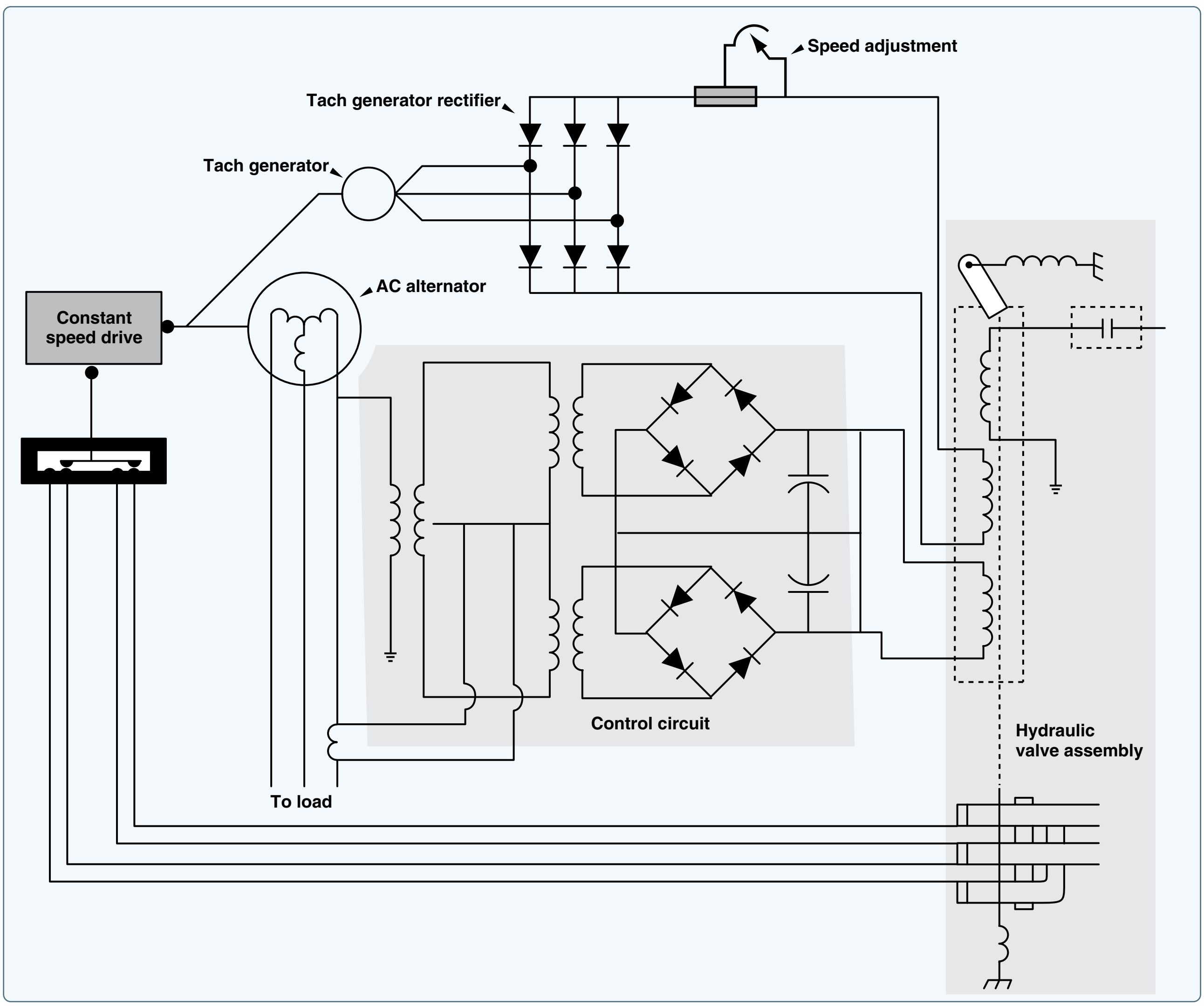


Figure 9-80. *Speed control circuit.*

Figure 9-81. *Line replaceable units in an equipment rack.*

failures and take protective measures to ensure the integrity of the electrical system. The two most common units used to control AC alternators are the bus power control unit (BPCU) and the GCU. In this case, the term "generator" is used, and not alternator, although the meaning is the same.

The GCU is the main computer that controls alternator functions. The BPCU is the computer that controls the distribution of AC power to the power distribution busses located throughout the aircraft. There is typically one GCU used to monitor and control each AC alternator, and there can be one or more BPCUs on the aircraft. BPCUs are described later in this chapter; however, please note that the BPCU works in conjunction with the GCUs to control AC on modern aircraft.

A typical GCU ensures the AC alternator maintains a constant voltage, typically between 115 to 120 volts. The GCU ensures the maximum power output of the alternator is never exceeded. The GCU provides fault detection and circuit protection in the event of an alternator failure. The GCU monitors AC frequency and ensures the output if the alternator remains 400 Hz. The basic method of voltage regulation is similar to that found in all alternator systems; the output of the alternator is controlled by changing the strength of a magnetic field. As shown in *Figure 9-82,* the GCU controls the exciter field magnetism within the brushless alternator to control alternator output voltage. The frequency is controlled by the CDS hydraulic unit in conjunction with signals monitored by the GCU.

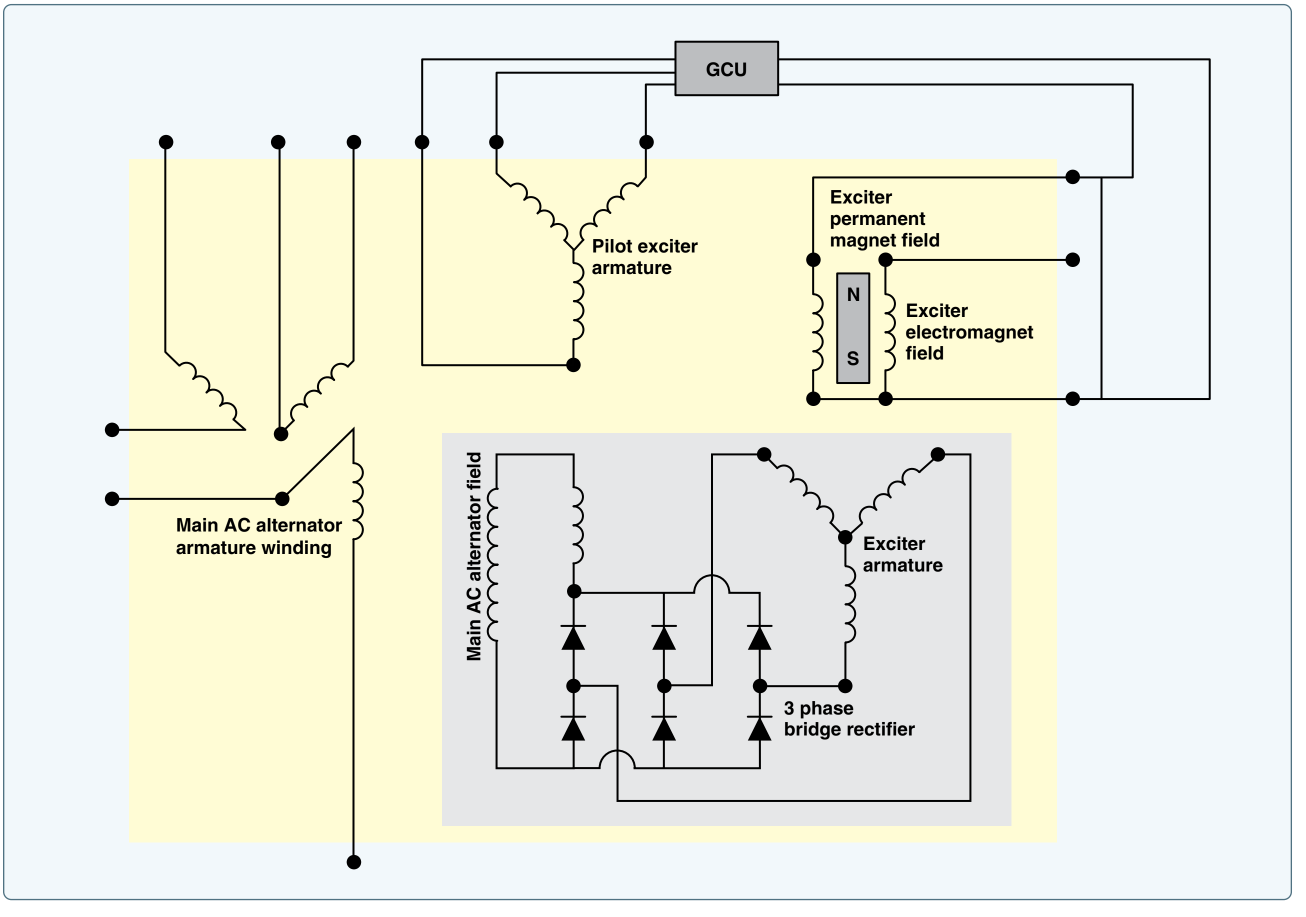


Figure 9-82. *Schematic GCU control of the exciter field magnetism.*

The GCU is also used to turn the AC alternator on or off. When the pilot selects the operation of an AC alternator, the GCU monitors the alternator's output to ensure voltage and frequency are within limits. If the GCU is satisfied with the alternator's output, the GCU sends a signal to an electrical contactor that connects the alternator to the appropriate AC distribution bus. The contactor, often call the generator breaker, is basically an electromagnetic solenoid that controls a set of large contact points. The large contact points are necessary in order to handle the large amounts of current produced by most AC alternators. This same contactor is activated in the event the GCU detects a fault in the alternator output; however, in this case the contactor would disconnect the alternator from the bus.

Aircraft Electrical Systems

Virtually all aircraft contain some form of an electrical system. The most basic aircraft must produce electricity for operation of the engine's ignition system. Modern aircraft have complex electrical systems that control almost every aspect of flight. In general, electrical systems can be divided into different categories according to the function of the system. Common systems include lighting, engine starting, and power generation.

Small Single-Engine Aircraft

Light aircraft typically have a relatively simple electrical system because simple aircraft generally require less redundancy and less complexity than larger transport category aircraft. On most light aircraft, there is only one electrical system powered by the engine-driven alternator or generator. The aircraft battery is used for emergency power and engine starting. Electrical power is typically distributed through one or more common points known as an electrical bus (or bus bar).

Almost all electrical circuits must be protected from faults that can occur in the system. Faults are commonly known as opens or shorts. An open circuit is an electrical fault that occurs when a circuit becomes disconnected. A short circuit is an electrical fault that occurs when one or more circuits create an unwanted connection. The most dangerous short circuit occurs when a positive wire creates an unwanted connection to a negative connection or ground. This is typically called a short to ground.

There are two ways to protect electrical systems from faults: mechanically and electrically. Mechanically, wires and components are protected from abrasion and excess wear through proper installation and by adding protective covers and shields. Electrically, wires can be protected using circuit breakers and fuses. The circuit breakers protect each system in the event of a short circuit. It should be noted that fuses can be used instead of circuit breakers. Fuses are typically found on older aircraft. A circuit breaker panel from a light aircraft is shown in *Figure 9-83*.

Figure 9-83. *Light aircraft circuit breaker panel.*

Battery Circuit

The aircraft battery and battery circuit is used to supply power for engine starting and to provide a secondary power supply in the event of an alternator (or generator) failure. A schematic of a typical battery circuit is shown in *Figure 9-84*. This diagram shows the relationship of the starter and external power circuits that are discussed later in this chapter. The bold lines found on the diagram represent large wire (see the wire leaving the battery positive connection), which is used in the battery circuit due to the heavy current provided through these wires. Because batteries can supply large current flows, a battery is typically connected to the system through an electrical solenoid. At the start/end of each flight, the battery is connected/disconnected from the electrical distribution bus through the solenoid contacts. A battery master switch on the flight deck is used to control the solenoid.

Although they are very similar, there is often confusion between the terms "solenoid" and "relay." A solenoid is typically used for switching high current circuits and relays used to control lower current circuits. To help illuminate the confusion, the term "contactor" is often used when describing a magnetically operated switch. For general purposes, an aircraft technician may consider the terms relay, solenoid, and contactor synonymous. Each of these three terms may be used on diagrams and schematics to describe electrical switches controlled by an electromagnet.

Here it can be seen that the battery positive wire is connected to the electrical bus when the battery master switch is active. A battery solenoid is shown in *Figure 9-85*. The battery switch is often referred to as the master switch since it turns

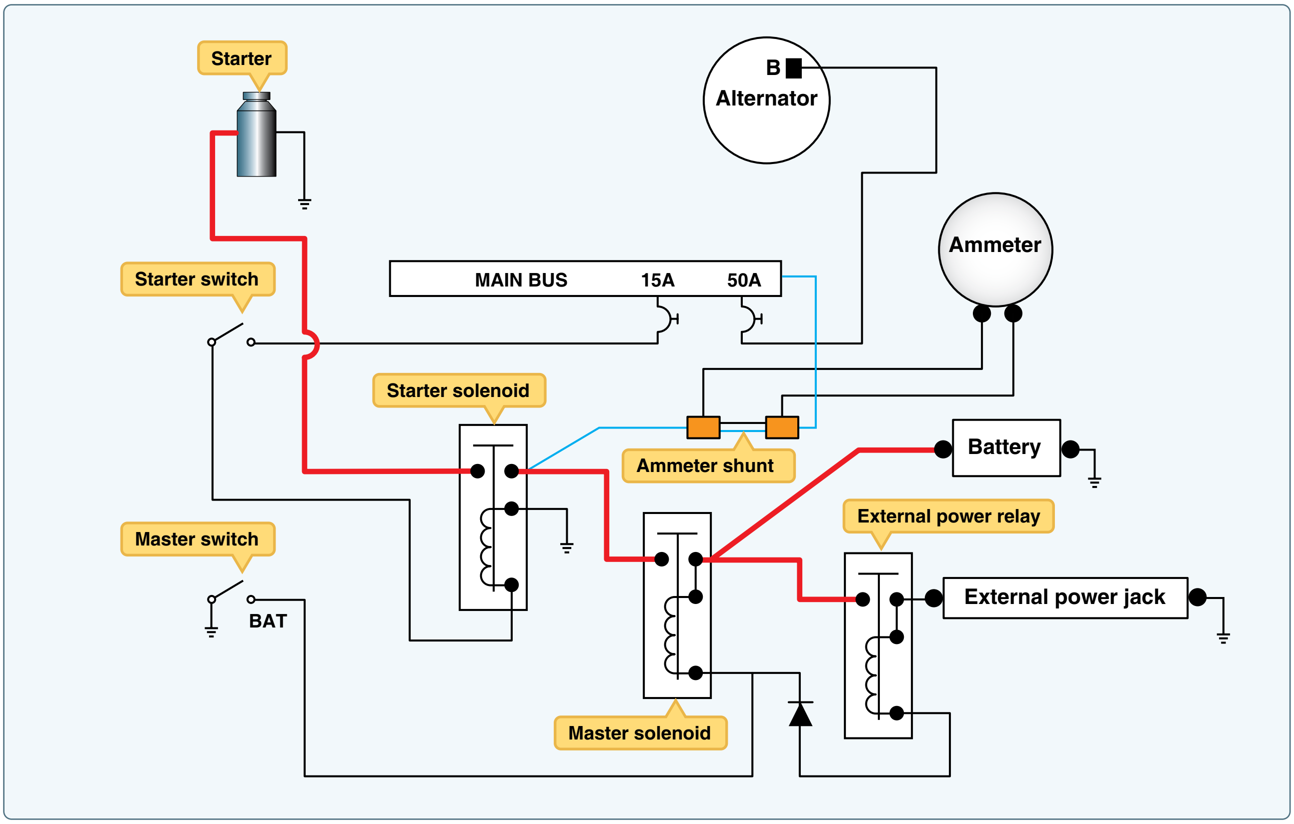


Figure 9-84. *Schematic of typical battery circuit.*

Figure 9-85. *Battery solenoid.*

off or on virtually all electrical power by controlling the battery connection. Note how the electrical connections of the battery solenoid are protected from electrical shorts by rubber covers at the end of each wire.

The ammeter shown in the battery circuit is used to monitor the current flow from the battery to the distribution bus. When all systems are operating properly, battery current should flow from the main bus to the battery giving a positive indication on the ammeter. In this case, the battery is being charged. If the aircraft alternator (or generator) experiences a malfunction, the ammeter indicates a negative value. A negative indication means current is leaving the battery to power any electrical load connected to the bus. The battery is being discharged and the aircraft is in danger of losing all electrical power.

Generator Circuit

Generator circuits are used to control electrical power between the aircraft generator and the distribution bus. Typically, these circuits are found on older aircraft that have not upgraded to an alternator. Generator circuits control power to the field winding and electrical power from the generator to the electrical bus. A generator master switch is used to turn on the generator typically by controlling field current. If the generator is spinning and current is sent to the field circuit, the generator produces electrical power. The power output of the generator is controlled through the generator control unit (or voltage regulator). A simplified generator control circuit is shown in *Figure 9-86*.

As can be seen in *Figure 9-86,* the generator switch controls the power to the generator field (F terminal). The generator output current is supplied to the aircraft bus through the armature circuit (A terminal) of the generator.

Alternator Circuit

Alternator circuits, like generator circuits, must control power both to and from the alternator. The alternator is

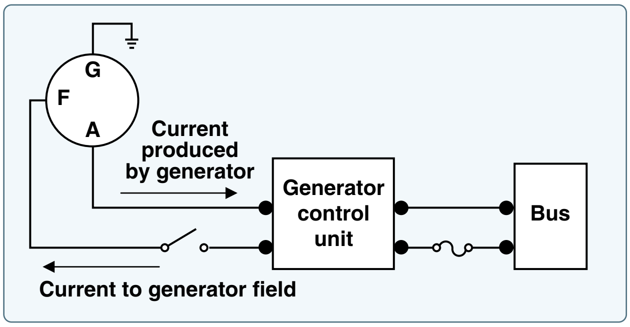


Figure 9-86. *Simplified generator control circuit.*

controlled by the pilot through the alternator master switch. The alternator master switch in turn operates a circuit within the alternator control unit (or voltage regulator) and sends current to the alternator field. If the alternator is powered by the aircraft engine, the alternator produces electrical power for the aircraft electrical loads. The alternator control circuit contains the three major components of the alternator circuit: alternator, voltage regulator, and alternator master switch. *[Figure 9-87]*

The voltage regulator controls the generator field current according to aircraft electrical load. If the aircraft engine is running and the alternator master switch is on, the voltage regulator adjusts current to the alternator field as needed. If more current flows to the alternator field, the alternator output increases and feeds the aircraft loads through the distribution bus.

All alternators must be monitored for correct output. Most light aircraft employ an ammeter to monitor alternator output. *Figure 9-88* shows a typical ammeter circuit used to monitor alternator output. An ammeter placed in the alternator circuit is a single polarity meter that shows current flow in only one direction. This flow is from the alternator to the bus. Since

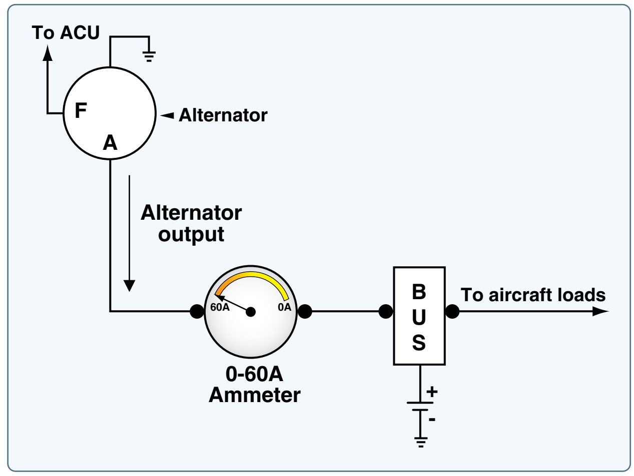


Figure 9-88. *Typical ammeter circuit used to monitor alternator output.*

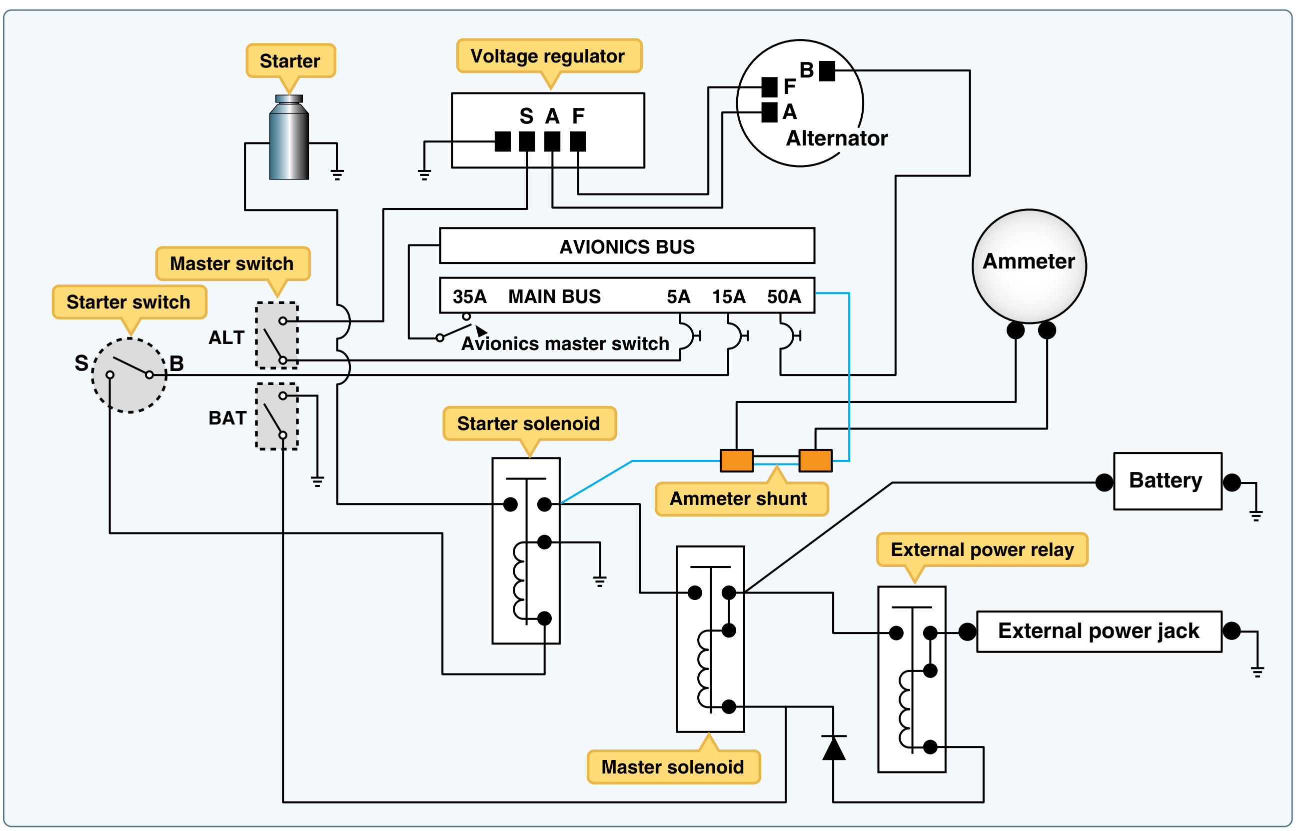


Figure 9-87. *Alternator control circuit.*

the alternator contains diodes in the armature circuit, current cannot reverse flow from the bus to the alternator.

When troubleshooting an alternator system, be sure to monitor the aircraft ammeter. If the alternator system is inoperative, the ammeter gives a zero indication. In this case, the battery is being discharged. A voltmeter is also a valuable tool when troubleshooting an alternator system. The voltmeter should be installed in the electrical system while the engine is running and the alternator operating. A system operating normally produces a voltage within the specified limits (approximately 14 volts or 28 volts depending on the electrical system). Consult the aircraft manual and verify the system voltage is correct. If the voltage is below specified values, the charging system should be inspected.

External Power Circuit

Many aircraft employ an external power circuit that provides a means of connecting electrical power from a ground source to the aircraft. External power is often used for starting the engine or maintenance activities on the aircraft. This type of system allows operation of various electrical systems without discharging the battery. The external power systems typically consists of an electrical plug located in a convenient area of the fuselage, an electrical solenoid used to connect external power to the bus, and the related wiring for the system. A common external power receptacle is shown in *Figure 9-89*.

Figure 9-90 shows how the external power receptacle connects to the external power solenoid through a reverse polarity diode. This diode is used to prevent any accidental connection in the event the external power supply has the incorrect polarity (i.e., a reverse of the positive and negative electrical connections). A reverse polarity connection could be catastrophic to the aircraft's electrical system. If a ground power source with a reverse polarity is connected, the diode blocks current and the external power solenoid does not close.

Figure 9-89. *External power receptacle.*

This diagram also shows that external power can be used to charge the aircraft battery or power the aircraft electrical loads. For external power to start the aircraft engine or power electrical loads, the battery master switch must be closed.

Starter Circuit

Virtually all modern aircraft employ an electric motor to start the aircraft engine. Since starting the engine requires several horsepower, the starter motor can often draw 100 or more amperes. For this reason, all starter motors are controlled through a solenoid. *[Figure 9-91]*

The starter circuit must be connected as close as practical to the battery since large wire is needed to power the starter motor and weight savings can be achieved when the battery and the starter are installed close to each other in the aircraft. As shown in the starter circuit diagram, the start switch can be part of a multifunction switch that is also used to control the engine magnetos. *[Figure 9-92]*

The starter can be powered by either the aircraft battery or the external power supply. Often when the aircraft battery

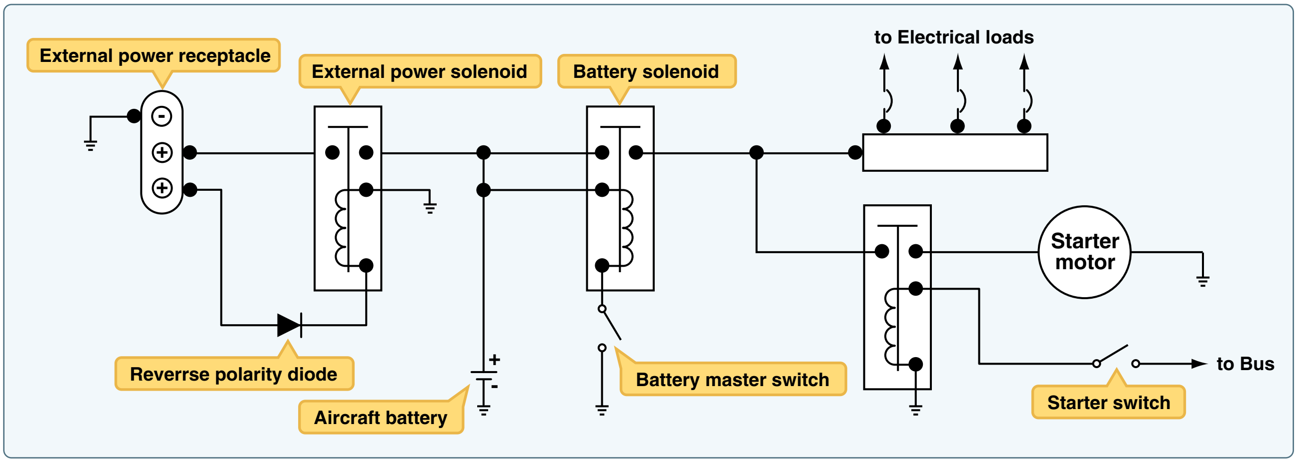


Figure 9-90. *A simple external power circuit diagram.*

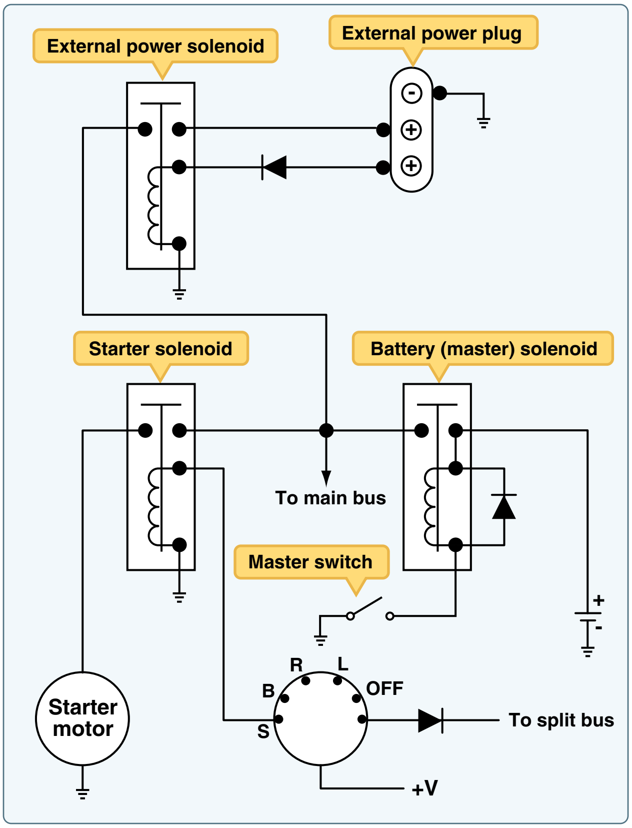


Figure 9-91. *Starter circuit.*

Figure 9-92. *Multifunction starter switch.*

is weak or in need of charging, the external power circuit is used to power the starter. During most typical operations, the starter is powered by the aircraft battery. The battery master must be on and the master solenoid closed in order to start the engine with the battery.

Avionics Power Circuit

Many aircraft contain a separate power distribution bus specifically for electronics equipment. This bus is often referred to as an avionics bus. Since modern avionics equipment employs sensitive electronic circuits, it is often advantageous to disconnect all avionics from electrical power to protect their circuits. For example, the avionics bus is often depowered when the starter motor is activated. This helps to prevent any transient voltage spikes produced by the starter from entering the sensitive avionics. *[Figure 9-93]*

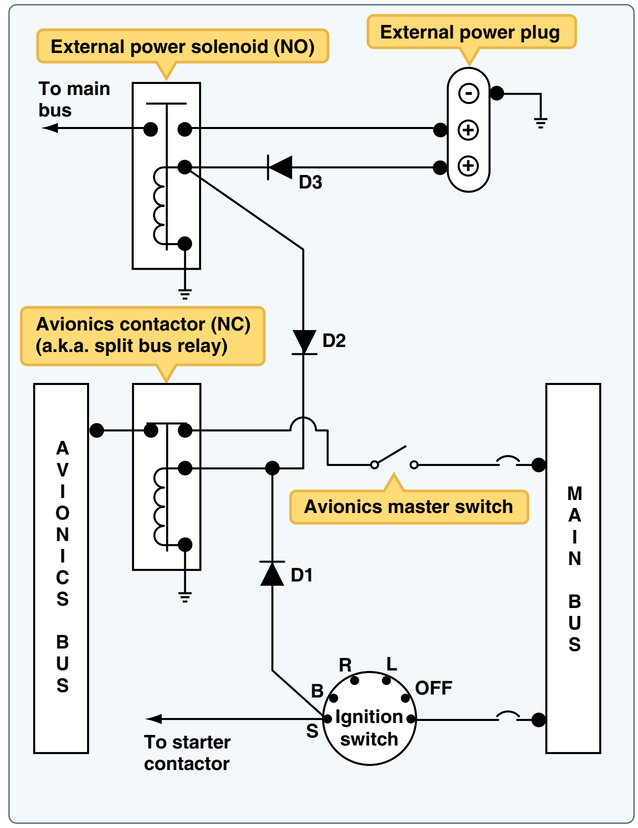


Figure 9-93. *Avionics power circuit.*

The circuit employs a normally closed (NC) solenoid that connects the avionics bus to the main power bus. The electromagnet of the solenoid is activated whenever the starter is engaged. Current is sent from the starter switch through Diode D1, causing the solenoid to open and depower the avionics bus. At that time, all electronics connected to the avionics bus will lose power. The avionics contactor is also activated whenever external power is connected to the aircraft. In this case, current travels through diodes D2 and D3 to the avionics bus contactor.

A separate avionics power switch may also be used to disconnect the entire avionics bus. A typical avionics power switch is shown wired in series with the avionics power bus. In some cases, this switch is combined with a circuit breaker and performs two functions (called a circuit breaker switch). It should also be noted that the avionics contactor is often referred to as a split bus relay, since the contactor separates (splits) the avionics bus from the main bus.

Landing Gear Circuit

Another common circuit found on light aircraft operates the retractable landing gear systems on high-performance light aircraft. These airplanes typically employ a hydraulic system to move the gear. After takeoff, the pilot moves the gear position switch to the retract position, starting an electric motor. The motor operates a hydraulic pump, and the hydraulic system moves the landing gear. To ensure correct operation of the system, the landing gear electrical system is relatively complex. The electrical system must detect the position of each gear (right, left, nose) and determine when each reaches full up or down; the motor is then controlled accordingly. There are safety systems to help prevent accidental actuation of the gear.

A series of limit switches are needed to monitor the position of each gear during the operation of the system. (A limit switch is simply a spring-loaded, momentary contact switch that is activated when a gear reaches it limit of travel.) Typically, there are six limit switches located in the landing gear wheel wells. The three up-limit switches are used to detect when the gear reaches the full retract (UP) position. Three down-limit switches are used to detect when the gear reach the full extended (DOWN) position. Each of these switches is mechanically activated by a component of the landing gear assembly when the appropriate gear reaches a given limit.

The landing gear system must also provide an indication to the pilot that the gear is in a safe position for landing. Many aircraft employ a series of three green lights when all three gears are down and locked in the landing position. These three lights are activated by the up- and down-limit switches found in the gear wheel well. A typical instrument panel showing the landing gear position switch and the three gears down indicators is shown in *Figure 9-94*.

The hydraulic motor/pump assembly located in the upper left corner of *Figure 9-95* is powered through either the UP or DOWN solenoids (top left). The solenoids are controlled by the gear selector switch (bottom left) and the six landing gear limit switches (located in the center of *Figure 9-95*). The three gear DOWN indicators are individual green lights (center of

Figure 9-94. *Instrument panel showing the landing gear position switch and the three gear down indicators.*

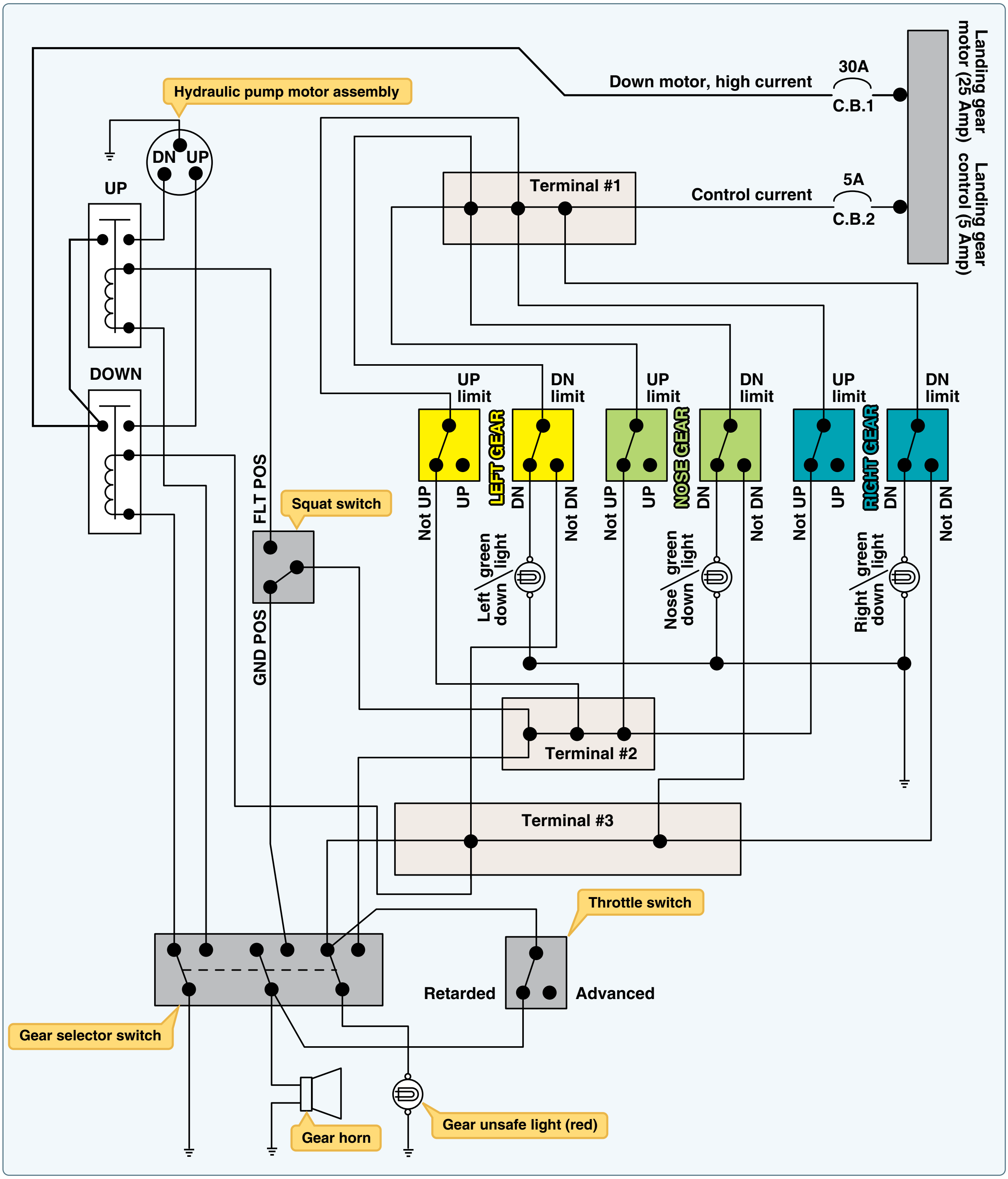


Figure 9-95. *Aircraft landing gear schematic while gear is in the DOWN and locked position.*

Figure 9-95) controlled by the three gear DOWN switches. As each gear reaches its DOWN position, the limit switch moves to the DOWN position, and the light is illuminated.

Figure 9-95 shows the landing gear in the full DOWN position. It is always important to know gear position when reading landing gear electrical diagrams. Knowing gear position helps the technician to analyze the diagram and understand correct operation of the circuits. Another important concept is that more than one circuit is used to operate the landing gear. On this system, there is a low current control circuit fused at 5 amps (CB2, top right of

Figure 9-95). This circuit is used for indicator lights and the control of the gear motor contactors. There is a separate circuit to power the gear motor fused at 30 amps (CB3, top right of *Figure 9-95*). Since this circuit carries a large current flow, the wires would be as short as practical and carefully protected with rubber boots or nylon insulators.

The following paragraphs describe current flow through the landing gear circuit as the system moves the gear up and down. Be sure to refer to *Figure 9-96* often during the following discussions. *Figure 9-96* shows current flow when the gear is traveling to the extend (DOWN) position. Current flow is highlighted in red for each description.

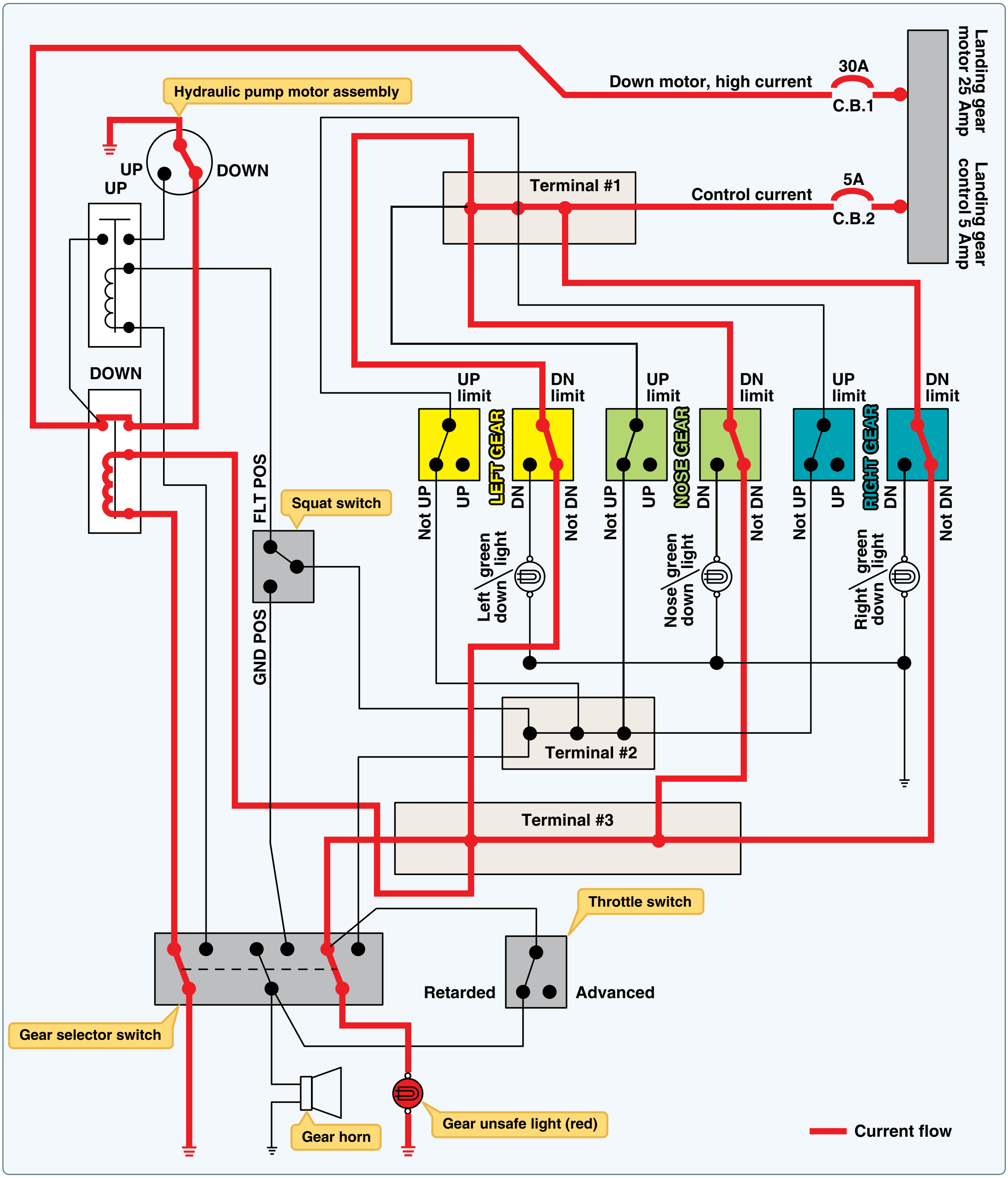


Figure 9-96. *Landing gear moving down diagram.*

To run the gear DOWN motor, current must flow in the control circuit leaving CB2 through terminal 1 to the NOT DOWN contacts of the DOWN limit switches, through terminal 3, to the DOWN solenoid positive terminal (upper left). The negative side of the DOWN solenoid coil is connected to ground through the gear selector switch. Remember, the gear DOWN switches are wired in parallel and activated when the gear reach the full-DOWN position. All three gears must reach full-DOWN to shut off the gear DOWN motor. Also note that the gear selector switch controls the negative side of the gear solenoids. The selector switch has independent control of the gear UP and DOWN motors through control of the ground circuit to both the UP and DOWN solenoids.

When the landing gear control circuit is sending a positive voltage to the DOWN solenoid, and the gear selector switch is sending negative voltage, the solenoid magnet is energized. When the gear-DOWN solenoid is energized, the high-current gear motor circuit sends current from CB1 through the down solenoid contact points to the gear DOWN motor. When the motor runs, the hydraulic pump produces pressure and the gear begins to move. When all three gears reach the DOWN position, the gear-DOWN switches move to the DOWN position, the three green lights illuminate, and the gear motor turns off completing the gear-DOWN cycle.

Figure 9-97 shows the landing gear electrical diagram with the current flow path shown in red as the gear moves to the retract (UP) position. Starting in the top right corner of the diagram, current must flow through CB2 in the control circuit through terminal 1 to each of the three gear-UP switches. With the gear-UP switches in the not UP position, current flows to terminal 2 and eventually through the squat switch to the UP solenoid electromagnet coil. The UP solenoid coil receives negative voltage through the gear selector switch. With the UP solenoid coil activated, the UP solenoid closes and power travels through the motor circuit. To power the motor, current leaves the bus through CB1 to the terminal at the DOWN solenoid onward through the UP solenoid to the UP motor. (Remember, current cannot travel through the DOWN solenoid at this time since the DOWN solenoid is not activated.) As the UP motor runs, each gear travels to the retract position. As this occurs, the gear UP switches move from the NOT UP position to the UP position. When the last gear reaches up, the current no longer travels to terminal 2 and the gear motor turns off. It should be noted that similar to DOWN, the gear switches are wired in parallel, which means the gear motor continues to run until all three gear reach the required position.

During both the DOWN and UP cycles of the landing gear operation, current travels from the limit switches to terminal 2. From terminal 2, there is a current path through the gear selector switch to the gear unsafe light. If the gear selector disagrees with the current gear position (e.g., gear is DOWN and pilot has selected UP), the unsafe light is illuminated. The gear unsafe light is shown at the bottom of *Figure 9-96*.

The squat switch (shown mid left of *Figure 9-96*) is used to determine if the aircraft is on the GROUND or in FLIGHT. This switch is located on a landing gear strut. When the weight of the aircraft compresses the strut, the switch is activated and moved to the GROUND position. When the switch is in the GROUND position, the gear cannot be retracted and a warning horn sounds if the pilot selects gear UP. The squat switch is sometimes referred to as the weight-on-wheels switch.

A throttle switch is also used in conjunction with landing gear circuits on most aircraft. If the throttle is retarded (closed) beyond a certain point, the aircraft descends and eventually lands. Therefore, many manufacturers activate a throttle switch whenever engine power is reduced. If engine power is reduced too low, a warning horn sounds telling the pilot to lower the landing gear. Of course, this horn need not sound if the gear is already DOWN or the pilot has selected the DOWN position on the gear switch. This same horn also sounds if the aircraft is on the ground, and the gear handle is moved to the UP position. *Figure 9-96* shows the gear warning horn in the bottom left corner.

AC Supply

Many modern light aircraft employ a low-power AC electrical system. Commonly, the AC system is used to power certain instruments and some lighting that operate only using AC. The electroluminescent panel has become a popular lighting system for aircraft instrument panels and requires AC. Electroluminescent lighting is very efficient and lightweight; therefore, excellent for aircraft installations. The electroluminescent material is a paste-like substance that glows when supplied with a voltage. This material is typically molded into a plastic panel and used for lighting.

A device called an inverter is used to supply AC when needed for light aircraft. Simply put, the inverter changes DC into AC. Two types of inverters may be found on aircraft: rotary inverters and static inverters. Rotary inverters are found only on older aircraft due to its poor reliability, excess weight, and inefficiency. The rotary inverters employee a DC motor that spins an AC generator. The unit is typically one unit and contains a voltage regulator circuit to ensure voltage stability. Most aircraft have a modern static inverter instead of a rotary inverter. Static inverters, as the name implies, contain no moving parts and use electronic circuitry to convert DC to AC. *Figure 9-98* shows a static inverter. Whenever AC is used on light aircraft, a distribution circuit separated from the DC system must be employed. *[Figure 9-99]*

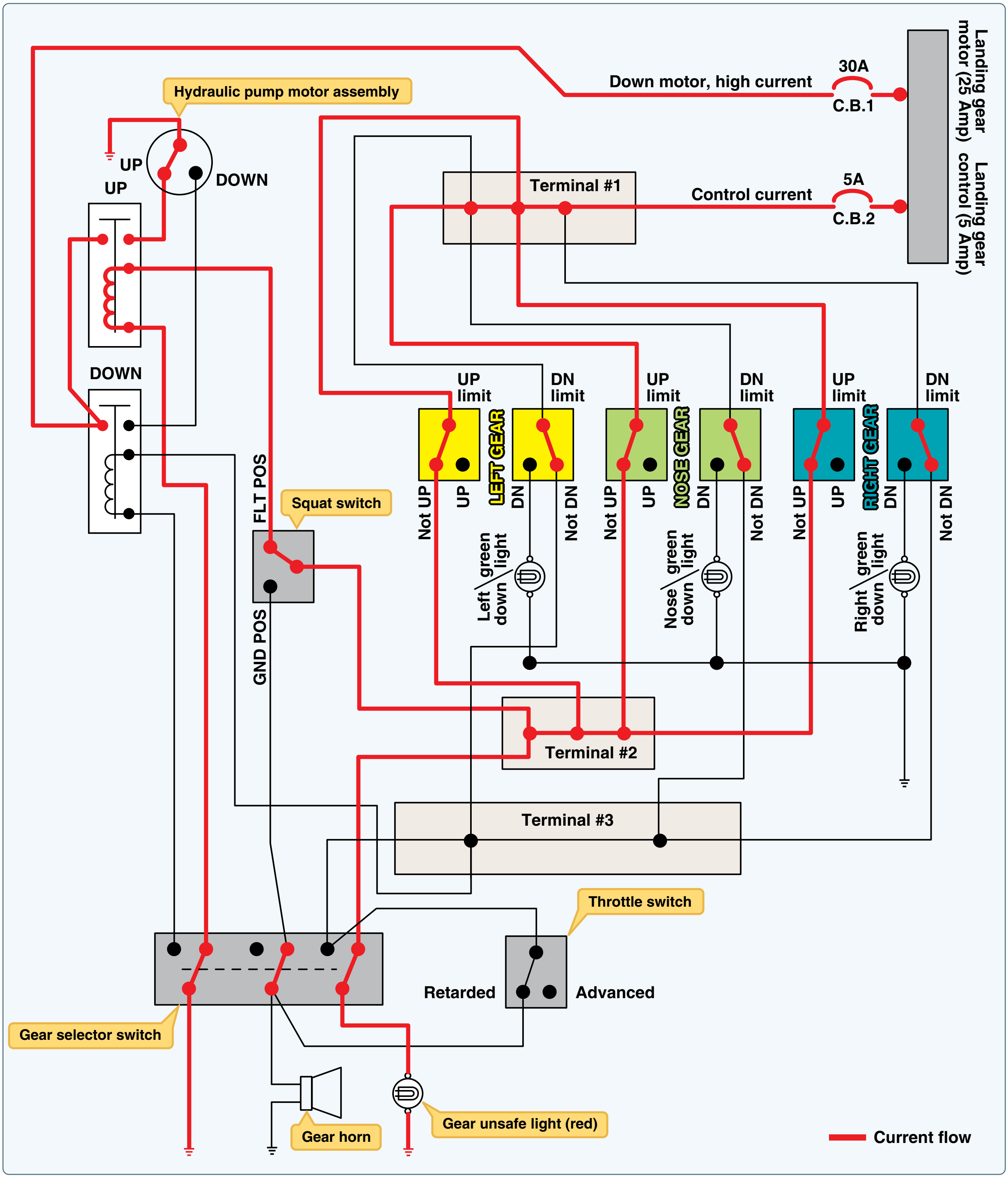


Figure 9-97. *Aircraft landing gear schematic while gear is moving to the UP position.*

Some aircraft use an inverter power switch to control AC power. Many aircraft simply power the inverter whenever the DC bus is powered and no inverter power switch is needed. On complex aircraft, more than one inverter may be used to provide a backup AC power source. Many inverters also offer more than one voltage output. Two common voltages found on aircraft inverters are 26VAC and 115VAC.

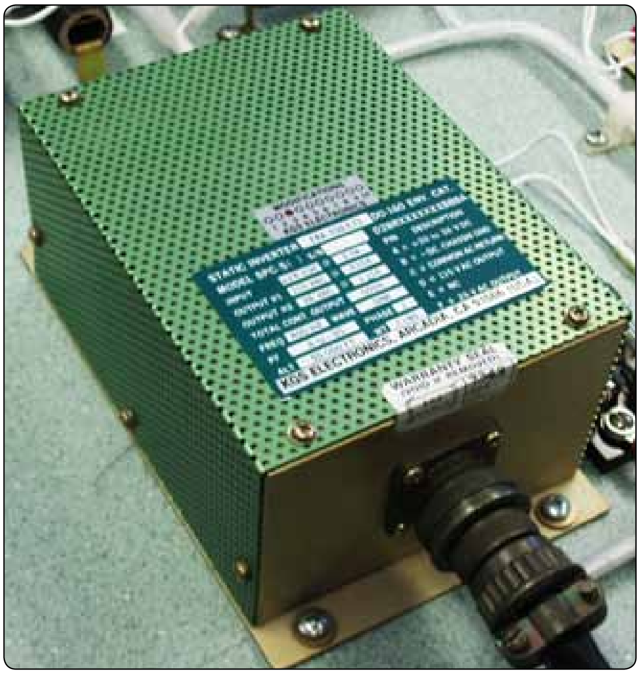


Figure 9-98. *A static inverter.*

Light Multiengine Aircraft

Multiengine aircraft typically fly faster, higher, and farther than single engine aircraft. Multiengine aircraft are designed for added safety and redundancy and, therefore, often contain a more complex power distribution system when compared to light single-engine aircraft. With two engines, these aircraft can drive two alternators (or generators) that supply current to the various loads of the aircraft. The electrical distribution bus system is also divided into two or more systems. These bus systems are typically connected through a series of circuit protectors, diodes, and relays. The bus system is designed to create a power distribution system that is extremely reliable by supplying current to most loads through more than one source.

Paralleling Alternators or Generators

Since two alternators (or generators) are used on twin engine aircraft, it becomes vital to ensure both alternators share the electrical load equally. This process of equalizing alternator outputs is often called paralleling. In general, paralleling is a simple process when dealing with DC power systems found on light aircraft. If both alternators are connected to the same load bus and both alternators produce the same output voltage, the alternators share the load equally. Therefore, the paralleling systems must ensure both power producers maintain system voltage within a few tenths of a volt. For most twin-engine aircraft, the voltage would be between 26.5-volt and 28-volt DC with the alternators operating. A simple vibrating point system used for paralleling alternators is found in *Figure 9-100*.

As can be seen in *Figure 9-100*, both left and right voltage regulators contain a paralleling coil connected to the output of each alternator. This paralleling coil works in conjunction with the voltage coil of the regulator to ensure proper alternator output. The paralleling coils are wired in series between the output terminals of both alternators. Therefore, if the two alternators provide equal voltages, the paralleling coil has no effect. If one alternator has a higher voltage output, the paralleling coils create the appropriate magnetic force to open/close the contact points, controlling field current and control alternator output.

Today's aircraft employ solid-state control circuits to ensure proper paralleling of the alternators. Older aircraft use vibrating point voltage regulators or carbon-pile regulators to monitor and control alternator output. For the most part, all carbon-pile regulators have been replaced except on historic aircraft. Many aircraft still maintain a vibrating point system, although these systems are no longer being

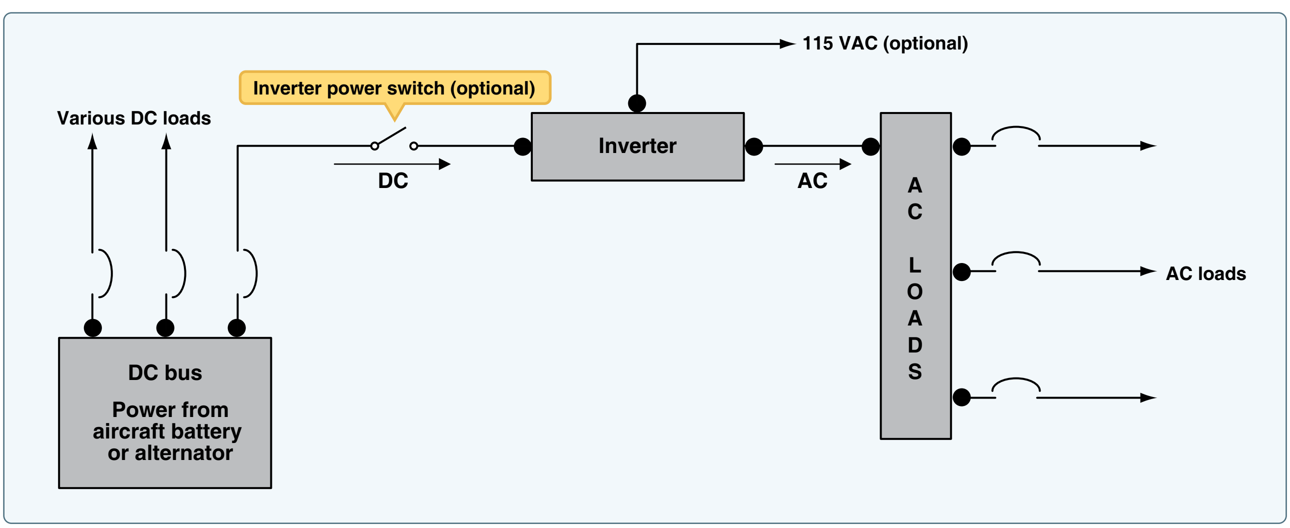


Figure 9-99. *Distribution circuit.*

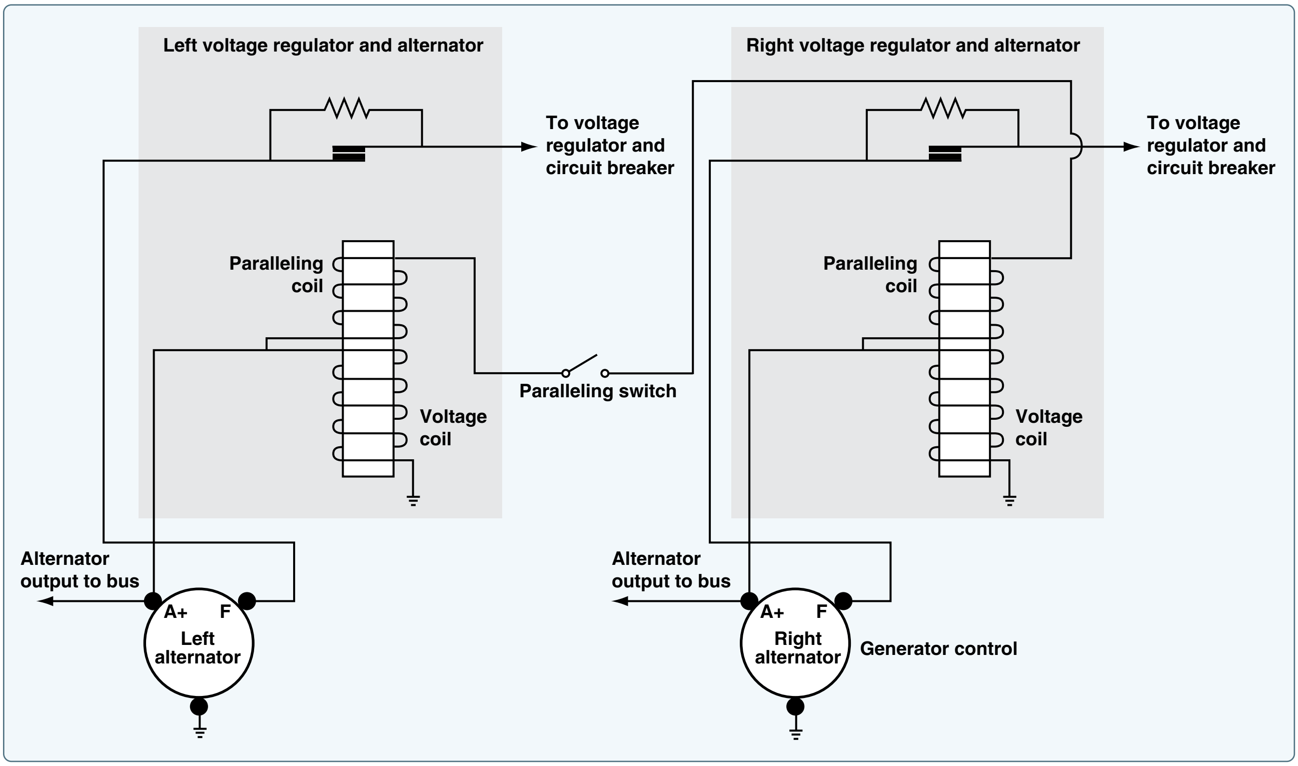


Figure 9-100. *Vibrating point system used for paralleling alternators.*

used on contemporary aircraft. The different types of voltage regulators were described earlier in this chapter.

Power Distribution on Multiengine Aircraft

The power distribution systems found on modern multiengine aircraft contain several distribution points (busses) and a variety of control and protection components to ensure the reliability of electrical power. As aircraft employ more electronics to perform various tasks, the electrical power systems becomes more complex and more reliable. One means to increase reliability is to ensure more than one power source can be used to power any given load. Another important design concept is to supply critical electrical loads from more than one bus. Twin-engine aircraft, such as a typical corporate jet or commuter aircraft, have two DC generators; they also have multiple distribution busses fed from each generator. *Figure 9-101* shows a simplified diagram of the power distribution system for a twin-engine turboprop aircraft.

This aircraft contains two starter generator units used to start the engines and generate DC electrical power. The system is typically defined as a split-bus power distribution system since there is a left and right generator bus that splits (shares) the electrical loads by connecting to each sub-bus through a diode and current limiter. The generators are operated in parallel and equally carry the loads.

The primary power supplied for this aircraft is DC, although small amounts of AC are supplied by two inverters. The aircraft diagram shows the AC power distribution at the top and mid left side of the diagram. One inverter is used for main AC power and the second operated in standby and ready as a backup. Both inverters produce 26-volt AC and 115-volt AC. There is an inverter select relay operated by a pilot controlled switch used to choose which inverter is active.

The hot battery bus (right side of *Figure 9-101)* shows a direct connection to the aircraft battery. This bus is always hot if there is a charged battery in the aircraft. Items powered by this bus may include some basics like the entry door lighting and the aircraft clock, which should always have power available. Other items on this bus would be critical to flight safety, such as fire extinguishers, fuel shut offs, and fuel pumps. During a massive system failure, the hot battery bus is the last bus on the aircraft that should fail.

If the battery switch is closed and the battery relay activated, battery power is connected to the main battery bus and the isolation bus. The main battery bus carries current for engine starts and external power. So the main battery bus must be large enough to carry the heaviest current loads of the aircraft. It is logical to place this bus as close as practical to the battery and starters and to ensure the bus is well protected from shorts to ground.

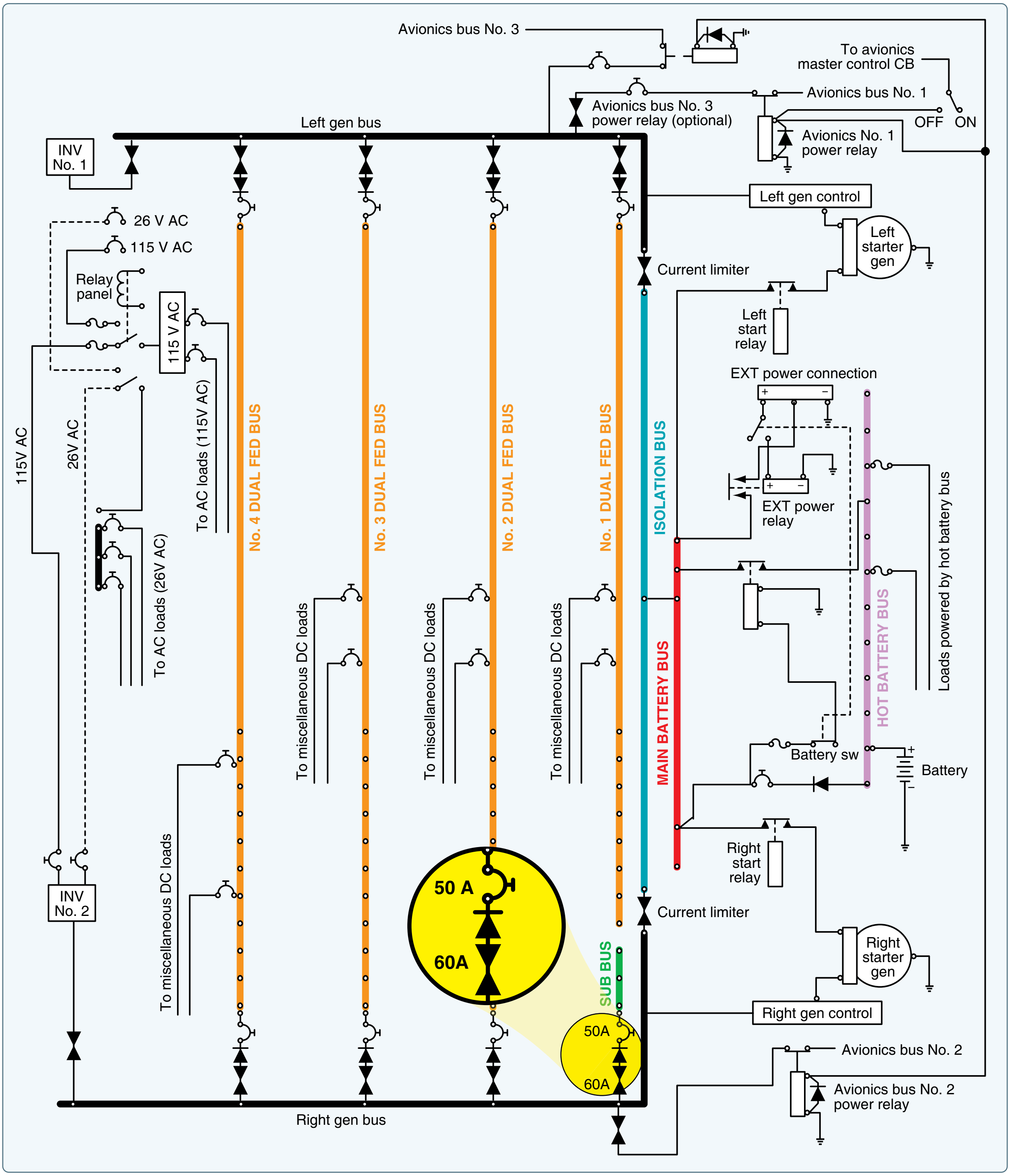


Figure 9-101. *Diagram of the power distribution system for a twin-engine turboprop aircraft.*

The isolation bus connects to the left and right busses and receives power whenever the main battery bus is energized. The isolation bus connects output of the left and right generators in parallel. The output of the two generators is then sent to the loads through additional busses. The generator busses are connected to the isolation bus through a fuse known as a current limiter. Current limiters are high amperage fuses that isolate busses if a short circuit occurs. There are several current limiters used in this system for protection between busses. As can be seen in *Figure 9-101*, a current limiter symbol looks like two triangles pointed toward each other. The current limiter between the isolation bus and the main generator busses are rated at 325 amps and can only be replaced on the ground. Most current limiters are designed for ground replacement only and only after the malfunction that caused the excess current draw is repaired.

The left and right DC generators are connected to their respective main generator busses. Each generator feeds its respective bus, and since the busses are connected under normal circumstances, the generators operate in parallel. Both generators feed all loads together. If one generator fails or a current limiter opens, the generators can operate independently. This design allows for redundancy in the event of failure and provides battery backup in the event of a dual generator failure.

In the center of *Figure 9-101* are four dual-feed electrical busses. These busses are considered dual-feed since they receive power from both the left and right generator busses. If a fault occurs, either generator bus can power any or all loads on a dual-feed bus. During the design phase of the aircraft, the electrical loads must be evenly distributed between each of the dual-feed busses. It is also important to power redundant systems from different busses. For example, the pilot's windshield heat would be powered by a different bus from the one that powers the copilot's windshield heat. If one bus fails, at least one windshield heat continues to work properly, and the aircraft can be landed safely in icing conditions.

Notice that the dual-feed busses are connected to the main generator busses through both a current limiter and a diode. Remember, a diode allows current flow in only one direction. *[Figure 9-102]*

The current can flow from the generator bus to the dual-feed bus, but the current cannot flow from the dual fed bus to the main generator bus. The diode is placed in the circuit so the main bus must be more positive than the sub bus for current flow. This circuit also contains a current limiter and a circuit breaker. The circuit breaker is located on the flight deck and can be reset by the pilot. The current limiter can only be replaced on the ground by a technician. The circuit breaker is rated at a slightly lower current value than the current limiter; therefore, the circuit breaker should open if a current overload exists. If the circuit breaker fails to open, the current limiter provides backup protection and disconnects the circuit.

Large Multiengine Aircraft

Transport category aircraft typically carry hundreds of passengers and fly thousands of miles each trip. Therefore, large aircraft require extremely reliable power distribution systems that are computer controlled. These aircraft have multiple power sources (AC generators) and a variety of distribution busses. A typical airliner contains two or more main AC generators driven by the aircraft turbine engines, as well as more than one backup AC generator. DC systems are also employed on large aircraft and the ship's battery is used to supply emergency power in case of a multiple failures.

The AC generator (sometimes called an alternator) produces three-phase 115-volt AC at 400 Hz. AC generators were discussed previously in this chapter. Since most modern transport category aircraft are designed with two engines, there are two main AC generators. The APU also drives an AC generator. This unit is available during flight if one of the main generators fails. The main and auxiliary generators are typically similar in output capacity and supply a maximum of 110 kilovolt amps (KVA). A fourth generator, driven by an emergency ram air turbine, is also available in the event the two main generators and one auxiliary generator fail. The emergency generator is typically smaller and produces less power. With four AC generators available on modern aircraft, it is highly unlikely that a complete power failure occurs. However, if all AC generators are lost, the aircraft battery will continue to supply DC electrical power to operate vital systems.

AC Power Systems

Transport category aircraft use large amounts of electrical power for a variety of systems. Passenger comfort requires power for lighting, audio visual systems, and galley power for food warmers and beverage coolers. A variety of electrical systems are required to fly the aircraft, such as flight control systems, electronic engine controls, communication, and navigation systems. The output capacity of one engine-driven AC generator can typically power all necessary electrical

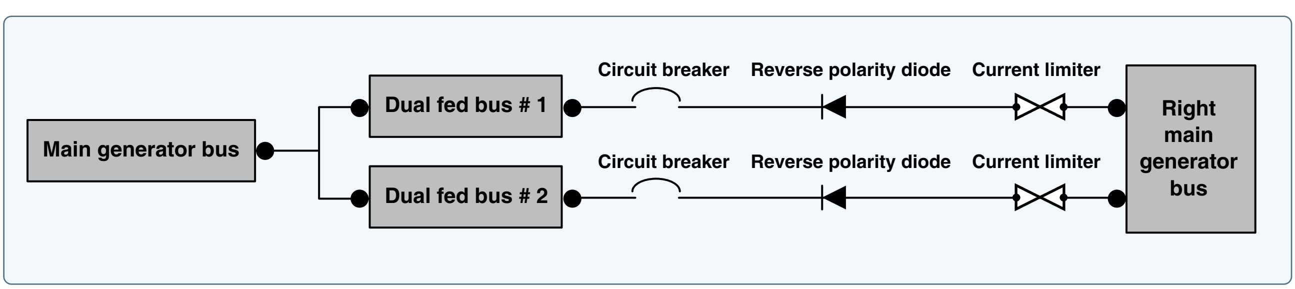


Figure 9-102. *Dual-feed bus system.*

systems. A second engine-driven generator is operated during flight to share the electrical loads and provide redundancy.

The complexity of multiple generators and a variety of distribution busses requires several control units to maintain a constant supply of safe electrical power. The AC electrical system must maintain a constant output of 115 to 120 volts at a frequency of 400 Hz (±10 percent). The system must ensure power limits are not exceeded. AC generators are connected to the appropriate distribution busses at the appropriate time, and generators are in phase when needed. There is also the need to monitor and control any external power supplied to the aircraft, as well as control of all DC electrical power.

Two electronic line replaceable units are used to control the electrical power on a typical large aircraft. The generator control unit (GCU) is used for control of AC generator functions, such as voltage regulation and frequency control. The bus power control unit (BPCU) is used to control the distribution of electrical power between the various distribution busses on the aircraft. The GCU and BPCU work together to control electrical power, detect faults, take corrective actions when needed, and report any defect to the pilots and the aircraft's central maintenance system. There is typically one GCU for each AC generator and at least one BPCU to control bus connections. These LRUs are located in the aircraft's electronics equipment bay and are designed for easy replacement.

When the pilot calls for generator power by activating the generator control switch on the flight deck, the GCU monitors the system to ensure correct operation. If all systems are operating within limits, the GCU energizes the appropriate generator circuits and provides voltage regulation for the system. The GCU also monitors AC output to ensure a constant 400-Hz frequency. If the generator output is within limits, the GCU then connects the electrical power to the main generator bus through an electrical contactor (solenoid). These contactors are often called generator breakers (GB) since they break (open) or make (close) the main generator circuit.

After generator power is available, the BPCU activates various contactors to distribute the electrical power. The BPCU monitors the complete electrical system and communicates with the GCU to ensure proper operation. The BPCU employs remote current sensors known as a current transformers (CT) to monitor the system. *[Figure 9-103]*

A CT is an inductive unit that surrounds the main power cables of the electrical distribution system. As AC power flows through the main cables, the CT receives an induced voltage. The amount of CT voltage is directly related to the current flowing through the cable. The CT connects to the BPCU, which allows accurate current monitoring of the system. A typical aircraft employs several CTs throughout the electrical system.

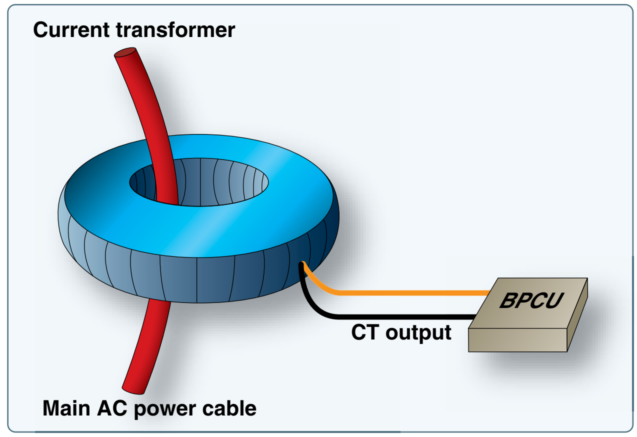


Figure 9-103. *Current transformer.*

The BPCU is a dedicated computer that controls the electrical connections between the various distribution busses found on the aircraft. The BPCU uses contactors (solenoids) called bus tie breakers (BTB) for connection of various circuits. These BTBs open/close the connections between the busses as needed for system operation as called for by the pilots and the BPCU. This sounds like a simple task, yet to ensure proper operation under a variety of conditions, the bus system becomes very complex. There are three common types of distribution bus systems found on transport category aircraft: split bus, parallel bus, and split parallel.

Split-Bus Power Distribution Systems

Modern twin-engine aircraft, such as the Boeing 737, 757, 777, Airbus A-300, A-320, and A-310, employ a split-bus power distribution system. During normal conditions, each engine-driven AC generator powers only one main AC bus. The busses are kept split from each other, and two generators can never power the same bus simultaneously. This is very important since the generator output current is not phase regulated. (If two out-of-phase generators were connected to the same bus, damage to the system would occur.) The split-bus system does allow both engine-driven generators to power any given bus, but not at the same time. Generators must remain isolated from each other to avoid damage. The GCUs and BPCU ensures proper generator operation and power distribution.

On all modern split bus systems, the APU can be started and operated during flight. This allows the APU generator to provide back-up power in the event of a main generator failure. A fourth emergency generator powered by the ram air turbine is also available if the other generators fail.

The four AC generators are shown at the bottom of *Figure 9-104*. These generators are connected to their respective busses through the generator breakers. For example, generator 1 sends current through GB1 to AC bus 1. AC bus 1 feeds a variety of primary electrical loads, and also feeds sub-busses that in turn power additional loads.

With both generators operating and all systems normal, AC bus 1 and AC bus 2 are kept isolated. Typically during flight, the APB (bottom center of *Figure 9-104*) would be open and the APU generator off; the emergency generator (bottom right) would also be off and disconnected. If generator one should fail, the following happens:

1. The GB 1 is opened by the GCU to disconnect the failed generator.
2. The BPCU closes BTB 1 and BTB 2. This supplies AC power to AC bus 1 from generator 2.
3. The pilots start the APU and connect the APU generator. At that time, the BPCU and GCUs move the appropriate BTBs to correctly configure the system so the APU powers bus 1 and generator 2 powers bus 2.

Once again, two AC generators operate independently to power AC bus 1 and 2.

If all generators fail, AC is also available through the static inverter (center of *Figure 9-104*). The inverter is powered from the hot battery bus and used for essential AC loads if all AC generators fail. Of course, the GCUs and BPCU take the appropriate actions to disconnect defective units and continue to feed essential AC loads using inverter power.

To produce DC power, AC bus 1 sends current to its transformer rectifier (TR), TR 1 (center left of *Figure 9-104*). The TR unit is used to change AC to DC. The TR contains a transformer to step down the voltage from 115-volt AC to 26-volt AC and a rectifier to change the 26-volt AC to 26-volt DC. The output of the TR is therefore compatible with the aircraft battery at 26-volt DC. Since DC power is not phase sensitive, the DC busses are connected during normal operation. In the event of a bus problem, the BPCU may isolate one or more DC busses to ensure correct distribution of DC power. This aircraft contains two batteries that are used to supply emergency DC power.

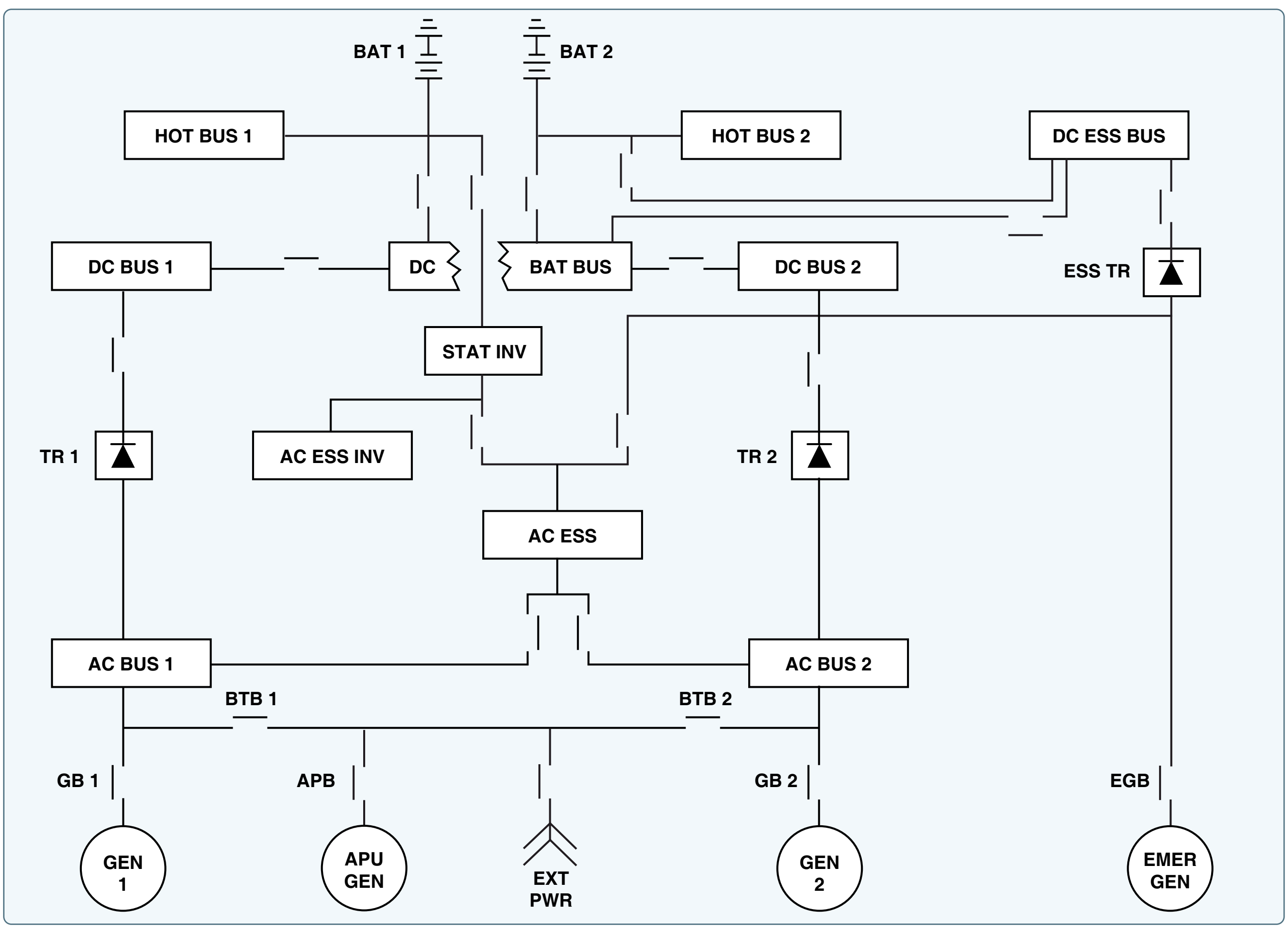


Figure 9-104. *Schematic of split-bus power distribution system.*

Parallel Systems

Multiengine aircraft, such as the Boeing 727, MD-11, and the early Boeing 747, employ a parallel power distribution system. During normal flight conditions, all engine-driven generators connect together and power the AC loads. In this configuration, the generators are operated in parallel; hence the name parallel power distribution system. In a parallel system, all generator output current must be phase regulated. Before generators are connected to the same bus, their output frequency must be adjusted to ensure the AC output reaches the positive and negative peaks simultaneously. During the flight, generators must maintain this in-phase condition for proper operation.

One advantage of parallel systems is that in the event of a generator failure, the busses are already connected and the defective generator need only be isolated from the system. A paralleling bus, or synchronizing bus, is used to connect the generators during flight. The synchronizing bus is often referred to as the sync bus. Most of these systems are less automated and require that flight crew monitor systems and manually control bus contactors. BTBs are operated by the flight crew through the electrical control panel and used to connect all necessary busses. GBs are used to connect and disconnect the generators.

Figure 9-105 shows a simplified parallel power distribution system. This aircraft employs three main-engine driven generators and one APU generator. The APU (bottom right) is not operational in flight and cannot provide backup power. The APU generator is for ground operations only. The three main generators (bottom of *Figure 9-105*) are connected to their respective AC bus through GBs one, two, and three. The AC busses are connected to the sync bus through three BTBs. In this manner, all three generators share the entire AC electrical loads. Keep in mind, all generators connected to the sync bus must be in phase. If a generator fails, the flight crew would simply isolate the defective generator and the flight would continue without interruption.

The number one and two DC busses (*Figure 9-105* top left) are used to feed the DC electrical loads of the aircraft. DC bus 1 receives power form AC bus 1 though TR1. DC bus 2 is fed in a similar manner from AC bus 2. The DC busses

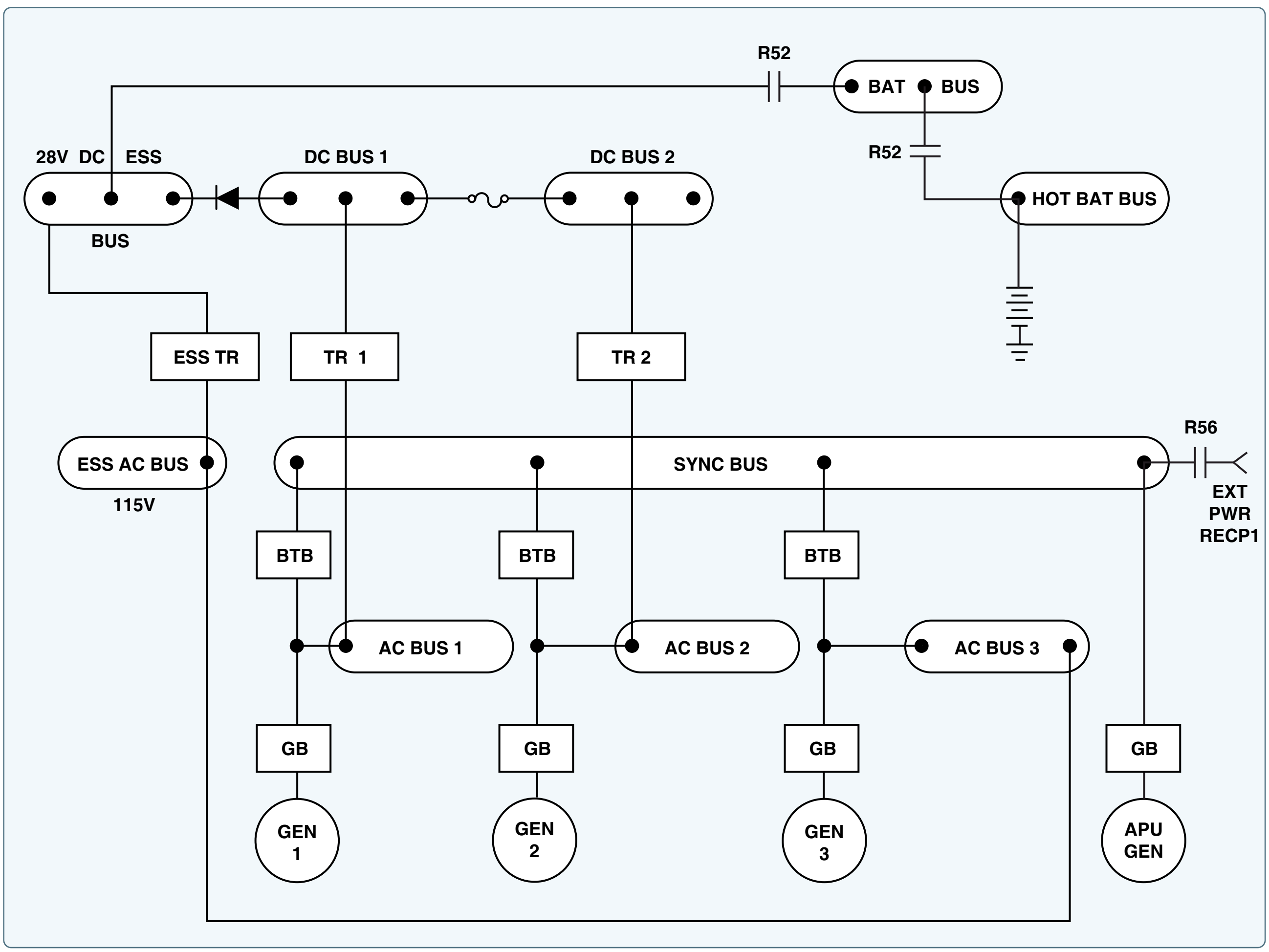


Figure 9-105. *Parallel power distribution system.*

also connect to the battery bus and eventually to the battery. The essential DC bus (top left) can be fed from DC bus 1 or the essential TR. A diode prevents the essential DC bus from powering DC bus 1. The essential DC bus receives power from the essential TR, which receives power from the essential AC bus. This provides an extra layer of redundancy since the essential AC bus can be isolated and fed from any main generator. *Figure 9-105* shows generator 3 powering the essential AC bus.

Split-Parallel Systems

A split-parallel bus basically employs the best of both split-bus and the parallel-bus systems. The split-parallel system is found on the Boeing 747-400 and contains four generators driven by the main engines and two APU-driven generators. The system can operate with all generators in parallel, or the generators can be operated independently as in a split-bus system. During a normal flight, all four engine-driven generators are operated in parallel. The system is operated in split-bus mode only under certain failure conditions or when using external power. The Boeing 747-400 split-parallel system is computer controlled using four GCU and two BPCU. There is one GCU controlling each generator; BPCU 1 controls the left side bus power distribution, and BPCU 2 controls the right side bus power. The GCUs and BPCUs operate similarly to those previously discussed under the split-bus system.

Figure 9-106 shows a simplified split-parallel power distribution system. The main generators (top of *Figure 9-106*) are driven by the main turbine engines. Each generator is connected to its load bus through a generator control breaker (GCB). The generator control unit closes the GCB when the pilot calls for generator power and all systems are operating normally. Each load bus is connected to various electrical systems and additional sub-busses. The BTB are controlled by the BPCU and connect each load bus to the left and right sync bus. A split systems breaker (SSB) is used to connect the left and right sync busses and is closed during a normal flight. With the SSB, GCBs, and BTBs, in the closed position the generators operate in parallel. When operating in parallel, all generators must be in phase.

If the aircraft electrical system experiences a malfunction, the control units make the appropriate adjustments to ensure all necessary loads receive electrical power. For example, if generator 1 fails, GCU 1 detects the fault and command GCB 1 to open. With GCB 1 open, load bus 1 now feeds from the sync bus and the three operating generators. In another example, if load bus 4 should short to ground, BPCU 4 opens the GCB 4 and BTB 4. This isolates the shorted bus (load bus 4). All loads on the shorted bus are no longer powered, and generator 4 is no longer available. However, with three remaining generators operational, the flight continues safely.

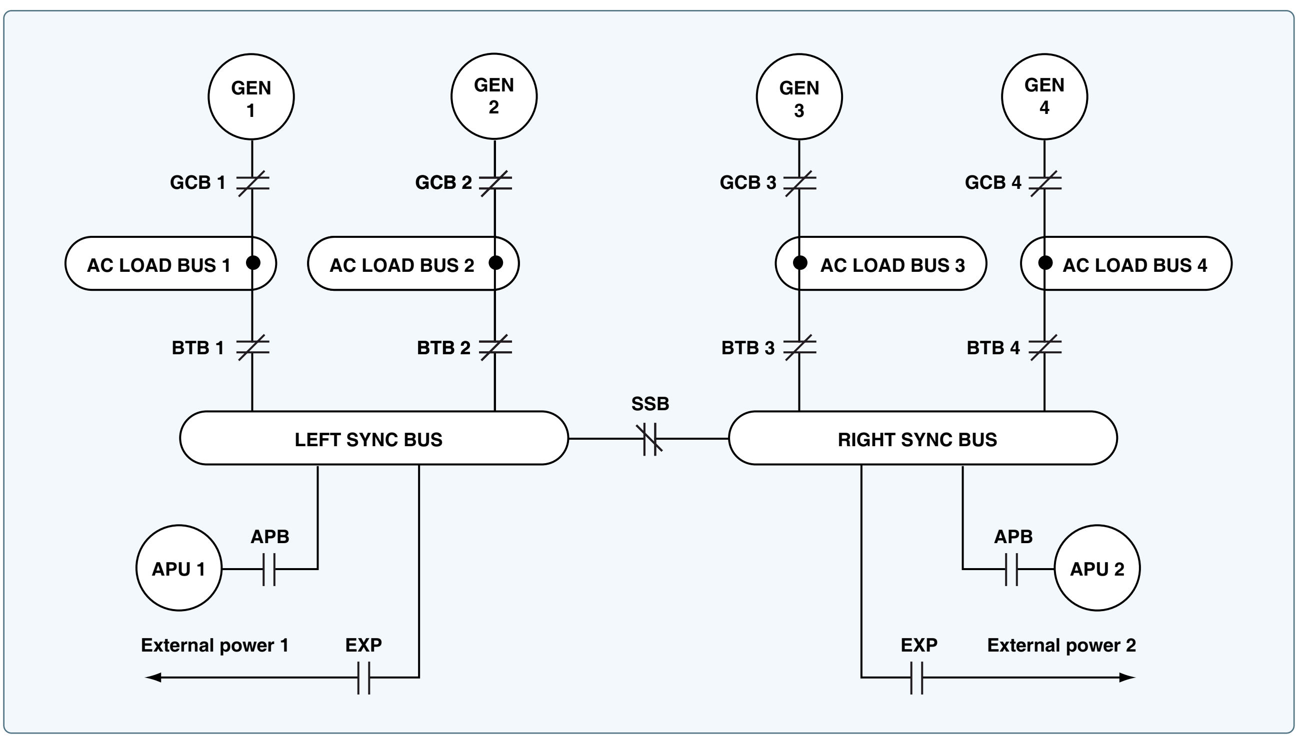


Figure 9-106. *Split-parallel distribution system.*

As do all large aircraft, the Boeing 747-400 contains a DC power distribution system. The DC system is used for battery and emergency operations. The DC system is similar to those previously discussed, powered by TR units. The TRs are connected to the AC busses and convert AC into 26-volt DC. The DC power systems are the final backups in the event of a catastrophic electrical failure. The systems most critical to fly the aircraft can typically receive power from the battery. This aircraft also contains two static inverters to provide emergency AC power when needed.

Wiring Installation

Wiring Diagrams

Electrical wiring diagrams are included in most aircraft service manuals and specify information, such as the size of the wire and type of terminals to be used for a particular application. Furthermore, wiring diagrams typically identify each component within a system by its part number and its serial number, including any changes that were made during the production run of an aircraft. Wiring diagrams are often used for troubleshooting electrical malfunctions.

Block Diagrams

A block diagram is used as an aid for troubleshooting complex electrical and electronic systems. A block diagram consists of individual blocks that represent several components, such as a printed circuit board or some other type of replaceable module. *Figure 9-107* is a block diagram of an aircraft electrical system.

Pictorial Diagrams

In a pictorial diagram, pictures of components are used instead of the conventional electrical symbols found in schematic diagrams. A pictorial diagram helps the maintenance technician visualize the operation of a system. *[Figure 9-108]*

Schematic Diagrams

A schematic diagram is used to illustrate a principle of operation, and therefore does not show parts as they actually appear or function. *[Figure 9-109]* However, schematic diagrams do indicate the location of components with respect to each other. Schematic diagrams are best utilized for troubleshooting.

Wire Types

The satisfactory performance of any modern aircraft depends to a very great degree on the continuing reliability of electrical systems and subsystems. Improperly or carelessly maintained wiring can be a source of both immediate and potential danger. The continued proper performance of electrical systems depends on the knowledge and techniques of the technician who installs, inspects, and maintains the electrical system wires and cables.

Procedures and practices outlined in this section are general recommendations and are not intended to replace the manufacturer's instructions and approved practices.

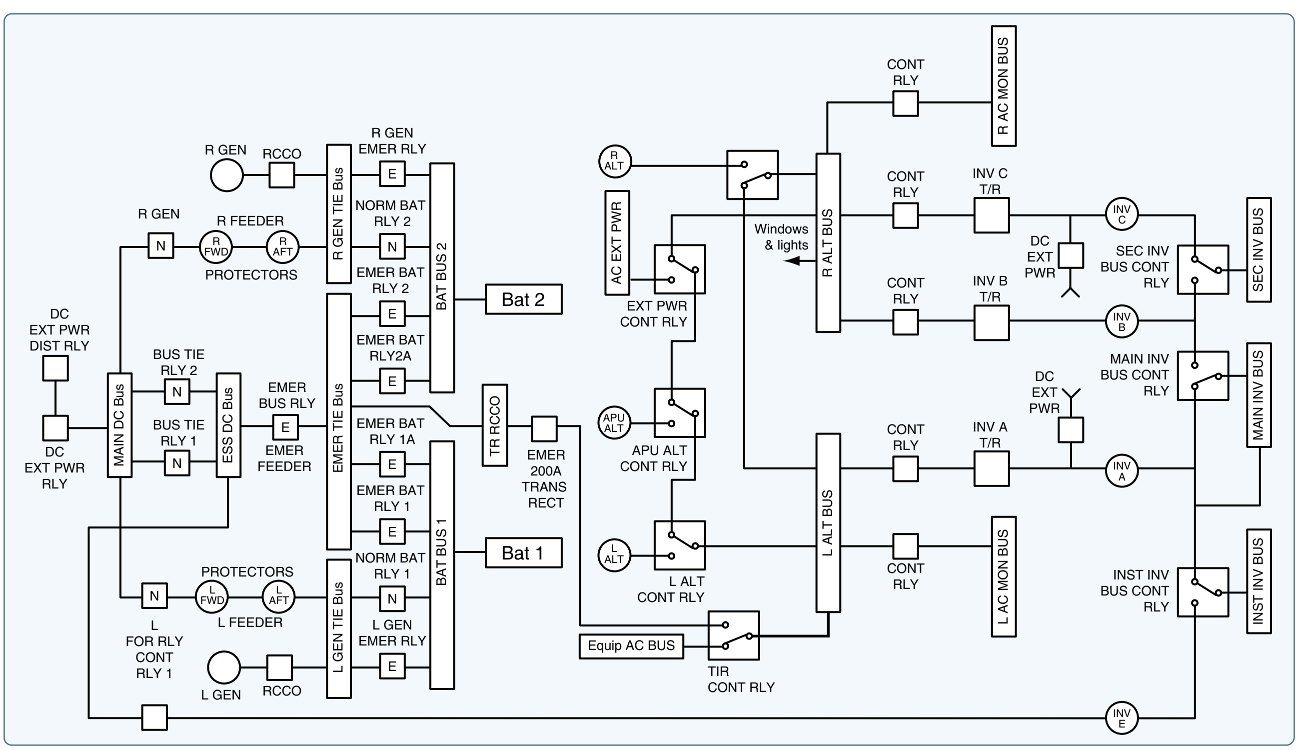


Figure 9-107. *Block diagram of an aircraft electrical system.*

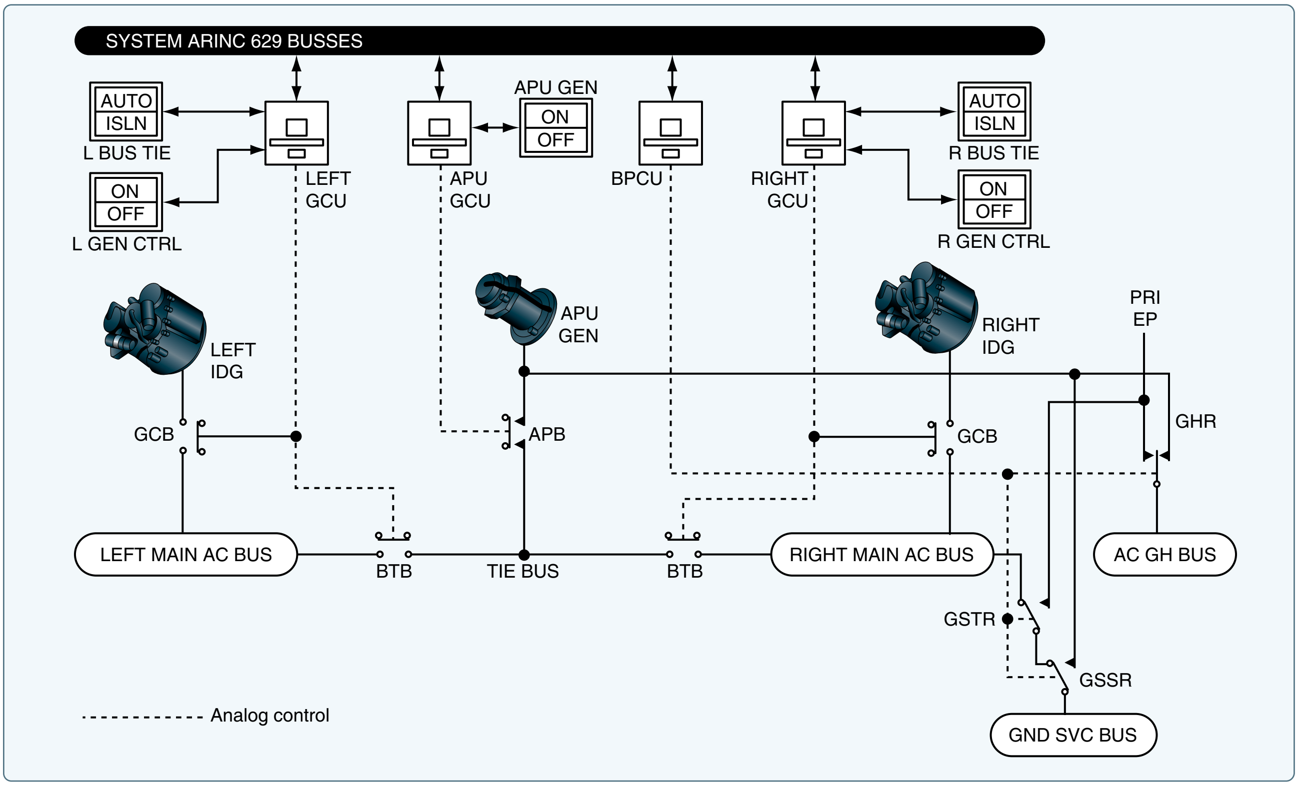


Figure 9-108. *Pictorial diagram of an aircraft electrical system.*

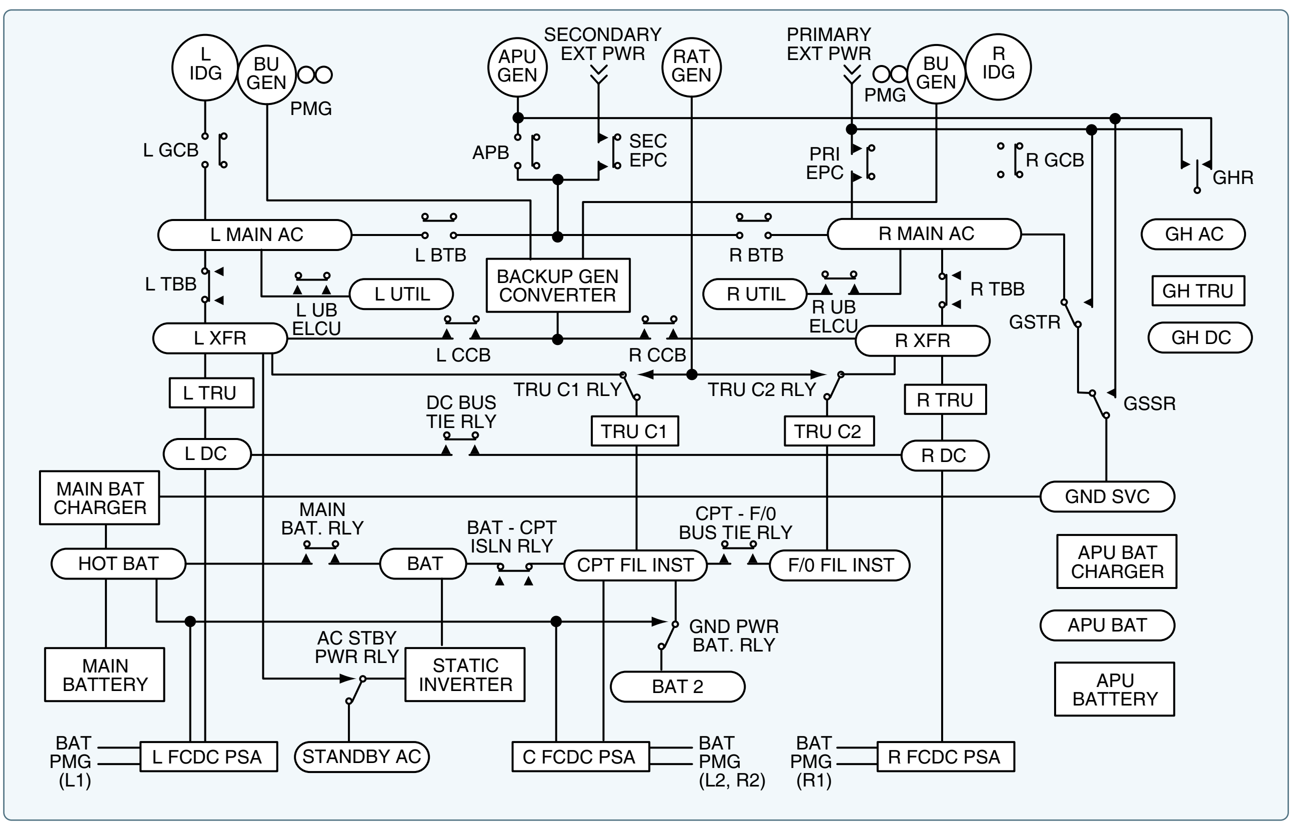


Figure 9-109. *Schematic diagram.*

A wire is described as a single, solid conductor, or as a stranded conductor covered with an insulating material. *Figure 9-110* illustrates these two definitions of a wire. Because of in-flight vibration and flexing, conductor round wire should be stranded to minimize fatigue breakage.

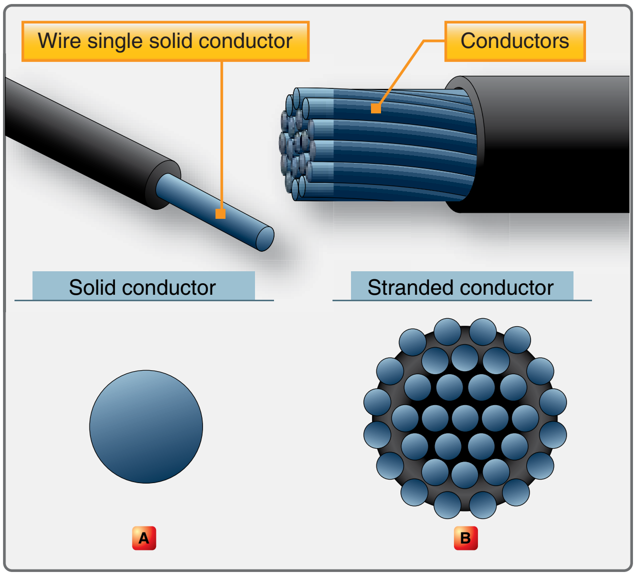


Figure 9-110. *Aircraft electrical cable.*

The term "cable," as used in aircraft electrical installations, includes:

1. Two or more separately insulated conductors in the same jacket.
2. Two or more separately insulated conductors twisted together (twisted pair).
3. One or more insulated conductors covered with a metallic braided shield (shielded cable).
4. A single insulated center conductor with a metallic braided outer conductor (radio frequency cable).

The term "wire harness" is used when an array of insulated conductors are bound together by lacing cord, metal bands, or other binding in an arrangement suitable for use only in specific equipment for which the harness was designed; it may include terminations. Wire harnesses are extensively used in aircraft to connect all the electrical components. *[Figure 9-111]*

For many years, the standard wire in light aircraft has been MIL-W-5086A, which uses a tin-coated copper conductor rated at 600 volts and temperatures of 105 °C. This basic wire is then coated with various insulating coatings. Commercial and military aircraft use wire that is manufactured under MIL-W-22759 specification, which complies with current military and FAA requirements.

Figure 9-111. *Shielded wire harness.*

The most important consideration in the selection of aircraft wire is properly matching the wire's construction to the application environment. Wire construction that is suitable for the most severe environmental condition to be encountered should be selected. Wires are typically categorized as being suitable for either open wiring or protected wiring application. The wire temperature rating is typically a measure of the insulation's ability to withstand the combination of ambient temperature and current-related conductor temperature rise.

Conductor

The two most generally used conductors are copper and aluminum. Each has characteristics that make its use advantageous under certain circumstances. Also, each has certain disadvantages. Copper has a higher conductivity; is more ductile; has relatively high tensile strength; and can be easily soldered. Copper is more expensive and heavier than aluminum. Although aluminum has only about 60 percent of the conductivity of copper, it is used extensively. Its lightness makes possible long spans, and its relatively large diameter for a given conductivity reduces corona (the discharge of electricity from the wire when it has a high potential). The discharge is greater when small diameter wire is used than when large diameter wire is used. Some bus bars are made of aluminum instead of copper where there is a greater radiating surface for the same conductance. The characteristics of copper and aluminum are compared in *Figure 9-112*.

Characteristic	Copper	Aluminum
Tensile strength (lb-in)	55,000	25,000
Tensile strength for same conductivity (lb)	55,000	40,000
Weight for same conductivity (lb)	100	48
Cross section for same conductivity (CM)	100	160
Specific resistance (ohm/mil ft)	10.6	17

Figure 9-112. *Aircraft electrical cable.*

Plating

Bare copper develops a surface oxide coating at a rate dependent on temperature. This oxide film is a poor conductor of electricity and inhibits determination of wire. Therefore, all aircraft wiring has a coating of tin, silver, or nickel that has far slower oxidation rates.

1. Tin-coated copper is a very common plating material. Its ability to be successfully soldered without highly active fluxes diminishes rapidly with time after manufacture. It can be used up to the limiting temperature of 150 °C.
2. Silver-coated wire is used where temperatures do not exceed 200 °C (392 °F).
3. Nickel-coated wire retains its properties beyond 260 °C, but most aircraft wire using such coated strands has insulation systems that cannot exceed that temperature on long-term exposure. Soldered terminations of nickel-plated conductor require the use of different solder sleeves or flux than those used with tin- or silver-plated conductor.

Insulation

Two fundamental properties of insulation materials are insulation resistance and dielectric strength. These are entirely different and distinct properties.

Insulation resistance is the resistance to current leakage through and over the surface of insulation materials. Insulation resistance can be measured with a megohmmeter/insulation tester without damaging the insulation, and data so obtained serves as a useful guide in determining the general condition of the insulation. However, the data obtained in this manner may not give a true picture of the condition of the insulation. Clean, dry insulation having cracks or other faults might show a high value of insulation resistance but would not be suitable for use.

Dielectric strength is the ability of the insulator to withstand potential difference and is usually expressed in terms of the voltage at which the insulation fails because of the electrostatic stress. Maximum dielectric strength values can be measured by raising the voltage of a test sample until the insulation breaks down.

The type of conductor insulation material varies with the type of installation. Characteristics should be chosen based on environment, such as abrasion resistance, arc resistance, corrosion resistance, cut-through strength, dielectric strength, flame resistant, mechanical strength, smoke emission, fluid resistance, and heat distortion. Such types of insulation materials (e.g., PVC/nylon, Kapton®, and Teflon®) are no longer used for new aircraft designs, but might still be installed on older aircraft. Insulation materials for new aircraft designs are made of Tefzel®, Teflon®/Kapton®/Teflon® and PTFE/Polyimide/PTFE. The development of better and safer insulation materials is ongoing.

Since electrical wire may be installed in areas where inspection is infrequent over extended periods of time, it is necessary to give special consideration to heat-aging characteristics in the selection of wire. Resistance to heat is of primary importance in the selection of wire for aircraft use, as it is the basic factor in wire rating. Where wire may be required to operate at higher temperatures due either to high ambient temperatures, high current loading, or a combination of the two, selection should be made on the basis of satisfactory performance under the most severe operating conditions.

Wire Shielding

With the increase in number of highly sensitive electronic devices found on modern aircraft, it has become very important to ensure proper shielding for many electric circuits. Shielding is the process of applying a metallic covering to wiring and equipment to eliminate electromagnetic interference (EMI). EMI is caused when electromagnetic fields (radio waves) induce high frequency (HF) voltages in a wire or component. The induced voltage can cause system inaccuracies or even failure.

Use of shielding with 85 percent coverage or greater is recommended. Coaxial, triaxial, twinaxial, or quadraxial cables should be used, wherever appropriate, with their shields connected to ground at a single point or multiple points, depending upon the purpose of the shielding. *[Figure 9-113]* The airframe grounded structure may also be used as an EMI shield.

Figure 9-113. *Shielded wire harness for flight control.*

Wire Substitutions

When a replacement wire is required in the repair and modification of existing aircraft, the maintenance manual for that aircraft must first be reviewed to determine if the original aircraft manufacturer (OAM) has approved any substitution. If not, then the manufacturer must be contacted for an acceptable replacement.

Areas Designated as Severe Wind and Moisture Problem (SWAMP)

SWAMP areas differ from aircraft to aircraft but are usually wheel wells, near wing flaps, wing folds, pylons, and other exterior areas that may have a harsh environment. Wires in these areas have often an exterior jacket to protect them from the environment. Wires for these applications often have design features incorporated into their construction that may make the wire unique; therefore, an acceptable substitution may be difficult, if not impossible, to find. It is very important to use the wire type recommended in the aircraft manufacturer's maintenance handbook. Insulation or jacketing varies according to the environment. *[Figure 9-114]*

Figure 9-114. *Wire harness with protective jacket.*

Wire Size Selection

Wire is manufactured in sizes according to a standard known as the American wire gauge (AWG). As shown in *Figure 9-115*, the wire diameters become smaller as the gauge numbers become larger. Typical wire sizes range from a number 40 to number 0000.

Gauge numbers are useful in comparing the diameter of wires, but not all types of wire or cable can be measured accurately with a gauge. Larger wires are usually stranded to increase their flexibility. In such cases, the total area can be determined by multiplying the area of one strand (usually computed in circular mils when diameter or gauge number is known) by the number of strands in the wire or cable.

Several factors must be considered in selecting the size of wire for transmitting and distributing electric power.

1. Wires must have sufficient mechanical strength to allow for service conditions.
2. Allowable power loss (I2 R loss) in the line represents electrical energy converted into heat. The use of large conductors reduces the resistance and therefore the I2 R loss. However, large conductors are more expensive, heavier, and need more substantial support.
3. If the source maintains a constant voltage at the input to the lines, any variation in the load on the line causes a variation in line current and a consequent variation in the IR drop in the line. A wide variation in the IR drop in the line causes poor voltage regulation at the load. The obvious remedy is to reduce either current or resistance. A reduction in load current lowers the amount of power being transmitted, whereas a reduction in line resistance increases the size and weight of conductors required. A compromise is generally reached whereby the voltage variation at the load is within tolerable limits and the weight of line conductors is not excessive.
4. When current is drawn through the conductor, heat is generated. The temperature of the wire rises until the heat radiated, or otherwise dissipated, is equal to the heat generated by the passage of current through the line. If the conductor is insulated, the heat generated in the conductor is not so readily removed as it would be if the conductor were not insulated. Thus, to protect the insulation from too much heat, the current through the conductor must be maintained below a certain value. When electrical conductors are installed in locations where the ambient temperature is relatively high, the heat generated by external sources constitutes an appreciable part of the total conductor heating. Allowance must be made for the influence of external heating on the allowable conductor current, and each case has its own specific limitations. The maximum allowable operating temperature of insulated conductors varies with the type of conductor insulation being used.

If it is desirable to use wire sizes smaller than #20, particular attention should be given to the mechanical strength and installation handling of these wires (e.g., vibration, flexing, and termination). Wires containing less than 19 strands must not be used. Consideration should be given to the use of high-strength alloy conductors in small-gauge wires to increase mechanical strength. As a general practice, wires smaller than size #20 should be provided with additional clamps and be grouped with at least three other wires. They should also have additional support at terminations, such as connector grommets, strain relief clamps, shrinkable sleeving, or telescoping bushings. They should not be used in

Cross Section				Ohms per 1,000 ft	
Gauge Number	Diameter (mils)	Circular (mils)	Square inches	25 °C (77 °F)	65 °C (149 °F)
0000	460.0	212,000.0	0.166	0.0500	0.0577
000	410.0	168,000.0	0.132	0.0630	0.0727
00	365.0	133,000.0	0.105	0.0795	0.0917
0	325.0	106,000.0	0.0829	0.100	0.166
1	289.0	83,700.0	0.0657	0.126	0.146
2	258.0	66,400.0	0.0521	0.159	0.184
3	229.0	52,600.0	0.0413	0.201	0.232
4	204.0	41,700.0	0.0328	0.253	0.292
5	182.0	33,100.0	0.0260	0.319	0.369
6	162.0	26,300.0	0.0206	0.403	0.465
7	144.0	20,800.0	0.0164	0.508	0.586
8	128.0	16,500.0	0.0130	0.641	0.739
9	114.0	13,100.0	0.0103	0.808	0.932
10	102.0	10,400.0	0.00815	1.02	1.18
11	91.0	8,230.0	0.00647	1.28	1.48
12	81.0	6,530.0	0.00513	1.62	1.87
13	72.0	5,180.0	0.00407	2.04	2.36
14	64.0	4,110.0	0.00323	2.58	2.97
15	57.0	3,260.0	0.00256	3.25	3.75
16	51.0	2,580.0	0.00203	4.09	4.73
17	45.0	2,050.0	0.00161	5.16	5.96
18	40.0	1,620.0	0.00128	6.51	7.51
19	36.0	1,290.0	0.00101	8.21	9.48
20	32.0	1,020.0	0.000802	10.40	11.90
21	28.5	810.0	0.000636	13.10	15.10
22	25.3	642.0	0.000505	16.50	19.00
23	22.6	509.0	0.000400	20.80	24.00
24	20.1	404.0	0.000317	26.20	30.20
25	17.9	320.0	0.000252	33.00	38.10
26	15.9	254.0	0.000200	41.60	48.00
27	14.2	202.0	0.000158	52.50	60.60
28	12.6	160.0	0.000126	66.20	76.40
29	11.3	127.0	0.0000995	83.40	96.30
30	10.0	101.0	0.0000789	105.00	121.00
31	8.9	79.7	0.0000626	133.00	153.00
32	8.0	63.2	0.0000496	167.00	193.00
33	7.1	50.1	0.0000394	211.00	243.00
34	6.3	39.8	0.0000312	266.00	307.00
35	5.6	31.5	0.0000248	335.00	387.00
36	5.0	25.0	0.0000196	423.00	488.00
37	4.5	19.8	0.0000156	533.00	616.00
38	4.0	15.7	0.0000123	673.00	776.00
39	3.5	12.5	0.0000098	848.00	979.00
40	3.1	9.9	0.0000078	1,070.00	1,230.00

Figure 9-115. *American wire gauge for standard annealed solid copper wire.*

applications where they are subjected to excessive vibration, repeated bending, or frequent disconnection from screw termination. *[Figure 9-116]*

Current Carrying Capacity

In some instances, the wire may be capable of carrying more current than is recommended for the contacts of the related connector. In this instance, it is the contact rating that dictates the maximum current to be carried by a wire. Wires of larger gauge may need to be used to fit within the crimp range of connector contacts that are adequately rated for the current being carried. *Figure 9-117* gives a family of curves whereby the bundle derating factor may be obtained.

Maximum Operating Temperature

The current that causes a temperature steady state condition equal to the rated temperature of the wire should not be exceeded. Rated temperature of the wire may be based upon the ability of either the conductor or the insulation to withstand continuous operation without degradation.

1. Single Wire in Free Air

Determining a wiring system's current-carrying capacity begins with determining the maximum current that a given-sized wire can carry without exceeding the allowable temperature difference (wire rating minus ambient °C). The curves are based upon a single copper wire in free air. *[Figure 9-117]*

2. Wires in a Harness

When wires are bundled into harnesses, the current derived for a single wire must be reduced, as shown in *Figure 9-118.* The amount of current derating is a function of the number of wires in the bundle and the percentage of the total wire bundle capacity that is being used.

3. Harness at Altitude

Since heat loss from the bundle is reduced with increased altitude, the amount of current should be derated. *Figure 9-119* gives a curve whereby the altitude-derating factor may be obtained.

4. Aluminum Conductor Wire

When aluminum conductor wire is used, sizes should be selected on the basis of current ratings shown in *Figure 9-120.* The use of sizes smaller than #8 is discouraged. Aluminum wire should not be attached to engine mounted accessories or used in areas having corrosive fumes, severe vibration, mechanical stresses, or where there is a need for frequent disconnection. Use of aluminum wire is also discouraged for runs of less than 3 feet. Termination hardware should be of the type specifically designed for use with aluminum conductor wiring.

Computing Current Carrying Capacity

The following section presents some examples on how to calculate the load carrying capacity of aircraft electrical wire. The calculation is a step by step approach and several graphs are used to obtain information to compute the current carrying capacity of a particular wire.

Example 1

Assume a harness (open or braided) consisting of 10 wires, size 20, 200 °C rated copper, and 25 wires size 22, 200 °C rated copper, is installed in an area where the ambient temperature is 60 °C and the aircraft is capable of operating at a 35,000 foot altitude. Circuit analysis reveals that 7 of the 35 wires in the bundle ($7/35$ = 20 percent) are carrying power currents near or up to capacity.

Step 1—Refer to the single wire in free air curves in *Figure 9-114.* Determine the change of temperature of the wire to determine free air ratings. Since the wire is in an ambient temperature of 60 °C and rated at 200 °C, the change of the temperature is 200 °C – 60 °C = 140 °C. Follow the 140 °C temperature difference horizontally until it intersects with wire size line on *Figure 9-113.* The free air rating for size 20 is 21.5 amps, and the free air rating for size 22 is 16.2 amps.

Step 2—Refer to the bundle derating curves in *Figure 9-118.* The 20 percent curve is selected since circuit analysis indicate that 20 percent or less of the wire in the harness would be carrying power currents and less than 20 percent of the bundle capacity would be used. Find 35 (on the horizontal axis), since there are 35 wires in the bundle, and determine a derating factor of 0.52 (on the vertical axis) from the 20 percent curve.

Step 3—Derate the size 22 free air rating by multiplying 16.2 by 0.52 to get 8.4 amps in harness rating. Derate the size 20 free air rating by multiplying 21.5 by 0.52 to get 11.2 amps in-harness rating.

Step 4—Refer to the altitude derating curve of *Figure 9-119.* Look for 35,000 feet (on the horizontal axis) since that is the altitude at which the aircraft is operating. Note that the wire must be derated by a factor of 0.86 (found on the vertical axis). Derate the size 22 harness rating by multiplying 8.4 amps by 0.86 to get 7.2 amps. Derate the size 20 harness rating by multiplying 11.2 amps by 0.86 to get 9.6 amps.

Step 5—To find the total harness capacity, multiply the total number of size 22 wires by the derated capacity (25 × 7.2 = 180.0 amps) and add to that the number of size 20 wires multiplied by the derated capacity (10 × 9.6 = 96.8 amps) and multiply the sum by the 20 percent harness capacity factor. Thus, the total harness capacity is (180.0 + 96.0) × 0.20 = 55.2 amps. It has been determined that the total harness

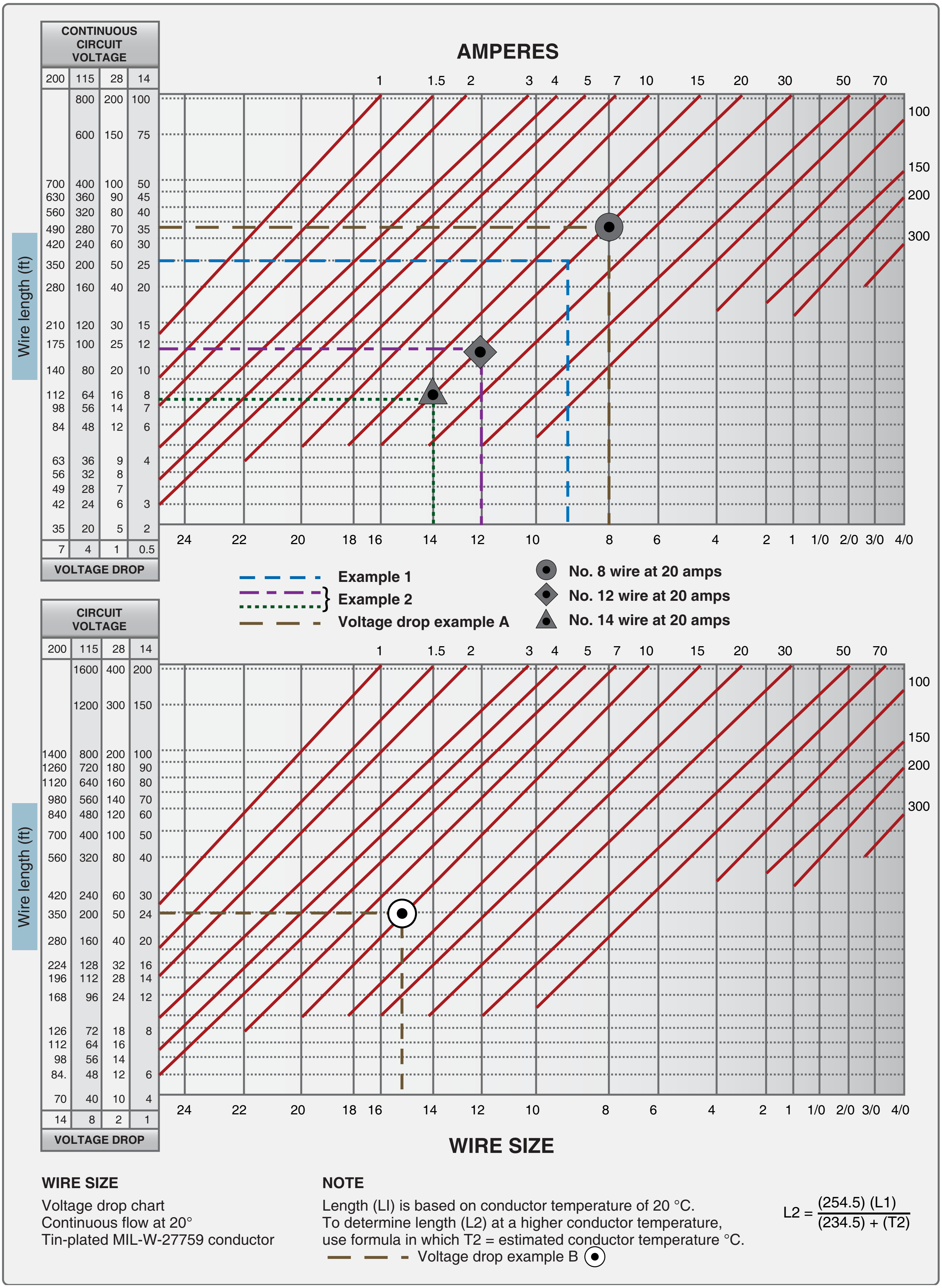


Figure 9-116. *Conductor chart, continuous (top) and intermittent flow (bottom).*

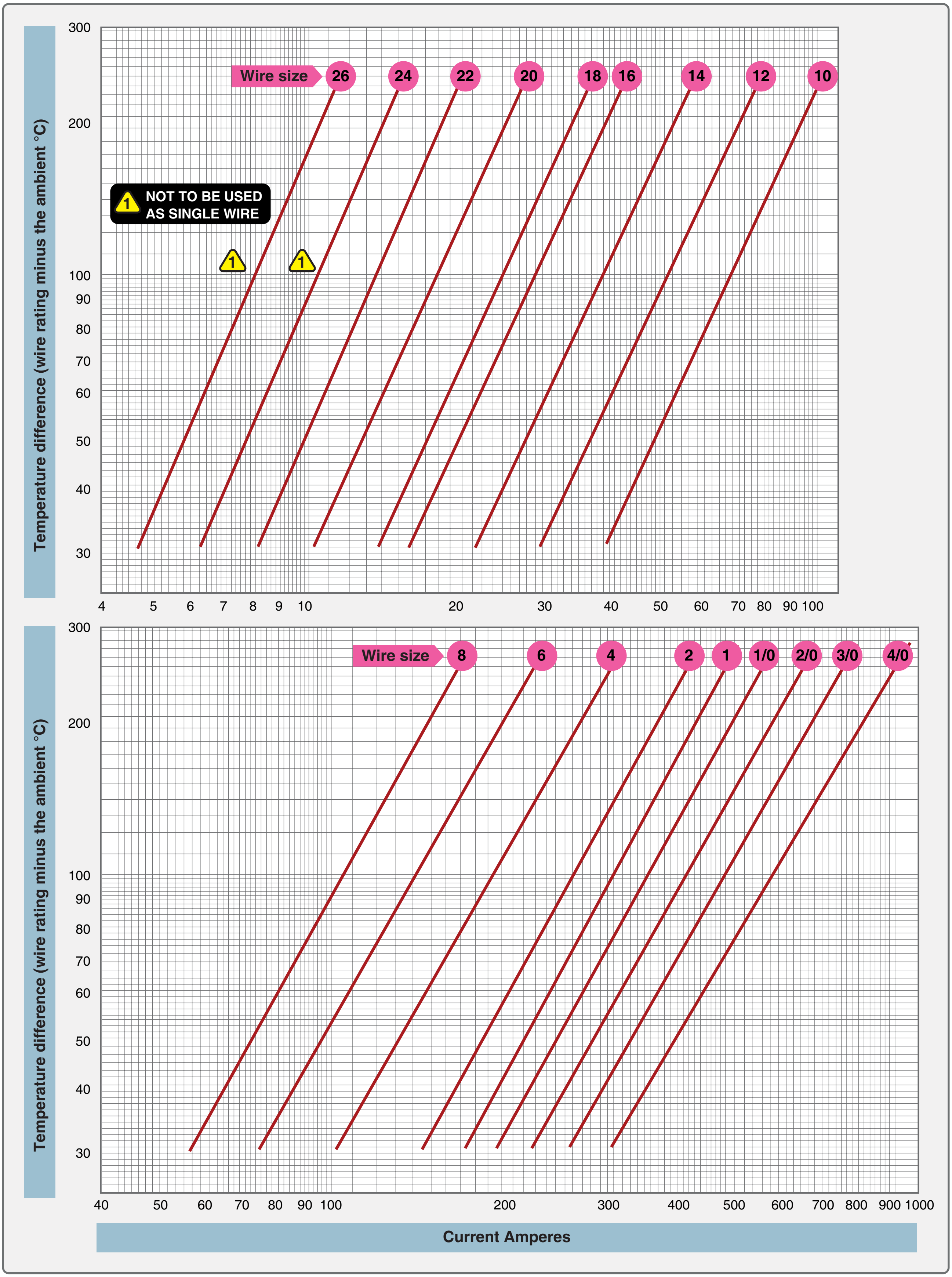


Figure 9-117. *Single copper wire in free air.*

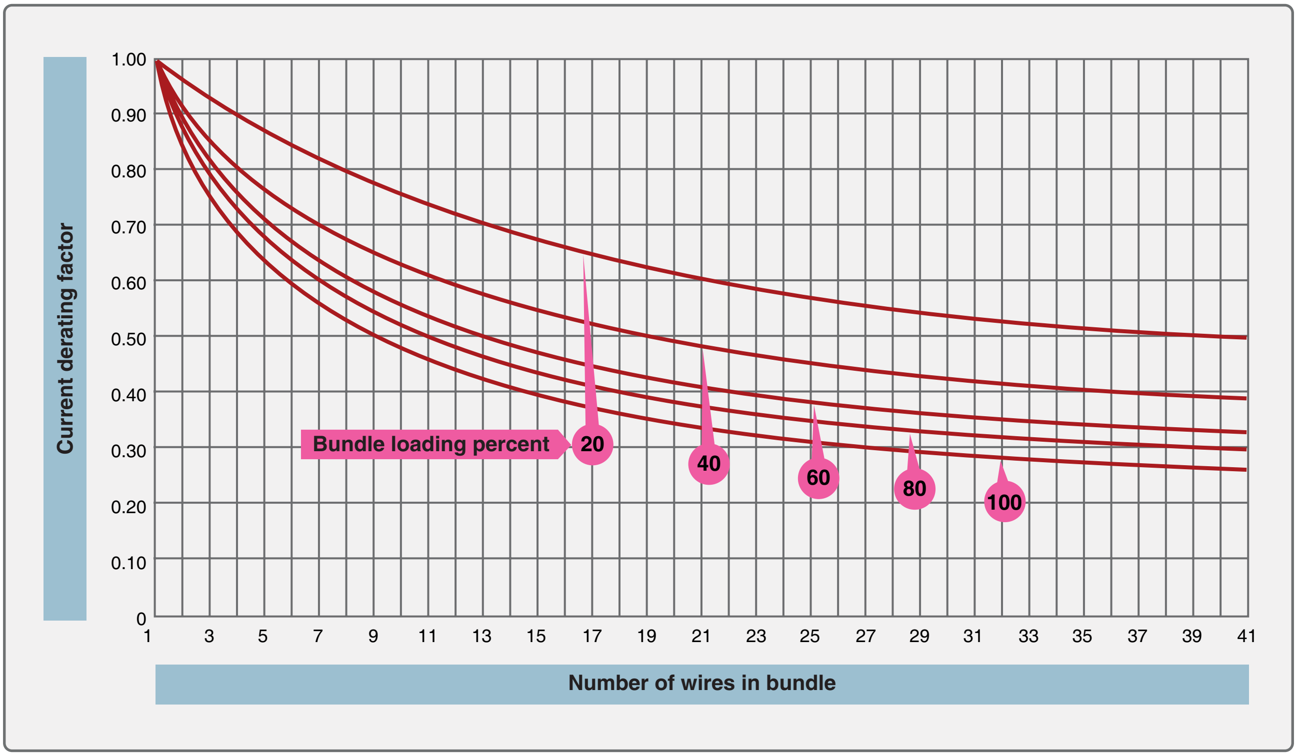


Figure 9-118. *Bundle derating curve.*

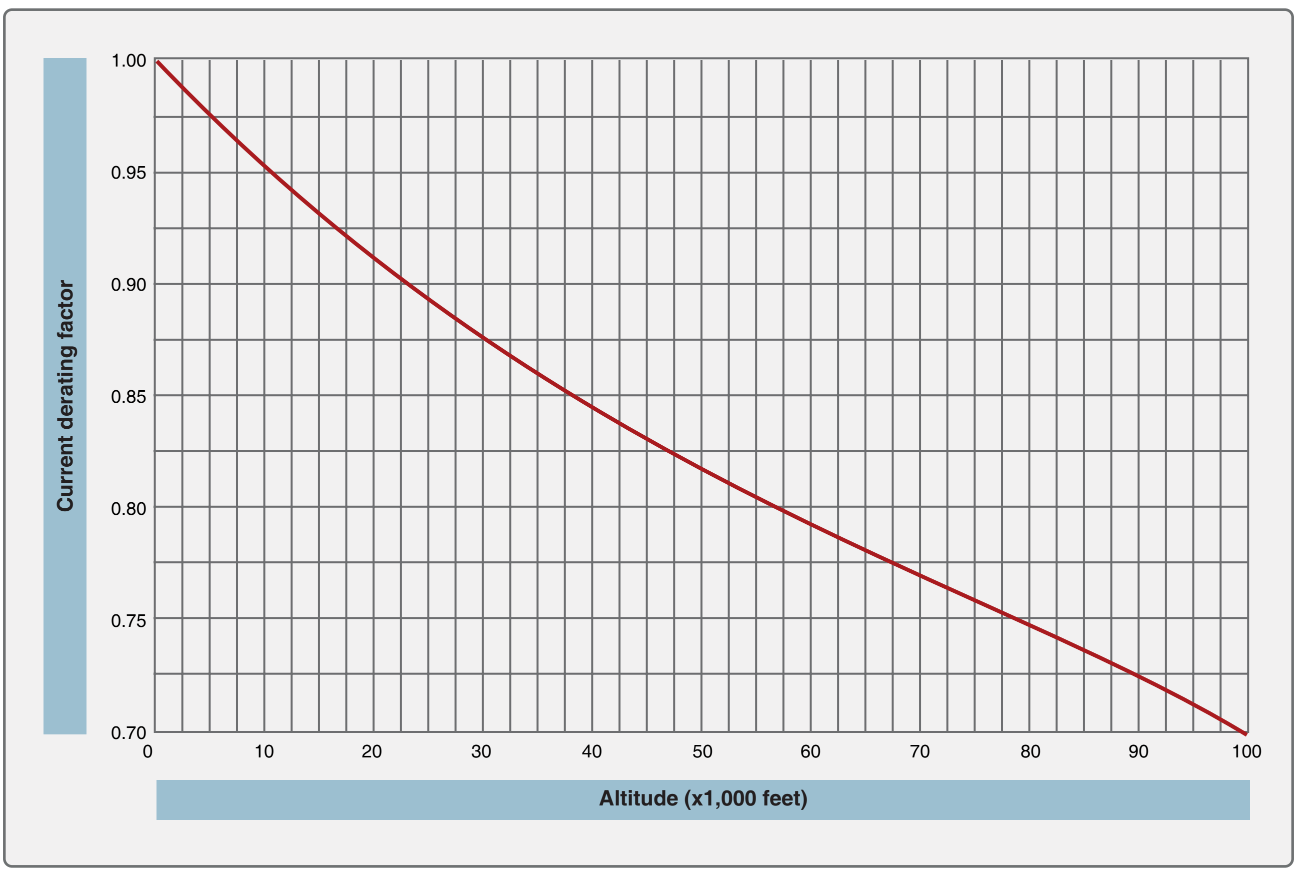


Figure 9-119. *Altitude derating curve.*

current should not exceed 55.2 A, size 22 wire should not carry more than 7.2 amps and size 20 wire should not carry more than 9.6 amps.

Step 6—Determine the actual circuit current for each wire in the bundle and for the whole bundle. If the values calculated in step 5 are exceeded, select the next larger size wire and repeat the calculations.

Example 2

Assume a harness (open or braided), consisting of 12 size 12, 200 °C rated copper wires, is operated in an ambient temperature of 25 °C at sea level and 60 °C at a 20,000-foot altitude. All 12 wires are operated at or near their maximum capacity.

Step 1—Refer to the single wire in free air curve in *Figure 9-117*, determine the temperature difference of the wire to determine free air ratings. Since the wire is in ambient temperature of 25 °C and 60 °C and is rated at 200 °C, the temperature differences are 200 °C – 25 °C = 175 °C and 200 °C – 60 °C = 140 °C, respectively. Follow the 175 °C and the 140 °C temperature difference lines on *Figure 9-116* until each intersects wire size line. The free air ratings of size 12 are 68 amps and 59 amps, respectively.

Step 2—Refer to the bundling derating curves in *Figure 9-120*. The 100 percent curve is selected because we know all 12 wires are carrying full load. Find 12 (on the horizontal axis) since there are 12 wires in the bundle and determine a derating factor of 0.43 (on the vertical axis) from the 100 percent curve.

Wire size	Continuous duty current (amp) wires in bundles, groups, or harnesses or conduits		Max. resistance ohms/1000feet
	Wire conductor temperature rating		
	@ 105 °C	@ 150 °C	@ 20 °C
#8	30	45	1.093
#6	40	61	0.641
#4	54	82	0.427
#2	76	113	0.268
#1	90	133	0.214
#0	102	153	0.169
#00	117	178	0.133
#000	138	209	0.109
#0000	163	248	0.085

Figure 9-120. *Current-carrying capacity and resistance of aluminum wire.*

Step 3—Derate the size #12 free air ratings by multiplying 68 amps and 61 amps by 0.43 to get 29.2 amps and 25.4 amps, respectively.

Step 4—Refer to the altitude derating curve of *Figure 9-119*, look for sea level and 20,000 feet (on the horizontal axis) since these are the conditions at which the load is carried. The wire must be derated by a factor of 1.0 and 0.91, respectively.

Step 5—Derate the size 12 in a bundle ratings by multiplying 29.2 amps at sea level and 25.4 amps at 20,000 feet by 1.0 and 0.91, respectively to obtain 29.2 amps and 23.1 amps. The total bundle capacity at sea level and 25 °C ambient temperature is 29.2 × 12=350.4 amps. At 20,000 feet and 60 °C ambient temperature, the bundle capacity is 23.1 × 12=277.2 amps. Each size 12 wire can carry 29.2 amps at sea level, 25 °C ambient temperature or 23.1 amps at 20,000 feet and 60 °C ambient temperature.

Step 6—Determine the actual circuit current for each wire in the bundle and for the bundle. If the values calculated in Step 5 are exceeded, select the next larger size wire and repeat the calculations.

Allowable Voltage Drop

The voltage drop in the main power wires from the generation source or the battery to the bus should not exceed 2 percent of the regulated voltage when the generator is carrying rated current or the battery is being discharged at the 5-minute rate. The tabulation shown in *Figure 9-121* defines the maximum acceptable voltage drop in the load circuits between the bus and the utilization equipment ground.

Nominal system voltage	Allowable voltage drop during continuous operation	Intermittent operation
14	0.5	1
28	1	2
115	4	8
200	7	14

Figure 9-121. *Tabulation chart (allowable voltage drop between bus and utilization equipment ground).*

The resistance of the current return path through the aircraft structure is generally considered negligible. However, this is based on the assumption that adequate bonding to the structure or a special electric current return path has been provided that is capable of carrying the required electric current with a negligible voltage drop. To determine circuit resistance, check the voltage drop across the circuit. If the voltage drop does not exceed the limit established by the aircraft or product manufacturer, the resistance value for the circuit may be considered satisfactory. When checking a circuit, the input voltage should be maintained at a constant value. *Figures 9-122* and *9-123* show formulas that may be used to determine electrical resistance in wires and some typical examples.

Voltage drop	Run lengths (feet)	Circuit current (amps)	Wire size from chart	Check calculated voltage drop (VD) = (resistance/feet) (length) (current)
1	107	20	No. 6	VD = (0.00044 ohms/feet) (107 x 20) = 0.942
0.5	90	20	No. 4	VD = (0.00028 ohms/feet) (90 x 20) = 0.504
4	88	20	No. 12	VD = (0.00202 ohms/feet) (88 x 20) = 3.60
7	100	20	No. 14	VD = (0.00306 ohms/feet) (100 x 20) = 6.12

Figure 9-122. *Determining required tin-plated copper wire size and checking voltage drop.*

Maximum Voltage drop	Wire size	Circuit current (amps)	Maximum wire run length (feet)	Check calculated voltage drop (VD) = (resistance/feet) (length) (current)
1	No. 10	20	39	VD = (0.00126 ohms/feet) (39 x 20) = 0.98
0.5	---		19.5	VD = (0.00126 ohms/feet) (19.5 x 20) = 0.366
4	---		156	VD = (0.00126 ohms/feet) (156 x 20) = 3.93
7	---		273	VD = (0.00126 ohms/feet) (273 x 20) = 6.88

Figure 9-123. *Determining maximum tin-plated copper wire length and checking voltage drop.*

The following formula can be used to check the voltage drop. The resistance/ft can be found in *Figures 9-122* and *9-123* for the wire size.

Calculated Voltage drop (VD) = resistance/ft × length × current

Electric Wire Chart Instructions

To select the correct size of electrical wire, two major requirements must be met:

1. The wire size should be sufficient to prevent an excessive voltage drop while carrying the required current over the required distance. *[Figure 9-121]*
2. The size should be sufficient to prevent overheating of the wire carrying the required current. (See Maximum Operating Temperature earlier in this chapter for computing current carrying capacity methods.)

To meet the two requirements for selecting the correct wire size using *Figure 9-116*, the following must be known:

1. The wire length in feet.
2. The number of amperes of current to be carried.
3. The allowable voltage drop permitted.
4. The required continuous or intermittent current.
5. The estimated or measured conductor temperature.
6. Is the wire to be installed in conduit and/or bundle?
7. Is the wire to be installed as a single wire in free air?

Example A.
Find the wire size in *Figure 9-116* using the following known information:

1. The wire run is 50 feet long, including the ground wire.
2. Current load is 20 amps.
3. The voltage source is 28 volts from bus to equipment.
4. The circuit has continuous operation.
5. Estimated conductor temperature is 20 °C or less. The scale on the left of the chart represents maximum wire length in feet to prevent an excessive voltage drop for a specified voltage source system (e.g., 14V, 28V, 115V, 200V). This voltage is identified at the top of scale and the corresponding voltage drop limit for continuous operation at the bottom. The scale (slant lines) on top of the chart represents amperes. The scale at the bottom of the chart represents wire gauge.

Step 1—From the left scale, find the wire length 50 feet under the 28V source column.

Step 2—Follow the corresponding horizontal line to the right until it intersects the slanted line for the 20-amp load.

Step 3—At this point, drop vertically to the bottom of the chart. The value falls between No. 8 and No. 10. Select the next larger size wire to the right, in this case No. 8. This is the smallest size wire that can be used without exceeding the voltage drop limit expressed at the bottom of the left scale. This example is plotted on the wire chart in *Figure 9-116*. Use *Figure 9-116 (top)* for continuous flow and *Figure 9-116 (bottom)* for intermittent flow.

Example B.
Find the wire size in *Figure 9-116* using the following known information:

1. The wire run is 200 feet long, including the ground wire.

2. Current load is 10 amps.
3. The voltage source is 115 volts from bus to equipment.
4. The circuit has intermittent operation.

Step 1—From the left scale, find the wire length of 200 feet under the 115V source column.

Step 2—Follow the corresponding horizontal line to the right until it intersects the slanted line for the 10 amp load.

Step 3—At this point, drop vertically to the bottom of the chart. The value falls between No. 16 and No. 14. Select the next larger size wire to the right—in this case, No. 14. This is the smallest size wire that can be used without exceeding the voltage drop limit expressed at the bottom of the left scale.

Wire Identification

The proper identification of electrical wires and cables with their circuits and voltages is necessary to provide safety of operation, safety to maintenance personnel, and ease of maintenance. All wire used on aircraft must have its type identification imprinted along its length. It is common practice to follow this part number with the five digit/letter Commercial and Government Entity (CAGE) code identifying the wire manufacturer. You can identify the performance capabilities of existing installed wire you need to replace, and avoid the inadvertent use of a lower performance and unsuitable replacement wire.

Placement of Identification Markings

Identification markings should be placed at each end of the wire and at 15-inch maximum intervals along the length of the wire. Wires less than 3 inches in length need not be identified. Wires 3 to 7 inches in length should be identified approximately at the center. Added identification marker sleeves should be located so that ties, clamps, or supporting devices need not be removed to read the identification. The wire identification code must be printed to read horizontally (from left to right) or vertically (from top to bottom). The two methods of marking wire or cable are as follows:

1. Direct marking is accomplished by printing the cable's outer covering. *[Figure 9-124B]*
2. Indirect marking is accomplished by printing a heat-shrinkable sleeve and installing the printed sleeve on the wire or cables outer covering. Indirectly-marked wire or cable should be identified with printed sleeves at each end and at intervals not longer than 6 feet. *[Figure 9-125]* The individual wires inside a cable should be identified within 3 inches of their termination. *[Figure 9-124A]*

Types of Wire Markings

The preferred method is to mark directly on the wire without causing insulation degradation. Teflon-coated wires, shielded wiring, multiconductor cable, and thermocouple wires usually require special sleeves to carry identification marks. There are some special wire marking machines available that can be used to stamp directly on the type wires mentioned above. Whatever method of marking is used, the marking should be legible and the color should contrast with the wire insulation or sleeve.

Several different methods can be used to mark directly on the wire: hot stamp marking, ink jet printers, and laser jet printers. *[Figure 9-126]* The hot stamp method can damage the insulation of a newer type of wire that utilizes thin

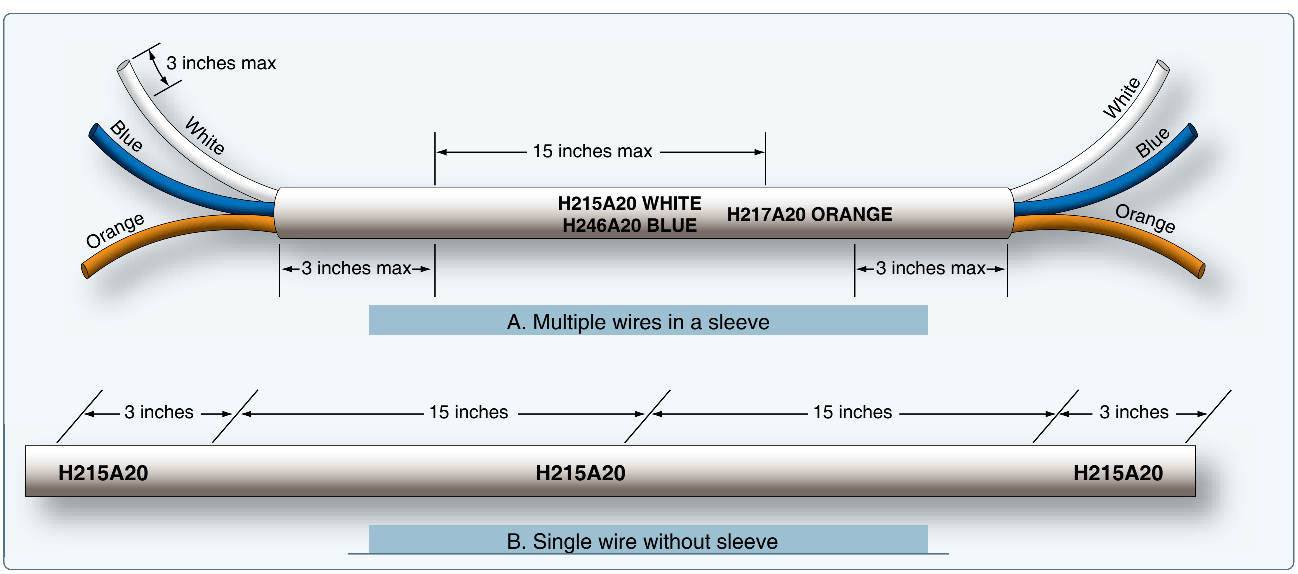


Figure 9-124. *Wire markings for single wire without sleeve.*

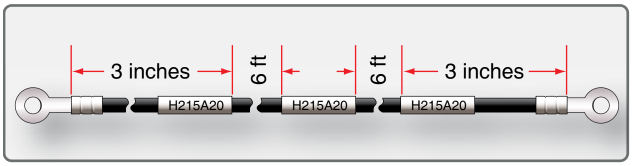


Figure 9-125. *Spacing of printed identification marks (indirect marking).*

Figure 9-126. *Laser wire printer.*

insulators. Fracture of the insulation wall and penetration to the conductor of these materials by the stamping dies have occurred. Later in service, when these openings have been wetted by various fluids or moisture, serious arcing and surface tracking have damaged wire bundles.

Identification sleeves can be used if the direct marking on the wire is not possible. *[Figure 9-127]*

Figure 9-127. *Alternate method of identifying wire bundles.*

Flexible sleeving, either clear or opaque, is satisfactory for general use. When color-coded or striped component wire is used as part of a cable, the identification sleeve should specify which color is associated with each wire identification code. Identification sleeves are normally used for identifying the following types of wire or cable: unjacketed shielded wire, thermocouple wire, coaxial cable, multiconductor cable, and high temperature wire. In most cases, identification tape can be used in place of sleeving. For sleeving exposed to high temperatures (over 400 °F), materials, such as silicone fiberglass, should be used. Polyolefin sleeving should be used in areas where resistance to solvent and synthetic hydraulic fluids is necessary. Sleeves may be secured in place with cable ties or by heat shrinking. The identification sleeving for various sizes of wire is shown in *Figure 9-128*.

Wire size		Sleeving size	
AN #	**AL #**	**No.**	**Nominal ID (inch)**
24		12	0.085
22		11	0.095
20		10	0.106
18		9	0.118
16		8	0.113
14		7	0.148
12		6	0.166
10		4	0.208
8	8	2	0.263
6	6	0	0.330
4	4	3/8 inch	0.375
2	2	1/2 inch	0.500
1	1	1/2 inch	0.500
0	0	5/8 inch	0.625
00	00	5/8 inch	0.625
000	000	3/4 inch	0.750
0000	0000	3/4 inch	0.750

Figure 9-128. *Recommended size of identification sleeving.*

Wire Installation and Routing

Open Wiring

Interconnecting wire is used in point-to-point open harnesses, normally in the interior or pressurized fuselage, with each wire providing enough insulation to resist damage from handling and service exposure. Electrical wiring is often installed in aircraft without special enclosing means. This practice is known as open wiring and offers the advantages of ease of maintenance and reduced weight.

Wire Groups and Bundles and Routing

Wires are often installed in bundles to create a more organized installation. These wire bundles are often called wire harnesses. Wire harnesses are often made in the factory or electrical shop on a jig board so that the wire bundles could be preformed to fit into the aircraft. *[Figure 9-129]* As a result, each harness for a particular aircraft installation is identical in shape and length. The wiring harness could be covered by a shielding (metal braid) to avoid EMI. Grouping or bundling certain wires, such as electrically unprotected power wiring and wiring going to duplicate vital equipment, should be avoided. Wire bundles should generally be less than 75 wires, or 1½ to 2 inches in diameter where practicable. When several wires are grouped at junction boxes, terminal blocks, panels, etc., identity of the groups within a bundle can be retained.

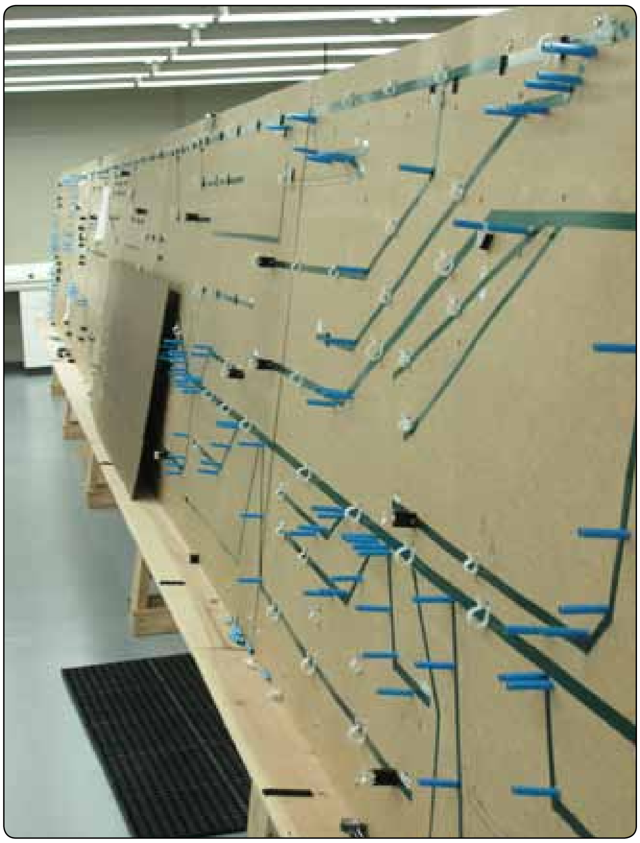


Figure 9-129. *Cable harness jig board.*

Slack in Wire Bundles

Wiring should be installed with sufficient slack so that bundles and individual wires are not under tension. Wires connected to movable or shock-mounted equipment should have sufficient length to allow full travel without tension on the bundle. Wiring at terminal lugs or connectors should have sufficient slack to allow two reterminations without replacement of wires. This slack should be in addition to the drip loop and the allowance for movable equipment. Normally, wire groups or bundles should not exceed ½ inch deflection between support points. *[Figure 9-130]* This measurement may be exceeded if there is no possibility of the wire group or bundle touching a surface that may cause abrasion. Sufficient slack should be provided at each end to permit replacement of terminals and ease of maintenance; prevent mechanical strain on the wires, cables, junctions, and supports; permit free movement of shock- and vibration-mounted equipment; and allow shifting of equipment, as necessary, to perform alignment, servicing, tuning, removal of dust covers, and changing of internal components while installed in aircraft.

Twisting Wires

When specified on the engineering drawing, or when accomplished as a local practice, parallel wires must sometimes be twisted. The following are the most common examples:

1. Wiring in the vicinity of magnetic compass or flux valve
2. Three-phase distribution wiring
3. Certain other wires (usually radio wiring) as specified on engineering drawings

Twist the wires so they lie snugly against each other, making approximately the number of twists per foot as shown in *Figure 9-131*. Always check wire insulation for damage after twisting. If the insulation is torn or frayed, replace the wire.

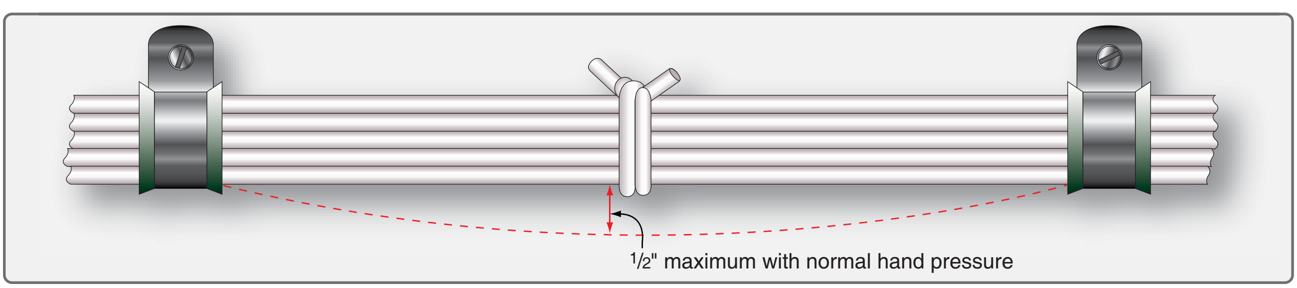


Figure 9-130. *Slack between supports of a cable harness.*

Gauge #	22	20	18	16	14	12	10	8	6	4
2 Wires	10	10	9	8	7 1/2	7	6 1/2	6	5	4
3 Wires	10	10	8 1/2	7	6 1/2	6	5 1/2	5	4	3

Figure 9-131. *Recommended number of wire twists per foot.*

Spliced Connections In Wire Bundles

Splicing is permitted on wiring as long as it does not affect the reliability and the electromechanical characteristics of the wiring. Splicing of power wires, coaxial cables, multiplex bus, and large-gauge wire must have approved data. Splicing of electrical wire should be kept to a minimum and avoided entirely in locations subject to extreme vibrations. Splicing of individual wires in a group or bundle should have engineering approval, and the splice(s) should be located to allow periodic inspection.

Many types of aircraft splice connector are available for use when splicing individual wires. Use of a self-insulated splice connector is preferred; however, a non-insulated splice connector may be used provided the splice is covered with plastic sleeving that is secured at both ends. Environmentally sealed splices that conform to MIL-T-7928 provide a reliable means of splicing in SWAMP areas. However, a non-insulated splice connector may be used, provided the splice is covered with dual-wall shrink sleeving of a suitable material.

There should be no more than one splice in any one wire segment between any two connectors or other disconnect points. Exceptions include when attaching to the spare pigtail lead of a potted connector, when splicing multiple wires to a single wire, when adjusting wire size to fit connector contact crimp barrel size, and when required to make an approved repair.

Splices in bundles must be staggered to minimize any increase in the size of the bundle, preventing the bundle from fitting into its designated space or causing congestion that adversely affects maintenance. *[Figure 9-132]*

Splices should not be used within 12 inches of a termination device, except when attaching to the pigtail spare lead of a potted termination device, to splice multiple wires to a single wire, or to adjust the wire sizes so that they are compatible with the contact crimp barrel sizes.

Bend Radii

The minimum radius of bends in wire groups or bundles must not be less than 10 times the outside diameter of the largest wire or cable, except that at the terminal strips where wires break out at terminations or reverse direction in a bundle. Where the wire is suitably supported, the radius may be three times the diameter of the wire or cable. Where it is not practical to install wiring or cables within the radius requirements, the bend should be enclosed in insulating tubing. The radius for thermocouple wire should be done in accordance with the manufacturer's recommendation and shall be sufficient to avoid excess losses or damage to the cable. Ensure that RF cables (e.g., coaxial and triaxial) are bent at a radius of no less than six times the outside diameter of the cable.

Protection Against Chafing

Wires and wire groups should be protected against chafing or abrasion in those locations where contact with sharp surfaces or other wires would damage the insulation, or chafing could occur against the airframe or other components. Damage to the insulation can cause short circuits, malfunction, or inadvertent operation of equipment.

Protection Against High Temperature

Wiring must be routed away from high-temperature equipment and lines to prevent deterioration of insulation. Wires must be rated so the conductor temperature remains within the wire specification maximum when the ambient temperature and heat rise related to current-carrying capacity are taken into account. The residual heating effects caused by exposure to sunlight when aircraft are parked for extended periods should also be taken into account. Wires, such as those used in fire detection, fire extinguishing, fuel shutoff, and fly-by-wire flight control systems that must operate during and after a fire, must be selected from types that are qualified to provide circuit integrity after exposure to fire for

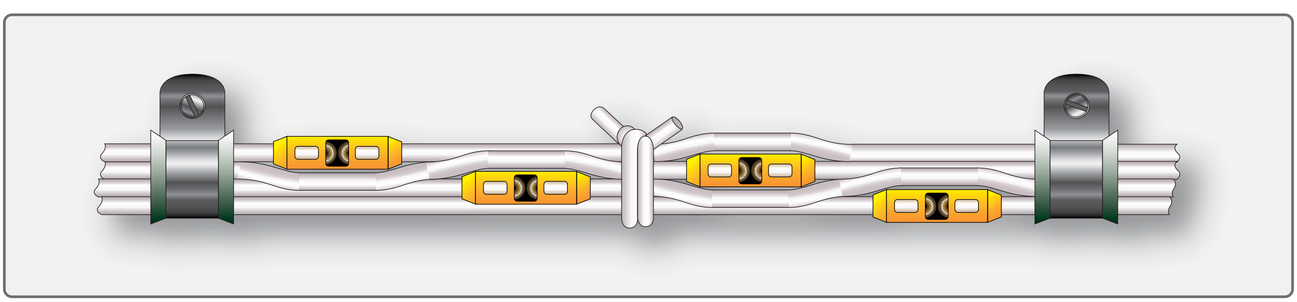


Figure 9-132. *Staggered splices in wire bundle.*

a specified period. Wire insulation deteriorates rapidly when subjected to high temperatures.

Separate wires from high-temperature equipment, such as resistors, exhaust stacks, heating ducts, to prevent insulation breakdown. Insulate wires that must run through hot areas with a high-temperature insulation material, such as fiberglass or PTFE. Avoid high-temperature areas when using cables with soft plastic insulation, such as polyethylene, because these materials are subject to deterioration and deformation at elevated temperatures. Many coaxial cables have this type of insulation.

Protection Against Solvents and Fluids

An arcing fault between an electrical wire and a metallic flammable fluid line may puncture the line and result in a fire. Every effort must be made to avoid this hazard by physical separation of the wire from lines and equipment containing oxygen, oil, fuel, hydraulic fluid, or alcohol. Wiring must be routed above these lines and equipment with a minimum separation of 6 inches or more whenever possible. When such an arrangement is not practicable, wiring must be routed so that it does not run parallel to the fluid lines. A minimum of 2 inches must be maintained between wiring and such lines and equipment, except when the wiring is positively clamped to maintain at least ½-inch separation, or when it must be connected directly to the fluid-carrying equipment. Install clamps as shown in *Figure 9-133*. These clamps should not be used as a means of supporting the wire bundle. Additional clamps should be installed to support the wire bundle and the clamps fastened to the same structure used to support the fluid line(s) to prevent relative motion.

Figure 9-133. *Positive separation of wire and fluid lines and wire clamps.*

Wires, or groups of wires, should enter a junction box, or terminate at a piece of equipment in an upward direction where practicable. Ensure that a trap, or drip loop, is provided to prevent fluids or condensation from running into wire or cable ends that slope downward toward a connector, terminal block, panel, or junction block. A drip loop is an area where the wire(s) are made to travel downward and then up to the connector. *[Figure 9-134]* Fluids and moisture will flow along the wires to the bottom of the loop and be trapped there to drip or evaporate without affecting electrical conductivity in the wire, junction, or connected device.

Figure 9-134. *Drip loop.*

Where wires must be routed downwards to a junction box or electrical unit and a drip loop is not possible, the entrance should be sealed according to manufacturer's specifications to prevent moisture from entering the box/unit. Wires and cables installed in bilges and other locations where fluids collect must be routed as far from the lowest point as possible or otherwise be provided with a moisture-proof covering.

Protection of Wires in Wheel Well Areas

Wires located on landing gear and in the wheel well area can be exposed to many hazardous conditions if not suitably protected. Where wire bundles pass flex points, there must not be any strain on attachments or excessive slack when parts are fully extended or retracted. The wiring and protective tubing must be inspected frequently and replaced at the first sign of wear.

Wires should be routed so that fluids drain away from the connectors. When this is not practicable, connectors must be potted. Wiring which must be routed in wheel wells or other external areas must be given extra protection in the form of harness jacketing and connector strain relief. Conduits or flexible sleeving used to protect wiring must be equipped with drain holes to prevent entrapment of moisture.

The technician should check during inspections that wires and cables are adequately protected in wheel wells and other areas where they may be exposed to damage from impact of rocks, ice, mud, etc. (If rerouting of wires or cables is not practical, protective jacketing may be installed). This type of installation must be held to a minimum.

Clamp Installation

Wires and wire bundles must be supported by clamps or plastic cable straps. *[Figure 9-135]* Clamps and other primary support devices must be constructed of materials that are compatible with their installation and environment, in terms of temperature, fluid resistance, exposure to ultraviolet (UV) light, and wire bundle mechanical loads. They should be spaced at intervals not exceeding 24 inches. Clamps on wire bundles should be selected so that they have a snug fit without pinching wires *[Figures 9-136* through *9-138]*

Figure 9-135. *Wire clamps.*

Caution: The use of metal clamps on coaxial RF cables may cause problems, if clamp fit is such that RF cable's original cross section is distorted.

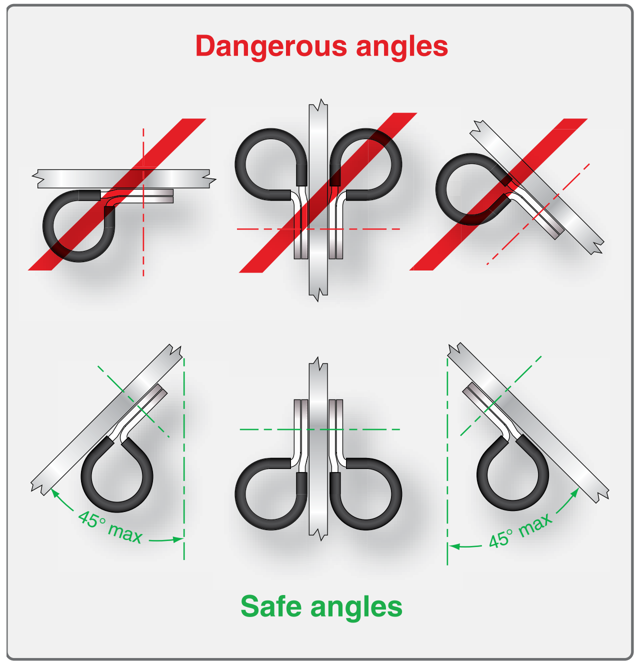


Figure 9-136. *Safe angle for cable clamps.*

Clamps on wire bundles should not allow the bundle to move through the clamp when a slight axial pull is applied. Clamps on RF cables must fit without crushing and must be snug enough to prevent the cable from moving freely through the clamp, but may allow the cable to slide through the clamp when a light axial pull is applied. The cable or wire bundle may be wrapped with one or more turns of electrical tape when required to achieve this fit. Plastic clamps or cable ties must not be used where their failure could result in interference with movable controls, wire bundle contact with movable equipment, or chafing damage to essential or unprotected wiring. They must not be used on vertical runs where inadvertent slack migration could result in chafing or other damage. Clamps must be installed with their attachment hardware positioned above them, wherever practicable, so that they are unlikely to rotate as the result of wire bundle weight or wire bundle chafing. *[Figure 9-136]*

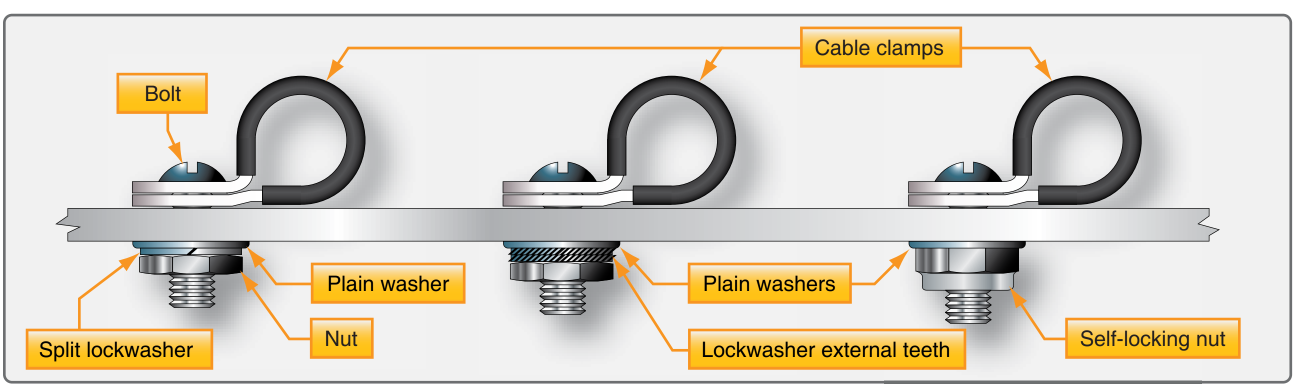


Figure 9-137. *Typical mounting hardware for MS-21919 cable clamps.*

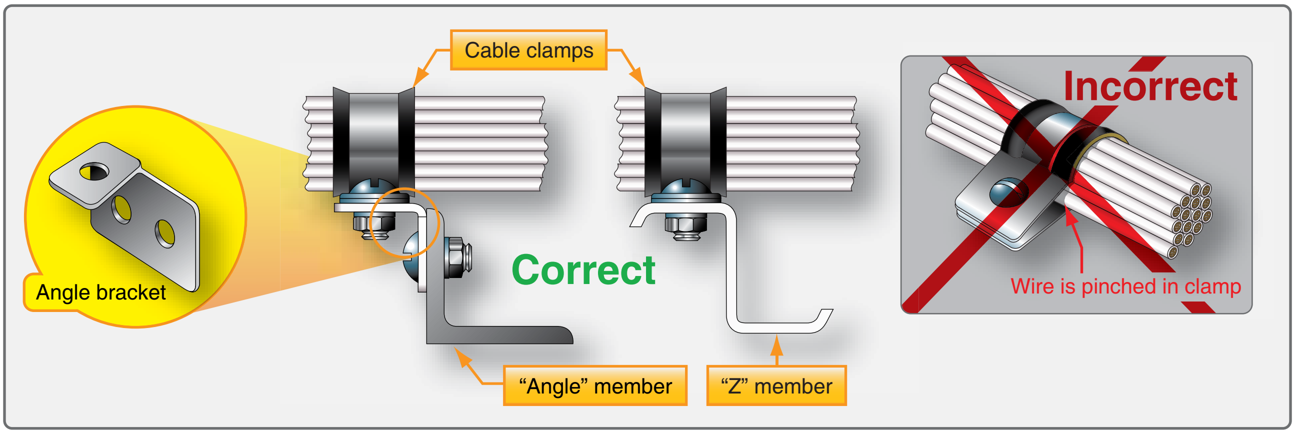


Figure 9-138. *Installing cable clamp to structure.*

Clamps lined with nonmetallic material should be used to support the wire bundle along the run. Tying may be used between clamps, but should not be considered as a substitute for adequate clamping. Adhesive tapes are subject to age deterioration and, therefore, are not acceptable as a clamping means. *[Figure 9-137]*

The back of the clamp, whenever practical, should be rested against a structural member. *[Figure 9-138]* Stand-offs should be used to maintain clearance between the wires and the structure. Clamps must be installed in such a manner that the electrical wires do not come in contact with other parts of the aircraft when subjected to vibration. Sufficient slack should be left between the last clamp and the electrical equipment to prevent strain at the terminal and to minimize adverse effects on shock-mounted equipment. Where wires or wire bundles pass through bulkheads or other structural members, a grommet or suitable clamp should be provided to prevent abrasion.

When a wire bundle is clamped into position, if there is less than ⅜-inch of clearance between the bulkhead cutout and the wire bundle, a suitable grommet should be installed as indicated in *Figure 9-139*. The grommet may be cut at a 45° angle to facilitate installation, provided it is cemented in place and the slot is located at the top of the cutout.

Wire and Cable Clamp Inspection

Inspect wire and cable clamps for proper tightness. Where cables pass through structure or bulkheads, inspect for proper clamping and grommets. Inspect for sufficient slack between the last clamp and the electronic equipment to prevent strain at the cable terminals and to minimize adverse effects on shock-mounted equipment. Wires and cables are supported by suitable clamps, grommets, or other devices at intervals of not more than 24 inches, except when contained in troughs, ducts, or conduits. The supporting devices should be of a suitable size and type, with the wires and cables held securely in place without damage to the insulation.

Use metal stand-offs to maintain clearance between wires and structure. Tape or tubing is not acceptable as an alternative to stand-offs for maintaining clearance. Install phenolic blocks, plastic liners, or rubber grommets in holes, bulkheads, floors, or structural members where it is impossible to install off-angle clamps to maintain wiring separation. In such cases, additional protection in the form of plastic or insulating tape may be used.

Properly secure clamp retaining bolts so the movement of wires and cables is restricted to the span between the points of support and not on soldered or mechanical connections at terminal posts or connectors.

Movable Controls Wiring Precautions

Clamping of wires routed near movable flight controls must be attached with steel hardware and must be spaced so that failure of a single attachment point cannot result in interference with controls. The minimum separation between wiring and movable controls must be at least ½ inch when the bundle is displaced by light hand pressure in the direction of the controls.

Conduit

Conduit is manufactured in metallic and nonmetallic materials and in both rigid and flexible forms. Primarily, its purpose is for mechanical protection of cables or wires. Conduit size should be selected for a specific wire bundle application to allow for ease in maintenance, and possible future circuit expansion, by specifying the conduit inner diameter (ID) about 25 percent larger than the maximum diameter of the wire bundle. *[Figure 9-140]*

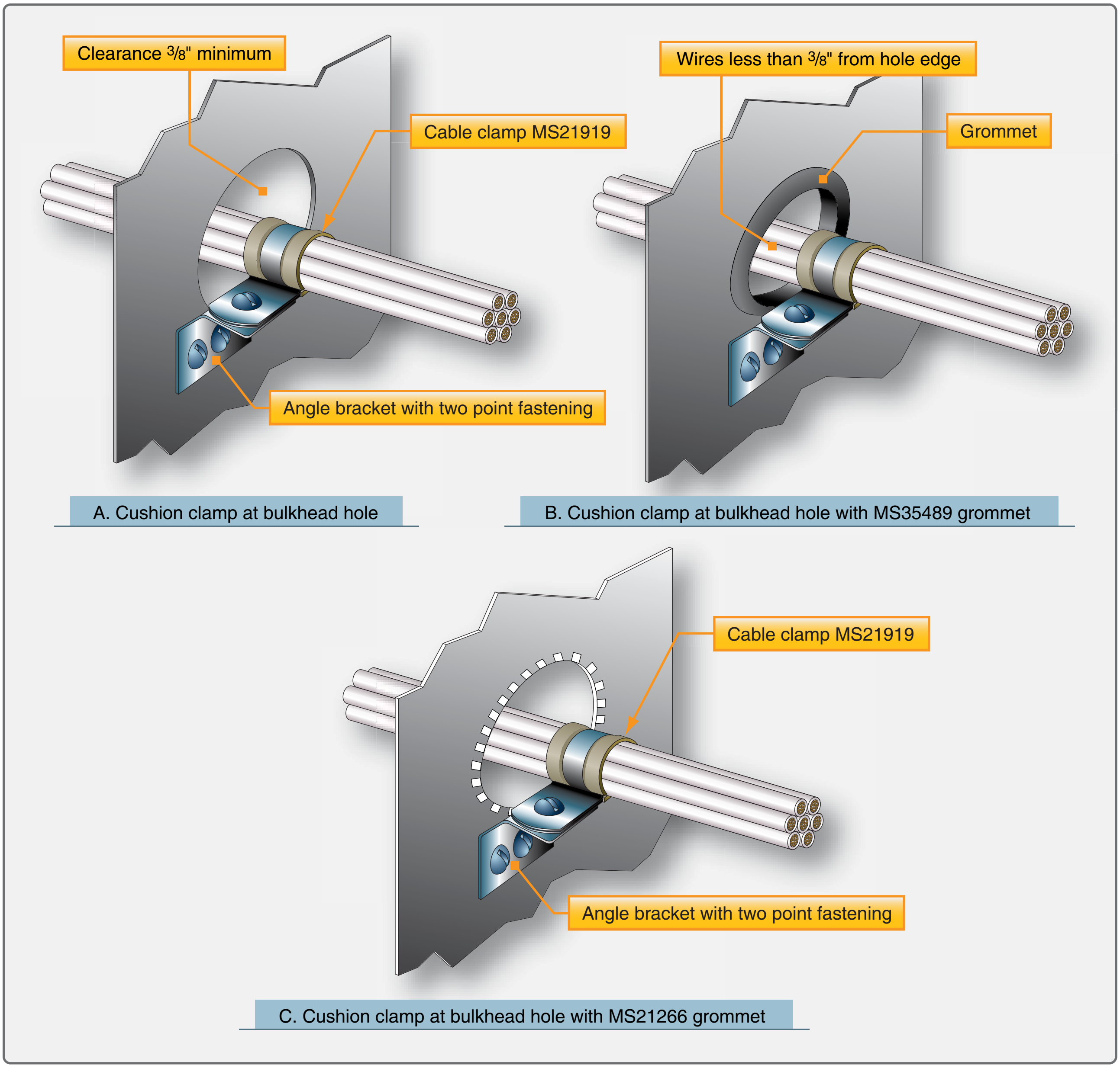


Figure 9-139. *Clamping at a bulkhead hole.*

Figure 9-140. *Flexible conduit.*

Conduit problems can be avoided by following these guidelines:

- Do not locate conduit where passengers or maintenance personnel might use it as a handhold or footstep.
- Provide drain holes at the lowest point in a conduit run. Drilling burrs should be carefully removed.
- Support conduit to prevent chafing against structure and to avoid stressing its end fittings.

Rigid Conduit

Damaged conduit sections should be repaired to preclude injury to the wires or wire bundle that may consume as much as 80 percent of the tube area. Minimum acceptable tube bend radii for rigid conduit are shown in *Figure 9-141*. Kinked or wrinkled bends in rigid conduits are not recommended and should be replaced. Tubing bends that have been flattened into an ellipse and have a minor diameter of less than 75 percent of the nominal tubing diameter should be replaced, because the tube area has been reduced by at least 10 percent. Tubing that has been formed and cut to final length should be deburred to prevent wire insulation damage. When installing replacement tube sections with fittings at both ends, care should be taken to eliminate mechanical strain.

Nominal tube OD (inches)	Minimum bend radius (inches)
1/8	3/8
3/16	7/16
1/4	9/16
3/8	15/16
1/2	1 1/4
5/8	1 1/2
3/4	1 3/4
1	3
1 1/4	3 3/4
1 1/2	5
1 3/4	7
2	8

Figure 9-141. *Minimum bend radii for rigid conduit.*

Flexible Conduit

Flexible aluminum conduit conforming to specification MIL-C-6136 is available in two types: Type I, bare flexible conduit, and Type II, rubber-covered flexible conduit. Flexible brass conduit conforming to specification MIL-C-7931 is available and normally used instead of flexible aluminum where necessary to minimize radio interference. Also available is a plastic flexible tubing. (Reference MIL-T-8191A.) Flexible conduit may be used where it is impractical to use rigid conduit, such as areas that have motion between conduit ends or where complex bends are necessary.

The use of transparent adhesive tape is recommended when cutting flexible tubing with a hacksaw to minimize fraying of the braid. The tape should be centered over the cutting reference mark with the saw cutting through the tape. After cutting the flexible conduit, the transparent tape should be removed, the frayed braid ends trimmed, burrs removed from inside the conduit, and coupling nut and ferrule installed. Minimum acceptable bending radii for flexible conduit are shown in *Figure 9-142*.

Nominal ID of conduit (inches)	Minimum bending radius inside (inches)
3/16	2 1/4
1/4	2 3/4
3/8	3 3/4
1/2	3 3/4
5/8	3 3/4
3/4	4 1/4
1	5 3/4
1 1/4	8
1 1/2	8 1/4
1 3/4	9
2	9 3/4
2 1/2	10

Figure 9-142. *Minimum bending radii for flexible aluminum or brass conduit.*

Wire Shielding

In conventional wiring systems, circuits are shielded individually, in pairs, triples, or quads depending on each circuit's shielding requirement called out for in the engineering documentation. A wire is normally shielded when it is anticipated that the circuit can be affected by another circuit in the wire harness. When the wires come close together, they can couple enough interference to cause a detrimental upset to attached circuitry. This effect is often called crosstalk. Wires must come close enough for their fields to interact, and they must be in an operating mode that produces the crosstalk effect. However, the potential for crosstalk is real, and the only way to prevent crosstalk is to shield the wire. *[Figure 9-143]*

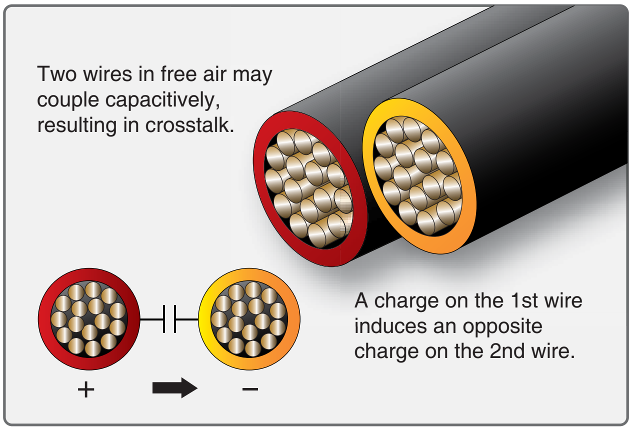


Figure 9-143. *Crosstalk.*

Bonding and Grounding

One of the more important factors in the design and maintenance of aircraft electrical systems is proper bonding and grounding. Inadequate bonding or grounding can lead to unreliable operation of systems, EMI, electrostatic discharge damage to sensitive electronics, personnel shock hazard, or damage from lightning strike.

Grounding

Grounding is the process of electrically connecting conductive objects to either a conductive structure or some other conductive return path for the purpose of safely completing either a normal or fault circuit. *[Figure 9-144]* If wires carrying return currents from different types of sources, such as signals of DC and AC generators, are connected to the same ground point or have a common connection in the return paths, an interaction of the currents occurs. Mixing return currents from various sources should be avoided because noise is coupled from one source to another and can be a major problem for digital systems. To minimize the interaction between various return currents, different types of ground should be identified and used. As a minimum, the design should use three ground types: (1) AC returns, (2) DC returns, and (3) all others.

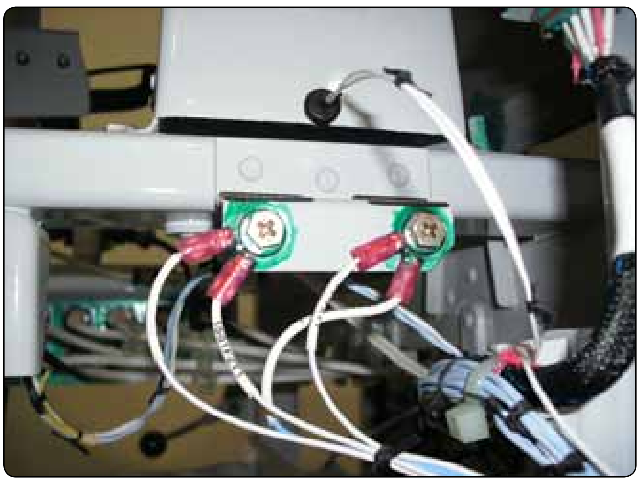


Figure 9-144. *Ground wires.*

For distributed power systems, the power return point for an alternative power source would be separated. For example, in a two-AC generator (one on the right side and the other on the left side) system, if the right AC generator were supplying backup power to equipment located in the left side, (left equipment rack) the backup AC ground return should be labeled "AC Right." The return currents for the left generator should be connected to a ground point labeled "AC Left."

The design of the ground return circuit should be given as much attention as the other leads of a circuit. A requirement for proper ground connections is that they maintain an impedance that is essentially constant. Ground return circuits should have a current rating and voltage drop adequate for satisfactory operation of the connected electrical and electronic equipment. EMI problems that can be caused by a system's power wire can be reduced substantially by locating the associated ground return near the origin of the power wiring (e.g., circuit breaker panel) and routing the power wire and its ground return in a twisted pair. Special care should be exercised to ensure replacement on ground return leads. The use of numbered insulated wire leads instead of bare grounding jumpers may aid in this respect. In general, equipment items should have an external ground connection, even when internally grounded. Direct connections to a magnesium structure must not be used for ground return because they may create a fire hazard.

Power ground connections for generators, transformer rectifiers, batteries, external power receptacles, and other heavy-current loads must be attached to individual grounding brackets that are attached to aircraft structure with a proper metal-to-metal bonding attachment. This attachment and the surrounding structure must provide adequate conductivity to accommodate normal and fault currents of the system without creating excessive voltage drop or damage to the structure. At least three fasteners, located in a triangular or rectangular pattern, must be used to secure such brackets in order to minimize susceptibility to loosening under vibration. If the structure is fabricated of a material, such as carbon fiber composite (CFC), that has a higher resistivity than aluminum or copper, it is necessary to provide an alternative ground path(s) for power return current. Special attention should be considered for composite aircraft.

Power return or fault current ground connections within flammable vapor areas must be avoided. If they must be made, make sure these connections do not arc, spark, or overheat under all possible current flow or mechanical failure conditions, including induced lightning currents. Criteria for inspection and maintenance to ensure continued airworthiness throughout the expected life of the aircraft should be established. Power return fault currents are normally the highest currents flowing in a structure. These can be the full generator current capacity. If full generator fault current flows through a localized region of the carbon fiber structure, major heating and failure can occur. CFC and other similar low-resistive materials must not be used in power return paths. Additional voltage drops in the return path can cause voltage regulation problems. Likewise, repeated localized material heating by current surges can cause material degradation. Both problems may occur without warning and cause no repeatable failures or anomalies.

The use of common ground connections for more than one circuit or function should be avoided except where it can be shown that related malfunctions that could affect more than one circuit do not result in a hazardous condition. Even when the loss of multiple systems does not, in itself, create a hazard, the effect of such failure can be quite distracting to the crew.

Bonding

Bonding is the electrical connecting of two or more conducting objects not otherwise adequately connected.

The following bonding requirements must be considered:

- Equipment bonding—low-impedance paths to aircraft structure are normally required for electronic equipment to provide radio frequency return circuits and for most electrical equipment to facilitate reduction in EMI. The cases of components that produce electromagnetic energy should be grounded to structure. To ensure proper operation of electronic equipment, it is particularly important to conform the system's installation specification when interconnections, bonding, and grounding are being accomplished.
- Metallic surface bonding—all conducting objects on the exterior of the airframe must be electrically connected to the airframe through mechanical joints, conductive hinges, or bond straps capable of conducting static charges and lightning strikes. Exceptions may be necessary for some objects, such as antenna elements, whose function requires them to be electrically isolated from the airframe. Such items should be provided with an alternative means to conduct static charges and/or lightning currents, as appropriate.
- Static bonds—all isolated conducting parts inside and outside the aircraft, having an area greater than 3 square inches and a linear dimension over 3 inches, that are subjected to appreciable electrostatic charging due to precipitation, fluid, or air in motion, should have a mechanically secure electrical connection to the aircraft structure of sufficient conductivity to dissipate possible static charges. A resistance of less than 1 ohm when clean and dry generally ensures such dissipation on larger objects. Higher resistances are permissible in connecting smaller objects to airframe structure.

Testing of Bonds and Grounds

The resistance of all bond and ground connections should be tested after connections are made before re-finishing. The resistance of each connection should normally not exceed 0.003 ohm. A high quality test instrument, an AN/USM-21A or equivalent, is required to accurately measure the very low resistance values.

Bonding Jumper Installation

Bonding jumpers should be made as short as practicable, and installed in such a manner that the resistance of each connection does not exceed .003 ohm. The jumper should not interfere with the operation of movable aircraft elements, such as surface controls, nor should normal movement of these elements result in damage to the bonding jumper. *[Figure 9-145]*

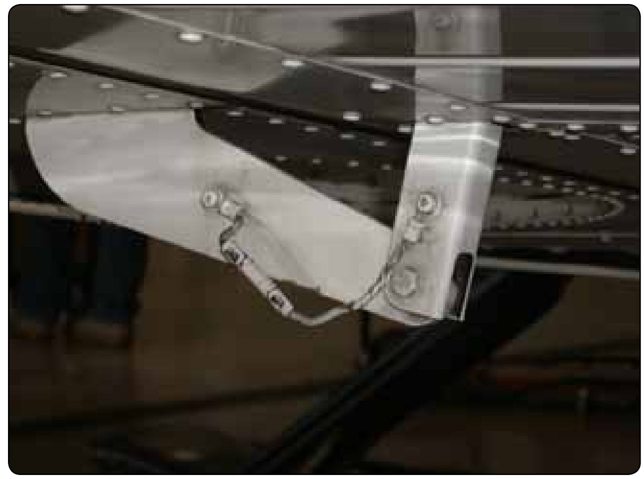
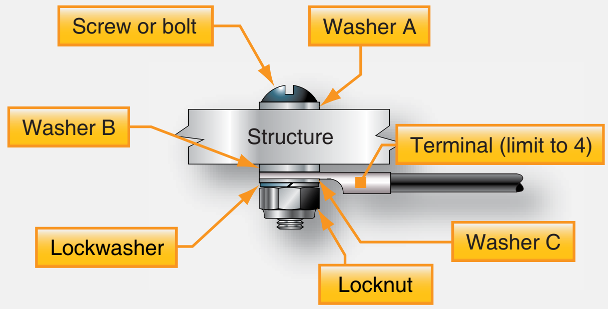


Figure 9-145. *Bonding jumpers.*

- Bonding connections—to ensure a low-resistance connection, nonconducting finishes, such as paint and anodizing films, should be removed from the attachment surface to be contacted by the bonding terminal. Electrical wiring should not be grounded directly to magnesium parts.
- Corrosion protection—one of the more frequent causes of failures in electrical system bonding and grounding is corrosion. The areas around completed connections should be post-finished quickly with a suitable finish coating.
- Corrosion prevention—electrolytic action may rapidly corrode a bonding connection if suitable precautions are not taken. Aluminum alloy jumpers are recommended for most cases; however, copper jumpers should be used to bond together parts made of stainless steel, cadmium plated steel, copper, brass, or bronze. Where contact between dissimilar metals cannot be avoided, the choice of jumper and hardware should be such that corrosion is minimized; the part likely to corrode should be the jumper or associated hardware.
- Bonding jumper attachment—the use of solder to attach bonding jumpers should be avoided. Tubular members should be bonded by means of clamps to which the jumper is attached. Proper choice of clamp material should minimize the probability of corrosion.
- Ground return connection—when bonding jumpers carry substantial ground return current, the current rating of the jumper should be determined to be adequate, and a negligible voltage drop is produced. *[Figure 9-146]*



Structure	Screw or bolt and nut plate	Locknut	Washer A	Washer B	Washer C
Aluminum Terminal and Jumper					
Aluminum alloys	Cadmium-plated steel	Cadmium-plated steel	Cadmium-plated steel or aluminum	None	Cadmium-plated steel or aluminum
Magnesium alloys	Cadmium-plated steel	Cadmium-plated steel	Magnesium-alloy	None or magnesium alloy	Cadmium-plated steel or aluminum
Cadmium-plated steel	Cadmium-plated steel	Cadmium-plated steel	Cadmium-plated steel	Cadmium-plated steel	Cadmium-plated steel or aluminum
Corrosion-resisting steel	Corrosion-resisting steel or Cadmium-plated steel	Cadmium-plated steel	Corrosion-resisting steel	Cadmium-plated steel	Cadmium-plated steel or aluminum
Tinned Copper Terminal and Jumper					
Aluminum alloys	Cadmium-plated steel	Cadmium-plated steel	Cadmium-plated steel	Aluminum alloys[2]	Cadmium-plated steel
Magnesium alloys[1]					
Cadmium-plated steel	Cadmium-plated steel	Cadmium-plated steel	Cadmium-plated steel	none	Cadmium-plated steel
Corrosion-resisting steel	Corrosion-resisting steel or cadmium-plated steel	Cadmium-plated steel	Corrosion-resisting steel	none	Cadmium-plated steel

[1]Avoid connecting copper to magnesium.
[2]Use washers with a conductive finish treated to prevent corrosion, such as AN960JD10L.

Figure 9-146. *Bolt and nut bonding or grounding to flat surface.*

Lacing and Tying Wire Bundles

Ties, lacing, and straps are used to secure wire groups or bundles to provide ease of maintenance, inspection, and installation. Straps may not be used in areas of SWAMP, such as wheel wells, near wing flaps, or wing folds. They may not be used in high vibration areas where failure of the strap would permit wiring to move against parts that could damage the insulation and foul mechanical linkages or other moving mechanical parts. They also may not be used where they could be exposed to UV light, unless the straps are resistant to such exposure. *[Figure 9-147]*

Figure 9-147. *Wire lacing.*

The single cord-lacing method and tying tape may be used for wire groups of bundles 1 inch in diameter or less. The recommended knot for starting the single cord-lacing method is a clove hitch secured by a double-looped overhand knot.

[Figure 9-148, step A] Use the double cordlacing method on wire bundles 1 inch in diameter or larger. When using the double cord-lacing method, employ a bowline-on-a-bight as the starting knot. *[Figure 9-149, step A]*

Tying

Use wire group or bundle ties where the supports for the wire are more than 12 inches apart. A tie consists of a clove hitch around the wire group or bundle, secured by a square knot. *[Figure 9-150]*

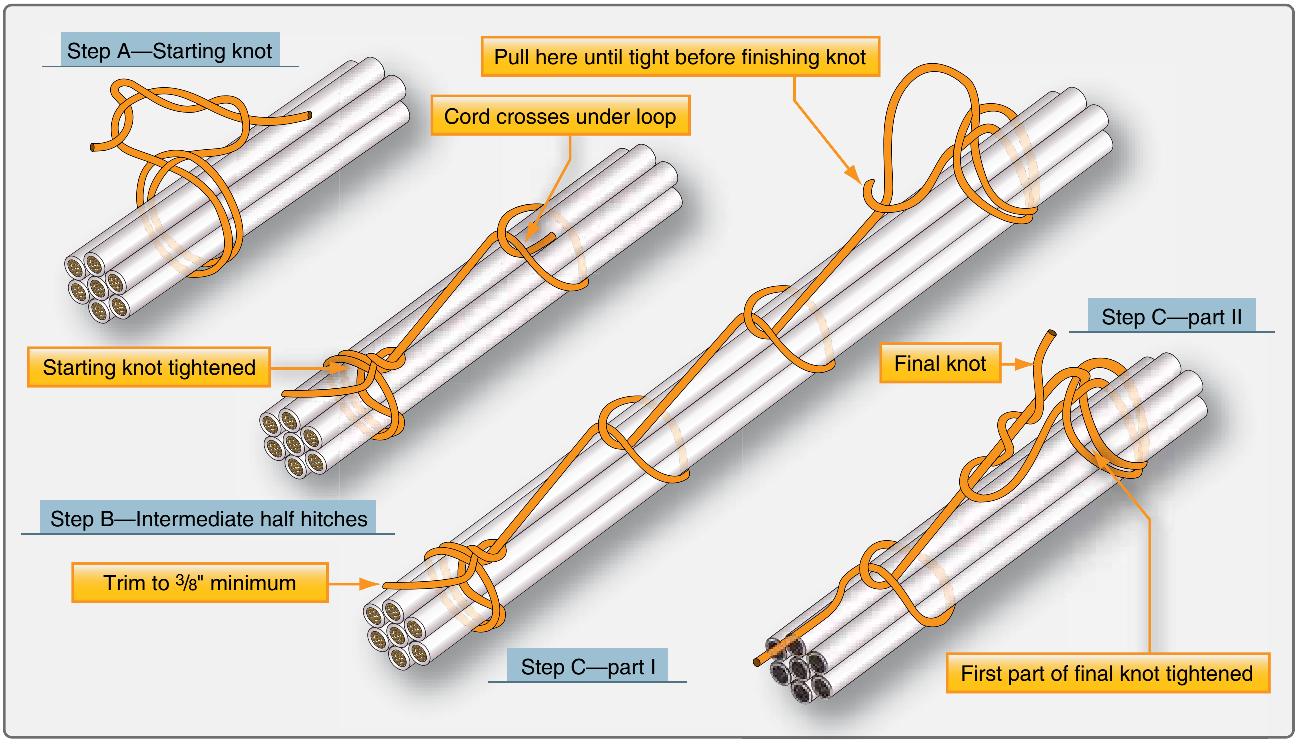


Figure 9-148. *Single cord lacing method.*

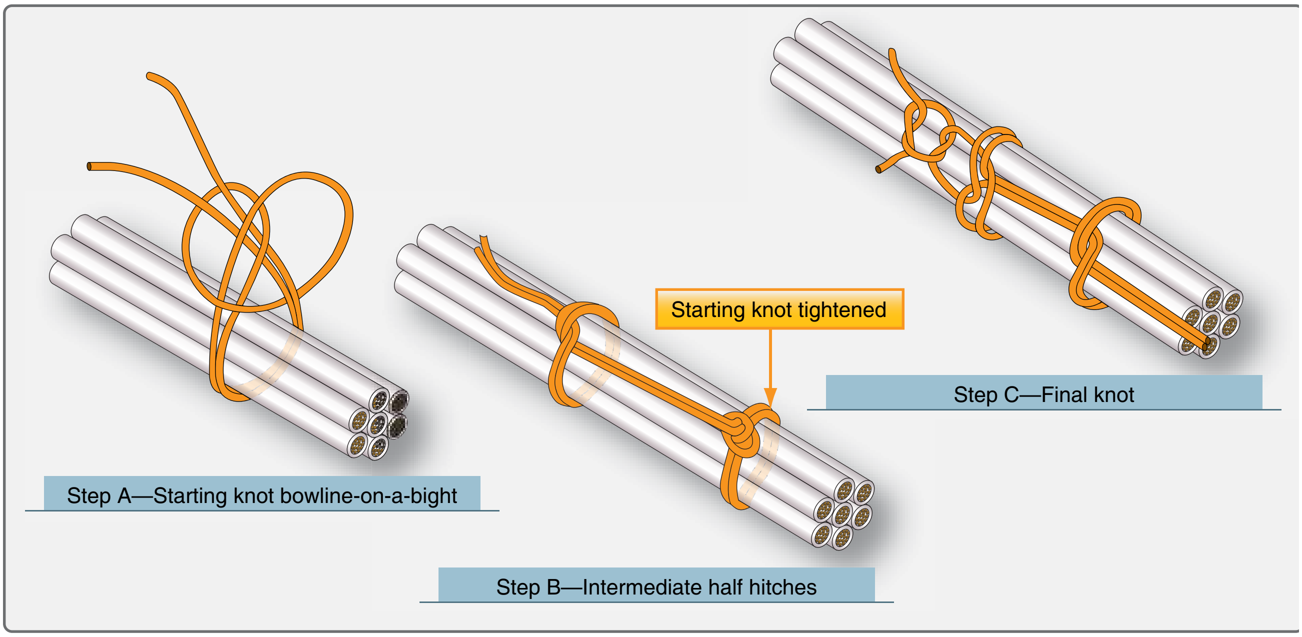


Figure 9-149. *Double cord lacing.*

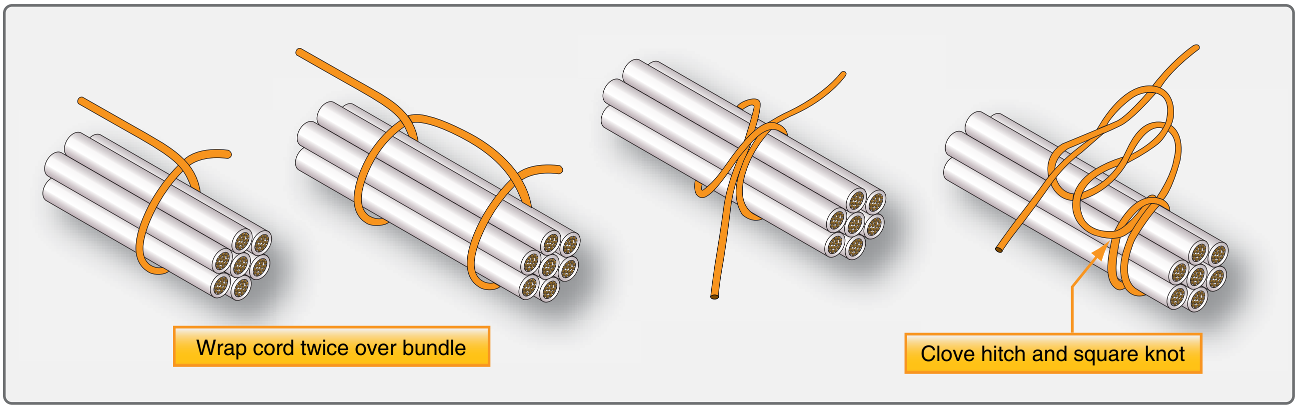


Figure 9-150. *Tying.*

Wire Termination

Stripping Wire

Before wire can be assembled to connectors, terminals, splices, etc., the insulation must be stripped from connecting ends to expose the bare conductor. Copper wire can be stripped in a number of ways depending on the size and insulation.

Aluminum wire must be stripped using extreme care, since individual strands break very easily after being nicked. The following general precautions are recommended when stripping any type of wire:

1. When using any type of wire stripper, hold the wire so that it is perpendicular to cutting blades.
2. Adjust automatic stripping tools carefully; follow the manufacturer's instructions to avoid nicking, cutting, or otherwise damaging strands. This is especially important for aluminum wires and for copper wires smaller than No. 10. Examine stripped wires for damage. Cut off and restrip (if length is sufficient), or reject and replace any wires having more than the allowable number of nicked or broken strands listed in the manufacturer's instructions.
3. Make sure insulation is clean-cut with no frayed or ragged edges. Trim, if necessary.
4. Make sure all insulation is removed from stripped area. Some types of wire are supplied with a transparent layer of insulation between the conductor and the primary insulation. If this is present, remove it.
5. When using hand-plier strippers to remove lengths of insulation longer than ¾ inch, it is easier to accomplish in two or more operations.
6. Retwist copper strands by hand or with pliers, if necessary, to restore natural lay and tightness of strands.

A pair of handheld wire strippers is shown in *Figure 9-151*. This tool is commonly used to strip most types of wire. The following general procedures describe the steps for stripping wire with a hand stripper.

Figure 9-151. *Wire strippers.*

1. Insert wire into exact center of correct cutting slot for wire size to be stripped. Each slot is marked with wire size.
2. Close handles together as far as they will go.
3. Release handles, allowing wire holder to return to the open position.
4. Remove stripped wire.

Terminals are attached to the ends of electrical wires to facilitate connection of the wires to terminal strips or items of equipment. *[Figure 9-152]* The tensile strength of the wire-to-terminal joint should be at least equivalent to the tensile strength of the wire itself, and its resistance negligible relative to the normal resistance of the wire.

The following should be considered in the selection of wire terminals: current rating, wire size (gauge) and insulation diameter, conductor material compatibility, stud size, insulation material compatibility, application environment, and solder versus solderless.

Figure 9-152. *Ring-tongue terminals.*

Preinsulated crimp-type ring-tongue terminals are preferred. The strength, size, and supporting means of studs and binding posts, as well as the wire size, may be considered when determining the number of terminals to be attached to any one post. In high-temperature applications, the terminal temperature rating must be greater than the ambient temperature plus current related temperature rise. Use of nickel-plated terminals and of uninsulated terminals with high-temperature insulating sleeves should be considered. Terminal blocks should be provided with adequate electrical clearance or insulation strips between mounting hardware and conductive parts.

Terminal Strips

Wires are usually joined at terminal strips. *[Figure 9-153]* A terminal strip fitted with barriers may be used to prevent the terminals on adjacent studs from contacting each other. Studs should be anchored against rotation. When more than four terminals are to be connected together, a small metal bus should be mounted across two or more adjacent studs. In all cases, the current should be carried by the terminal contact surfaces and not by the stud itself. Defective studs should be replaced with studs of the same size and material since terminal strip studs of the smaller sizes may shear due to overtightening the nut. The replacement stud should be securely mounted in the terminal strip and the terminal securing nut should be tight. Terminal strips should be mounted in such a manner that loose metallic objects cannot fall across the terminals or studs. It is good practice to provide at least one spare stud for future circuit expansion or in case a stud is broken.

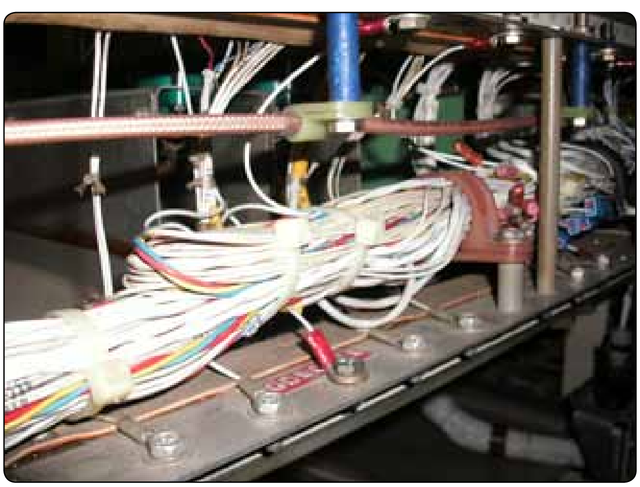


Figure 9-153. *Terminal strip.*

Terminal strips that provide connection of radio and electronic systems to the aircraft electrical system should be inspected for loose connections, metallic objects that may have fallen across the terminal strip, dirt and grease accumulation, etc. These conditions can cause arcing, which may result in a fire or system failures.

Terminal Lugs

Wire terminal lugs should be used to connect wiring to terminal block studs or equipment terminal studs. No more than four terminal lugs, or three terminal lugs and a bus bar, should be connected to any one stud. The total number of terminal lugs per stud includes a common bus bar joining adjacent studs. Four terminal lugs plus a common bus bar are not permitted on one stud. Terminal lugs should be selected with a stud hole diameter that matches the diameter of the stud. However, when the terminal lugs attached to a stud vary in diameter, the greatest diameter should be placed on the bottom and the smallest diameter on top. Tightening terminal connections should not deform the terminal lugs or the studs. Terminal lugs should be positioned so that bending of the terminal lug is not required to remove the fastening screw or nut, and movement of the terminal lugs tends to tighten the connection.

Copper Wire Terminals

Solderless crimp-style, copper wire, terminal lugs may be used which conform to MIL-T-7928. Spacers or washers should not be used between the tongues of terminal lugs. *[Figure 9-154]*

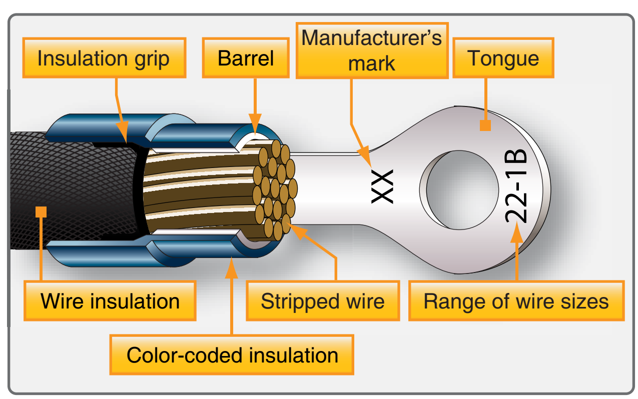


Figure 9-154. *Wire terminal.*

Aluminum Wire Terminals

The aluminum terminal lugs should be crimped to aluminum wire only. The tongue of the aluminum terminal lugs, or the total number of tongues of aluminum terminal lugs when stacked, should be sandwiched between two flat washers when terminated on terminal studs. Spacers or washers should not be used between the tongues of terminal lugs. Special attention should be given to aluminum wire and cable installations to guard against conditions that would result in excessive voltage drop and high resistance at junctions that may ultimately lead to failure of the junction. Examples of such conditions are improper installation of terminals and washers, improper torsion (torquing of nuts), and inadequate terminal contact areas.

Pre-Insulated Splices

Pre-insulated terminal lugs and splices must be installed using a high-quality crimping tool. Such tools are provided with positioners for the wire size and are adjusted for each wire size. It is essential that the crimp depth be appropriate for each wire size. If the crimp is too deep, it may break or cut individual strands. If the crimp is not deep enough, it may not be tight enough to retain the wire in the terminal or connector. Crimps that are not tight enough are also susceptible to high resistance due to corrosion buildup between the crimped terminal and the wire. *[Figure 9-155]*

Figure 9-155. *Terminal splices.*

Crimping Tools

Hand, portable, and stationary power tools are available for crimping terminal lugs. These tools crimp the barrel to the conductor, and simultaneously form the insulation support to the wire insulation. *[Figure 9-156]*

Figure 9-156. *Crimping pliers.*

Emergency Splicing Repairs

Broken wires can be repaired by means of crimped splices, by using terminal lugs from which the tongue has been cut off, or by soldering together and potting broken strands. These repairs are applicable to copper wire. Damaged aluminum wire must not be temporarily spliced. These repairs are for temporary emergency use only and should be replaced as soon as possible with permanent repairs. Since some manufacturers prohibit splicing, the applicable manufacturer's instructions should always be consulted.

Junction Boxes

Junction boxes are used for collecting, organizing, and distributing circuits to the appropriate harnesses that are attached to the equipment. *[Figure 9-157]* Junction boxes are also used to conveniently house miscellaneous components, such as relays and diodes. Junction boxes that are used in high-temperature areas should be made of stainless steel.

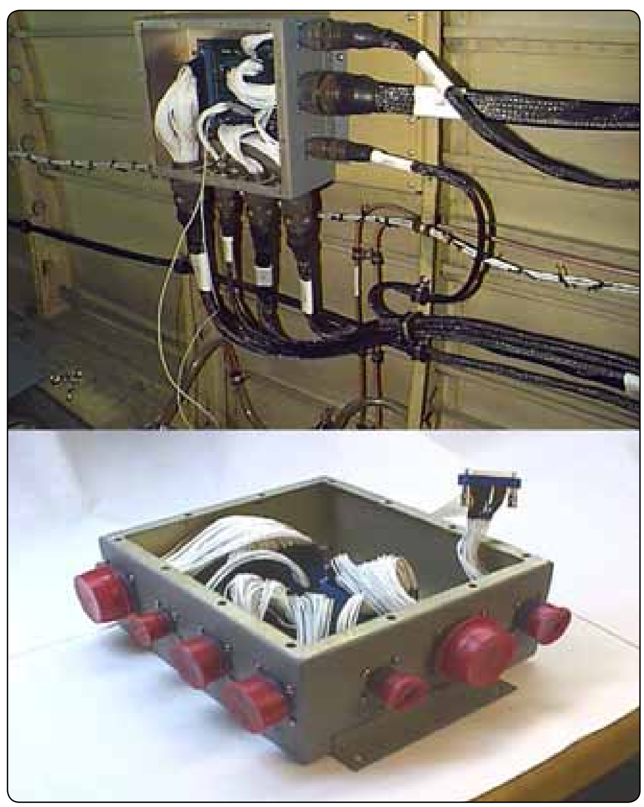


Figure 9-157. *Junction boxes.*

Replacement junction boxes should be fabricated using the same material as the original or from a fire-resistant, nonabsorbent material, such as aluminum, or an acceptable plastic material. Where fireproofing is necessary, a stainless steel junction box is recommended. Rigid construction prevents oil-canning of the box sides that could result in internal short circuits. In all cases, drain holes should be provided in the lowest portion of the box. Cases of electrical power equipment must be insulated from metallic structure to avoid ground fault related fires.

The junction box arrangement should permit easy access to any installed items of equipment, terminals, and wires. Where marginal clearances are unavoidable, an insulating material should be inserted between current carrying parts and any grounded surface. It is not good practice to mount equipment on the covers or doors of junction boxes, since inspection for internal clearance is impossible when the door or cover is in the closed position.

Junction boxes should be securely mounted to the aircraft structure in such a manner that the contents are readily accessible for inspection. When possible, the open side should face downward or at an angle so that loose metallic objects, such as washers or nuts, tend to fall out of the junction box rather than wedge between terminals.

Junction box layouts should take into consideration the necessity for adequate wiring space and possible future additions. Electrical wire bundles should be laced or clamped inside the box so that cables do not touch other components, prevent ready access, or obscure markings or labels. Cables at entrance openings should be protected against chafing by using grommets or other suitable means.

AN/MS Connectors

Connectors (plugs and receptacles) facilitate maintenance when frequent disconnection is required. There is a multitude of types of connectors. The connector types that use crimped contacts are generally used on aircraft. Some of the more common types are the round cannon type, the rectangular, and the module blocks. Environmentally resistant connectors should be used in applications subject to fluids, vibration, heat, mechanical shock, and/or corrosive elements.

When HIRF/lightning protection is required, special attention should be given to the terminations of individual or overall shields. The number and complexity of wiring systems have resulted in an increased use of electrical connectors. *[Figure 9-158]* The proper choice and application of connectors is a significant part of the aircraft wiring system. Connectors must be kept to a minimum, selected, and installed to provide the maximum degree of safety and reliability to the aircraft. For the installation of any particular connector assembly, the specification of the manufacturer or the appropriate governing agency must be followed.

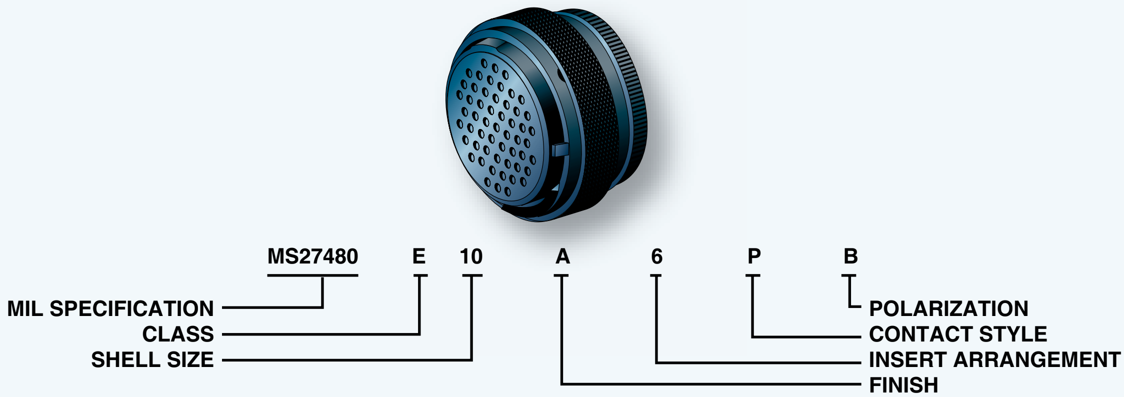
Figure 9-158. *Electrical connectors.*

Types of Connector

Connectors must be identified by an original identification number derived from MIL Specification (MS) or OEM specification. *Figure 9-159* provides information about MS style connectors.

Environment-resistant connectors are used in applications where they are probably subjected to fluids, vibration, heat, mechanical shock, corrosive elements, etc. Firewall class connectors incorporating these same features should, in addition, be able to prevent the penetration of the fire through the aircraft firewall connector opening and continue to function without failure for a specified period of time when exposed to fire. Hermetic connectors provide a pressure seal for maintaining pressurized areas. When EMI/RFI protection is required, special attention should be given to the termination of individual and overall shields. Backshell adapters designed for shield termination, connectors with conductive finishes, and EMI grounding fingers are available for this purpose.

Rectangular connectors are typically used in applications where a very large number of circuits are accommodated in a single mated pair. *[Figure 9-160]* They are available with a great variety of contacts, which can include a mix of standard, coaxial, and large power types. Coupling is accomplished by various means. Smaller types are secured with screws which hold their flanges together. Larger ones have integral guide pins that ensure correct alignment, or jackscrews that both align and lock the connectors. Rack and panel connectors use integral or rack-mounted pins for alignment and box mounting hardware for couplings.



MS27472 Wall mount receptacle
MS27473 Straight plug
MS27474 Jam nut receptacle
MS27475 Hermetic wall mount receptacle
MS27476 Hermetic box mount receptacle
MS27477 Hermetic jam nut receptacle
MS27478 Hermetic solder mount receptacle
MS27479 Wall mount receptacle (note 1)
MS27480 Straight plug(note 1)
MS27481 Jam nut receptacle (note 1)
MS27482 Hermetic wall mount receptacle (note 1)
MS27483 Hermetic jam nut receptacle (note 1)
MS27484 Straight plug, EMI grounding
MS27497 Wall receptacle, back panel mounting
MS27499 Box mounting receptacle
MS27500 90° Plug (note 1)
MS27503 Hermetic solder mount receptacle (note 1)
MS27504 Box mount receptacle (note 1)
MS27508 Box mount receptacle, back panel mounting
MS27513 Box mount receptacle, long grommet
MS27664 Wall mount receptacle, back panel mounting (note 1)
MS27667 Thru-bulkhead receptacle

NOTE

1. Active	Supersedes
MS27472	MS27479
MS27473	MS27480
MS27474	MS27481
MS27475	MS27482
MS27477	MS27483
MS27473 with MS27507 elbow	MS27500
MS27478	MS27503
MS27499	MS27504
MS27497	MS27664

CLASS

E Environment-resisting box and thru-bulkhead mounting types only (see class T)
P Potting—includes potting form and short rear grommet
T Environment-resisting wall and jam-nut mounting receptacle and plug types: thread and teeth for accessory attachment
Y Hermetically sealed

FINISH

A Silver to light iridescent yellow color cadmium plate over nickel (conductive) –65 °C to +150 °C (inactive for new design)
B Olive drab cadmium plate over suitable underplate (conductive), –65 °C to 175 °C
C Anodic (nonconductive), –65 °C to + 175 °C
D Fused tin, carbon steel(conductive), –65 °C to +150 °C
E Corrosion resistant steel (cres), passivated (conductive), –65 °C to +200 °C
F Electroless nickel coating (conductive), –65 °C to +200 °C
N Hermetic seal or environment resisting cres (conductive plating), –65 °C to +200 °C

CONTACT STYLE

A Without pin contacts
B Without socket contacts
C Feed through
P Pin contact—including hermetics with solder cups
S Socket contacts—including hermetics with solder cups
X Pin contacts with eyelet (hermetic)
Z Socket contacts with eyelet (hermetic)

POLARIZATION

A, B Normal—no letter required
C, or D

Figure 9-159. *MS connector information sheet.*

Module blocks are types of junctions that accept crimped contacts similar to those on connectors. Some use internal busing to provide a variety of circuit arrangements. They are useful where a number of wires are connected for power or signal distribution. When used as grounding modules, they save and reduce hardware installation on the aircraft. Standardized modules are available with wire end grommet seals for environmental applications and are track mounted. Function module blocks are used to provide an easily wired package for environment-resistant mounting of small resistors, diodes, filters, and suppression networks. In-line

Figure 9-160. *Rectangular connectors.*

terminal junctions are sometimes used in lieu of a connector when only a few wires are terminated and when the ability to disconnect the wires is desired. The in-line terminal junction is environment resistant. The terminal junction splice is small and may be tied to the surface of a wire bundle when approved by the OEM.

Voltage and Current Rating

Selected connectors must be rated for continuous operation under the maximum combination of ambient temperature and circuit current load. Hermetic connectors and connectors used in circuit applications involving high-inrush currents should be derated. It is good engineering practice to conduct preliminary testing in any situation where the connector is to operate with most or all of its contacts at maximum rated current load. When wiring is operating with a high conductor temperature near its rated temperature, connector contact sizes should be suitably rated for the circuit load. This may require an increase in wire size. Voltage derating is required when connectors are used at high altitude in nonpressurized areas.

Spare Contacts for Future Wiring

To accommodate future wiring additions, spare contacts are normally provided. Locating the unwired contacts along the outer part of the connector facilitates future access. A good practice is to provide two spares on connectors with 25 or fewer contacts; 4 spares on connectors with 26 to 100 contacts; and 6 spares on connectors with more than 100 contacts. Spare contacts are not normally provided on receptacles of components that are unlikely to have added wiring. Connectors must have all available contact cavities filled with wired or unwired contacts. Unwired contacts should be provided with a plastic grommet sealing plug.

Wire Installation Into the Connector

Wires that perform the same function in redundant systems must be routed through separate connectors. On systems critical to flight safety, system operation wiring should be routed through separate connectors from the wiring used for system failure warning. It is also good practice to route a system's indication wiring in separate connectors from its failure warning circuits to the extent practicable. These steps can reduce an aircraft's susceptibility to incidents that might result from connector failures.

Adjacent Locations

Mating of adjacent connectors should not be possible. In order to ensure this, adjacent connector pairs must be different in shell size, coupling means, insert arrangement, or keying arrangement. When such means are impractical, wires should be routed and clamped so that incorrectly mated pairs cannot reach each other. Reliance on markings or color stripes is not recommended as they are likely to deteriorate with age. *[Figure 9-161]*

Figure 9-161. *Connector arrangement to avoid wrong connection.*

Sealing

Connectors must be of a type that excludes moisture entry through the use of peripheral and interfacial seal that are compressed when the connector is mated. Moisture entry through the rear of the connector must be avoided by correctly matching the wire's outside diameter with the connector's rear grommet sealing range. It is recommended that no more than one wire be terminated in any crimp style contact. The use of heat-shrinkable tubing to build up the wire diameter, or the application of potting to the wire entry area as additional means of providing a rear compatibility with the rear grommet is recommended. These extra means have inherent penalties and should be considered only where other means cannot be used. Unwired spare contacts should have a correctly sized plastic plug installed.

Drainage

Connectors must be installed in a manner that ensures moisture and fluids drain out of and not into the connector when unmated. Wiring must be routed so that moisture accumulated on the bundle drains away from connectors. When connectors must be mounted in a vertical position, as through a shelf or floor, the connectors must be potted or environmentally sealed. In this situation, it is better to have the receptacle faced downward so that it is less susceptible to collecting moisture when unmated.

Wire Support

A rear accessory back shell must be used on connectors that are not enclosed. Connectors with very small size wiring, or subject to frequent maintenance activity, or located in high-vibration areas must be provided with a strain-relief-type back shell. The wire bundle should be protected from mechanical damage with suitable cushion material where it is secured by the clamp. Connectors that are potted or have molded rear adapters do not normally use a separate strain relief accessory. Strain relief clamps should not impart tension on wires between the clamp and contact. *[Figure 9-162]*

Figure 9-162. *Backshells with strain relief.*

Sufficient wire length must be provided at connectors to ensure a proper drip loop and that there is no strain on termination after a complete replacement of the connector and its contacts.

Coaxial Cable

All wiring needs to be protected from damage. However, coaxial and triaxial cables are particularly vulnerable to certain types of damage. Personnel should exercise care while handling or working around coaxial. *[Figure 9-163]* Coaxial damage can occur when clamped too tightly, or when they are bent sharply (normally at or near connectors). Damage can also be incurred during unrelated maintenance actions around the coaxial cable. Coaxial cable can be severely damaged on the inside without any evidence of damage on the outside. Coaxial cables with solid center conductors should not be used. Stranded center coaxial cables can be used as a direct replacement for solid center coaxial. *[Figure 9-164]* Coaxial cable precautions include:

Figure 9-163. *Coaxial cables.*

- Never kink coaxial cable.
- Never drop anything on coaxial cable.
- Never step on coaxial cable.
- Never bend coaxial cable sharply.
- Never loop coaxial cable tighter than the allowable bend radius.
- Never pull on coaxial cable except in a straight line.
- Never use coaxial cable for a handle, lean on it, or hang things on it (or any other wire).

Wire Inspection

Aircraft service imposes severe environmental condition on electrical wire. To ensure satisfactory service, inspect wire annually for abrasions, defective insulation, condition of terminations, and potential corrosion. Grounding connections for power, distribution equipment, and electromagnetic shielding must be given particular attention to ensure that electrical bonding resistance has not been significantly increased by the loosening of connections or corrosion.

Electrical System Components

Switches

Switches are devices that open and close circuits. They consist of one or more pair of contacts. The current in the circuit flows when the contacts are closed. Switches with

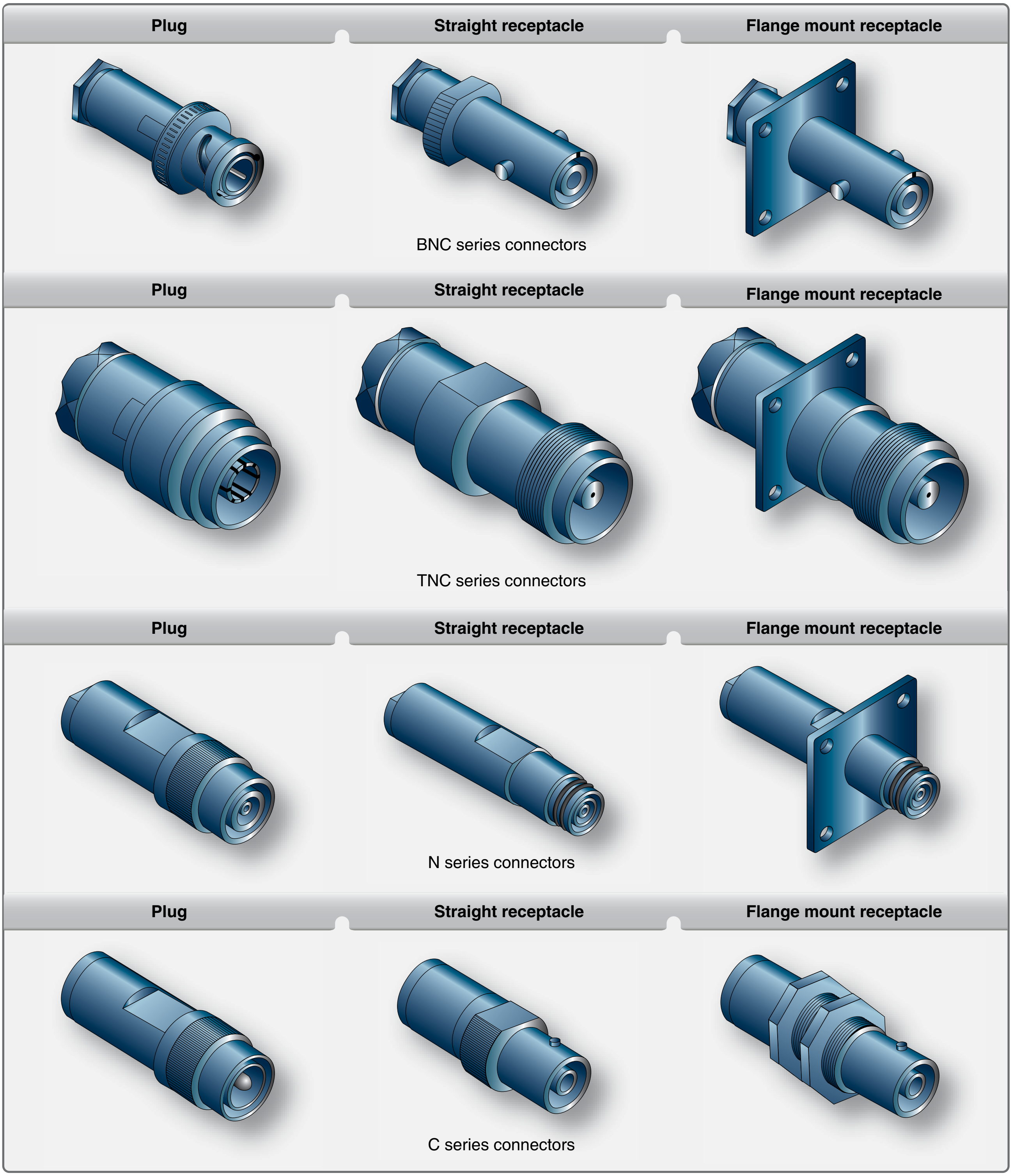


Figure 9-164. *Coaxial cable connectors.*

momentary contacts actuate the circuit temporarily, and they return to the normal position with an internal spring when the switch is released. Switches with continuous contacts remain in position when activated. Hazardous errors in switch operation can be avoided by logical and consistent installation. Two-position on/off switches should be mounted so that the on position is reached by an upward or forward movement of the toggle. When the switch controls movable aircraft elements, such as landing gear or flaps, the toggle should move in the same direction as the desired motion. Inadvertent operation of a switch can be prevented by mounting a suitable guard over the switch. *[Figure 9-165]*

Figure 9-165. *Switch guard.*

A specifically designed switch should be used in all circuits where a switch malfunction would be hazardous. Such switches are of rugged construction and have sufficient contact capacity to break, make, and carry continuously the connected load current. Snap action design is generally preferred to obtain rapid opening and closing of contacts regardless of the speed of the operating toggle or plunger, thereby minimizing contact arcing. The nominal current rating of the conventional aircraft switch is usually stamped on the switch housing. This rating represents the continuous current rating with the contacts closed. Switches should be derated from their nominal current rating for the following types of circuits:

1. High rush-in circuits—contain incandescent lamps that can draw an initial current 15 times greater than the continuous current. Contact burning or welding may occur when the switch is closed.
2. Inductive circuits—magnetic energy stored in solenoid coils or relays is released and appears as an arc when the control switch is opened.
3. Motors—DC motors draw several times their rated current during starting, and magnetic energy stored in their armature and field coils is released when the control switch is opened.

Figure 9-166 is used for selecting the proper nominal switch rating when the continuous load current is known. This selection is essentially a derating to obtain reasonable switch efficiency and service life.

Nominal system voltage (DC)	Type of load	Derating factor
28V	Lamp	8
28V	Inductive	4
28V	Resistive	2
28V	Motor	3
12V	Lamp	5
12V	Inductive	2
12V	Resistive	1
12V	Motor	2

Figure 9-166. *Derating table for switches.*

Type of Switches

Single-pole single-throw (SPST)—opens and closes a single circuit. Pole indicates the number of separate circuits that can be activated, and throw indicates the number of current paths.

Double-pole single-throw (DPST)—turn two circuits on and off with one lever.

Single-pole double-throw (SPDT)—route circuit current to either of two paths. The switch is ON in both positions. For example, switch turns on red lamp in one position and turns on green lamp in the other position.

Double-pole double-throw (DPDT)—activates two separate circuits at the same time.

Double-throw switches—have either two or three positions.

Two position switch—pole always connected to one of the two throws. Three-position switches have a center OFF position that disconnects the pole from both throws.

Spring loaded switches—available in two types: 1) normally open (NO) and 2) normally closed (NC). The contacts of the NO switch are disconnected in the normal position and become closed when the switch is activated. The switch returns to the normal position when the applied force to the switch is released. The contacts of the NC switch are connected in the normal position and become open when the switch is activated. The switch returns to the normal position when the applied force to the switch is released.

Toggle and Rocker Switches

Toggle and rocker switches control most of aircraft's electrical components. *[Figure 9-167]* Aircraft that are

Figure 9-167. *Toggle and rocker switches.*

outfitted with a glass cockpit often use push buttons to control electrical components.

Rotary Switches

Rotary switches are activated by twisting a knob or shaft and are commonly found on radio control panels. Rotary switches are utilized for controlling more than two circuits.

Precision (Micro) Switches

Micro switches require very little pressure to activate. These types of switches are spring loaded, once the pressure is removed, the contacts return to the normal position. These types of switches are typically single pole double throw (SPDT) or double pole double throw (DPDT) and have three contacts: normally open, normally closed, and common. Micro switches are used to detect position or to limit travel of moving parts, such as landing gear, flaps, spoilers, etc. *[Figure 9-168]*

Relays and Solenoids (Electromagnetic Switches)

Relays are used to control the flow of large currents using a small current. A low-power DC circuit is used to activate the relay and control the flow of large AC currents. They are used

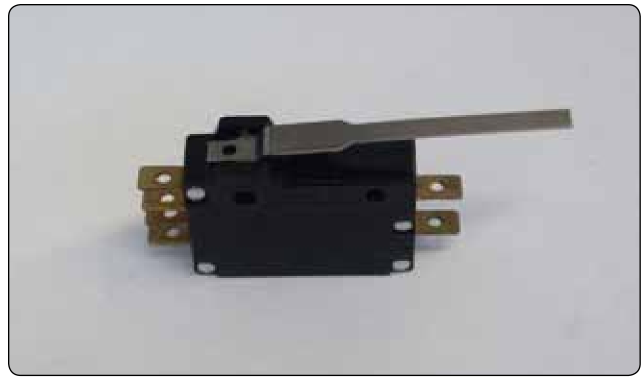


Figure 9-168. *A micro switch.*

to switch motors and other electrical equipment on and off and to protect them from overheating. A solenoid is a special type of relay that has a moving core. The electromagnet core in a relay is fixed. Solenoids are mostly used as mechanical actuators but can also be used for switching large currents. Relays are only used to switch currents.

Solenoids

Solenoids are used as switching devices where a weight reduction can be achieved or electrical controls can be simplified. The foregoing discussion of switch ratings is generally applicable to solenoid contact ratings. Solenoids have a movable core/armature that is usually made of steel or iron, and the coil is wrapped around the armature. The solenoid has an electromagnetic tube and the armature moves in and out of the tube. *[Figure 9-169]*

Figure 9-169. *Solenoid.*

Relays

The two main types of relays are electromechanical and solid state. Electromechanical relays have a fixed core and a moving plate with contacts on it, while solid-state relays work similar to transistors and have no moving parts. Current flowing through the coil of an electromechanical relay creates a magnetic field that attracts a lever and changes the switch contacts. The coil current can be on or off so relays have two switch positions, and they are double throw switches.

Residual magnetism is a common problem and the contacts may stay closed or are opened by a slight amount of residual magnetism. A relay is an electrically operated switch and is therefore subject to dropout under low system voltage conditions. Relays allow one circuit to switch a second circuit that can be completely separate from the first. For example, a low voltage DC battery circuit can use a relay to switch a 110-volt three-phase AC circuit. There is no electrical connection inside the relay between the two circuits; the link is magnetic and mechanical. *[Figure 9-170]*

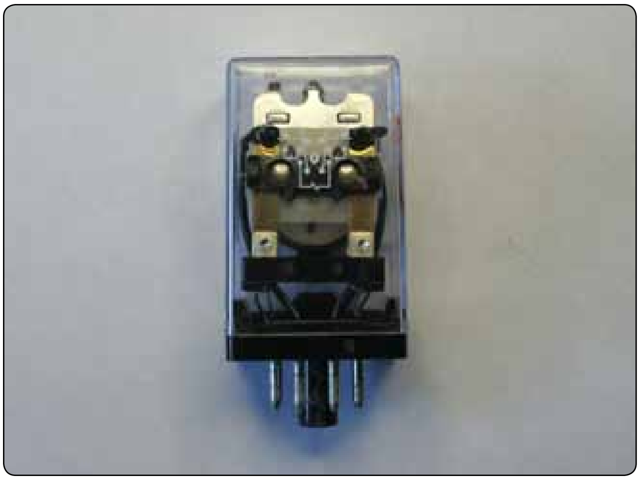


Figure 9-170. *Relay.*

Current Limiting Devices

Conductors should be protected with circuit breakers or fuses located as close as possible to the electrical power source bus. Normally, the manufacturer of the electrical equipment specifies the fuse or circuit breaker to be used when installing equipment. The circuit breaker or fuse should open the circuit before the conductor emits smoke. To accomplish this, the time current characteristic of the protection device must fall below that of the associated conductor. Circuit protector characteristics should be matched to obtain the maximum utilization of the connected equipment. *Figure 9-171* shows a chart used in selecting the circuit breaker and fuse protection for copper conductors. This limited chart is applicable to a specific set of ambient temperatures and wire bundle sizes and is presented as typical only. It is important to consult such guides before selecting a conductor for a specific purpose. For example, a wire run individually in the open air may be protected by the circuit breaker of the next higher rating to that shown on the chart.

Wire AN gauge copper	Circuit breaker amperage	Fuse amperage
22	5	5
20	7.5	5
18	10	10
16	15	10
14	20	15
12	30	20
10	40	30
8	50	50
6	80	70
4	100	70
2	125	100
1		150
0		150

Figure 9-171. *Wired and circuit protection chart.*

Fuses

A fuse is placed in series with the voltage source and all current must flow through it. *[Figure 9-172]* The fuse consists of a strip of metal that is enclosed in a glass or plastic housing. The metal strip has a low melting point and is usually made of lead, tin, or copper. When the current exceeds the capacity of the fuse the metal strip heats up and breaks. As a result of this, the flow of current in the circuit stops.

Figure 9-172. *A fuse.*

There are two basic types of fuses: fast acting and slow blow. The fast-acting type opens very quickly when their particular current rating is exceeded. This is important for electric devices that can quickly be destroyed when too much current flows through them for even a very small amount of time. Slow blow fuses have a coiled construction inside. They are designed to open only on a continued overload, such as a short circuit.

Circuit Breakers

A circuit breaker is an automatically operated electrical switch designed to protect an electrical circuit from damage caused by an overload or short circuit. Its basic function is to detect a fault condition and immediately discontinue electrical flow. Unlike a fuse that operates once and then has to be replaced, a circuit breaker can be reset to resume normal operation. All resettable circuit breakers should open the circuit in which they are installed regardless of the position of the operating control when an overload or circuit fault exists. Such circuit breakers are referred to as trip-free. Automatic reset circuit breakers automatically reset themselves. They should not be used as circuit protection devices in aircraft. When a circuit breaker trips, the electrical circuit should be checked and the fault removed before the circuit breaker is reset. Sometimes circuit breakers trip for no apparent reason, and the circuit breaker can be reset one time. If the circuit breaker trips again, there exists a circuit fault and the technician must troubleshoot the circuit before resetting the circuit breaker. *[Figure 9-173]*

Figure 9-173. *Circuit breaker panel.*

Some new aircraft designs use a digital circuit protection architecture. This system monitors the amperage through a particular circuit. When the maximum amperage for that circuit is reached, the power is rerouted away from the circuit. This system reduces the use of mechanical circuit breakers. The advantages are weight savings and the reduction of mechanical parts.

Aircraft Lighting Systems

Aircraft lighting systems provide illumination for both exterior and interior use. Lights on the exterior provide illumination for such operations as landing at night, inspection of icing conditions, and safety from midair collision. Interior lighting provides illumination for instruments, cockpits, cabins, and other sections occupied by crewmembers and passengers. Certain special lights, such as indicator and warning lights, indicate the operation status of equipment.

Exterior Lights

Position, anticollision, landing, and taxi lights are common examples of aircraft exterior lights. Some lights are required for night operations. Other types of exterior lights, such as wing inspection lights, are of great benefit for specialized flying operations.

Position Lights

Aircraft operating at night must be equipped with position lights that meet the minimum requirements specified by Title 14 of the Code of Federal Regulations. A set of position lights consist of one red, one green, and one white light. *[Figures 9-174* and *9-175]*

Figure 9-174. *A left wing tip position light (red) and a white strobe light.*

Figure 9-175. *A right wing tip position light, also known as a navigation light.*

On some types of installations, a switch in the cockpit provides for steady or flashing operation of the position lights. On many aircraft, each light unit contains a single lamp mounted on the surface of the aircraft. Other types of position light units contain two lamps and are often streamlined into the surface of the aircraft structure. The green light unit is always mounted at the extreme tip of the right wing. The red unit is mounted in a similar position on the left wing. The white unit is usually located on the vertical stabilizer in a position where it is clearly visible through a wide angle from the rear of the aircraft. *Figure 9-176* illustrates a schematic diagram of a position light circuit. Position lights are also known as navigation lights.

There are, of course, many variations in the position light circuits used on different aircraft. All circuits are protected by fuses or circuit breakers, and many circuits include flashing and dimming equipment. Small aircraft are usually equipped with a simplified control switch and circuitry. In some cases, one control knob or switch is used to turn on several sets of lights; for example, one type utilizes a control knob, the first movement of which turns on the position lights and the instrument panel lights. Further rotation of the control knob increases the intensity of only the panel lights. A flasher unit is seldom included in the position light circuitry of very light aircraft but is used in small twin-engine aircraft. Traditional position lights use incandescent light bulbs. LED lights have been introduced on modern aircraft because of their good visibility, high reliability, and low power consumption.

Anticollision Lights

An anticollision light system may consist of one or more lights. They are rotating beam lights that are usually installed on top of the fuselage or tail in such a location that the light does not affect the vision of the crewmember or detract from the visibility of the position lights. Large transport type aircraft use an anticollision light on top and one on the bottom of the aircraft. *Figure 9-177* shows a typical anticollision light installation in a vertical stabilizer.

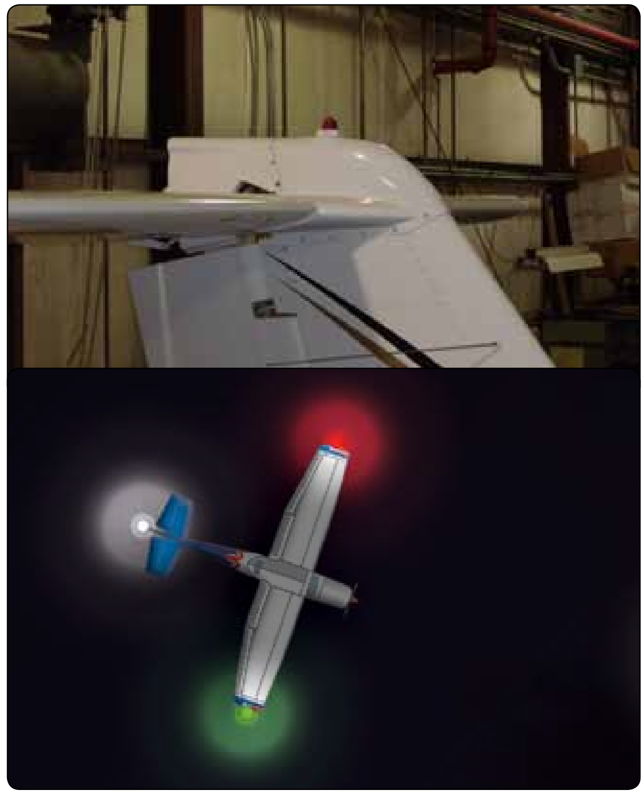


Figure 9-177. *Anticollision lights.*

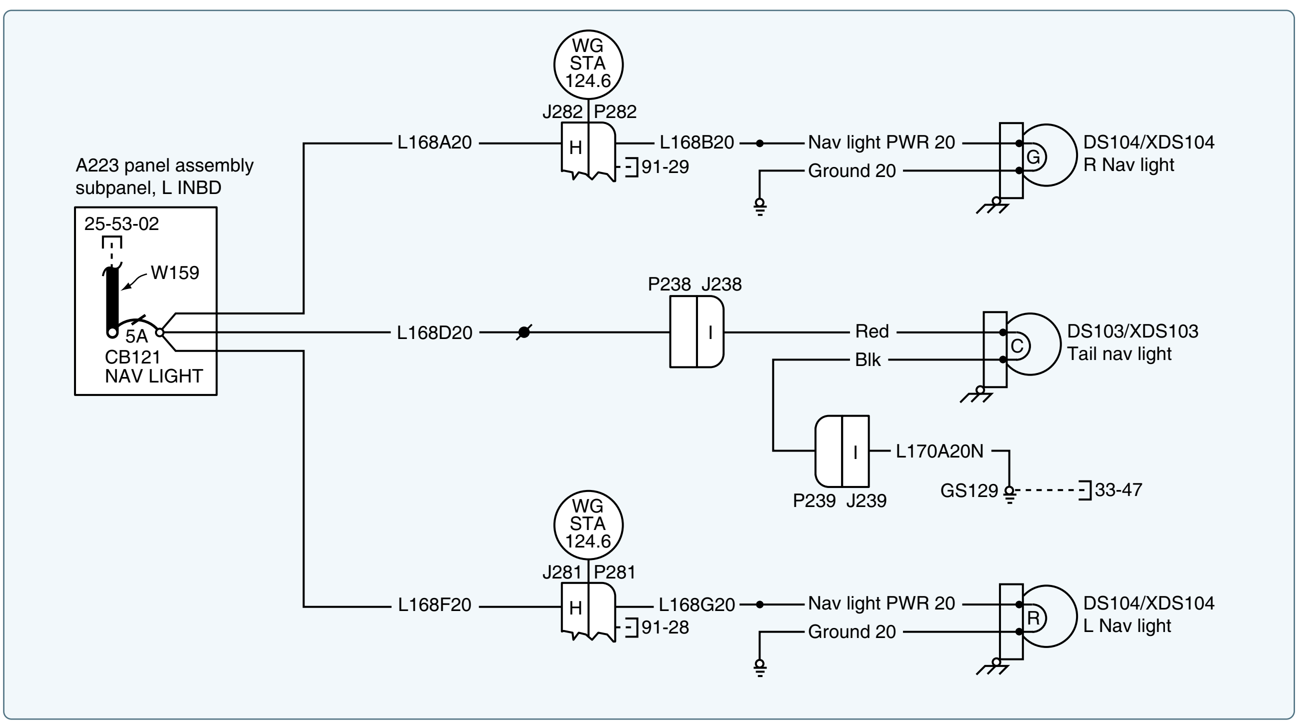


Figure 9-176. *Navigation light system schematic.*

An anticollision light unit usually consists of one or two rotating lights operated by an electric motor. The light may be fixed but mounted under rotating mirrors inside a protruding red glass housing. The mirrors rotate in an arc, and the resulting flash rate is between 40 and 100 cycles per minute. Newer aircraft designs use a LED type of anticollision light. The anticollision light is a safety light to warn other aircraft, especially in congested areas.

A white strobe light is a second type of anti-collision light that is also common. Usually mounted at the wing tips and, possibly, at empennage extremities, strobe lights produce an extremely bright intermittent flash of white light that is highly visible. The light is produced by a high voltage discharge of a capacitor. A dedicated power pack houses the capacitor and supplies voltage to a sealed xenon-filled tube. The xenon ionizes with a flash when the voltage is applied. A strobe light is shown in *Figure 9-174*.

Landing and Taxi Lights

Landing lights are installed in aircraft to illuminate runways during night landings. These lights are very powerful and are directed by a parabolic reflector at an angle providing a maximum range of illumination. Landing lights of smaller aircraft are usually located midway in the leading edge of each wing or streamlined into the aircraft surface. Landing lights for larger transport category aircraft are usually located in the leading edge of the wing close to the fuselage. Each light may be controlled by a relay, or it may be connected directly into the electric circuit. On some aircraft, the landing light is mounted in the same area with a taxi light. *[Figure 9-178]* A sealed beam, halogen, or high intensity xenon discharge lamp is used.

Figure 9-178. *Landing lights.*

Taxi lights are designed to provide illumination on the ground while taxiing or towing the aircraft to or from a runway, taxi strip, or in the hangar area. *[Figure 9-179]* Taxi lights are not designed to provide the degree of illumination necessary for landing lights. On aircraft with tricycle landing gear, either single or multiple taxi lights are often mounted on the non-steerable part of the nose landing gear. They are positioned at an oblique angle to the center line of the aircraft to provide illumination directly in front of the aircraft and also some illumination to the right and left of the aircraft's path. On some aircraft, the dual taxi lights are supplemented by wingtip clearance lights controlled by the same circuitry. Taxi lights are also mounted in the recessed areas of the wing leading edge, often in the same area with a fixed landing light.

Figure 9-179. *Taxi lights.*

Many small aircraft are not equipped with any type of taxi light, but rely on the intermittent use of a landing light to illuminate taxiing operations. Still other aircraft utilize a dimming resistor in the landing light circuit to provide reduced illumination for taxiing. A typical circuit for taxi lights is shown in *Figure 9-180.*

Some large aircraft are equipped with alternate taxi lights located on the lower surface of the aircraft, aft of the nose radome. These lights, operated by a separate switch from the main taxi lights, illuminate the area immediately in front of and below the aircraft nose.

Wing Inspection Lights

Some aircraft are equipped with wing inspection lights to illuminate the leading edge of the wings to permit observation of icing and general condition of these areas in flight. These lights permit visual detection of ice formation on wing leading edges while flying at night. They are usually controlled through a relay by an on/off toggle switch in the cockpit. Some wing inspection light systems may include or be supplemented by additional lights, sometimes called nacelle lights, that illuminate adjacent areas, such a cowl flaps or the landing gear. These are normally the same type of lights and can be controlled by the same circuits.

Interior Lights

Aircraft are equipped with interior lights to illuminate the cabin. *[Figure 9-181]* Often white and red light settings are provided. Commercial aircraft have a lighting systems that illuminates the main cabin, an independent lighting system so that passengers can read when the cabin lights are off, and an emergency lighting system on the floor of the aircraft to aid passengers of the aircraft during an emergency.

Figure 9-181. *Interior cockpit and cabin light system.*

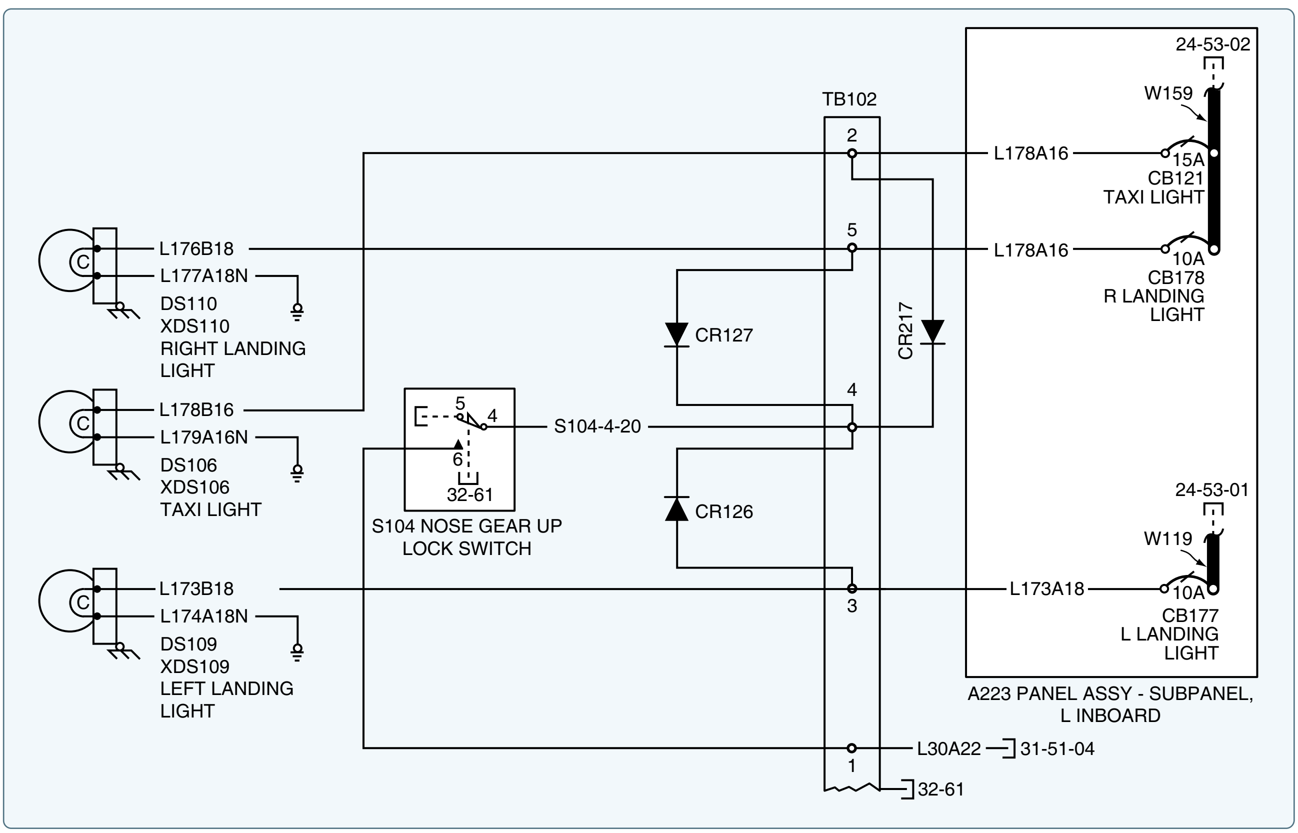


Figure 9-180. *Taxi light circuit.*

Maintenance and Inspection of Lighting Systems

Inspection of an aircraft's lighting system normally includes checking the condition and security of all visible wiring, connections, terminals, fuses, and switches. A continuity light or meter can be used in making these checks, since the cause of many troubles can often be located by systematically testing each circuit for continuity.