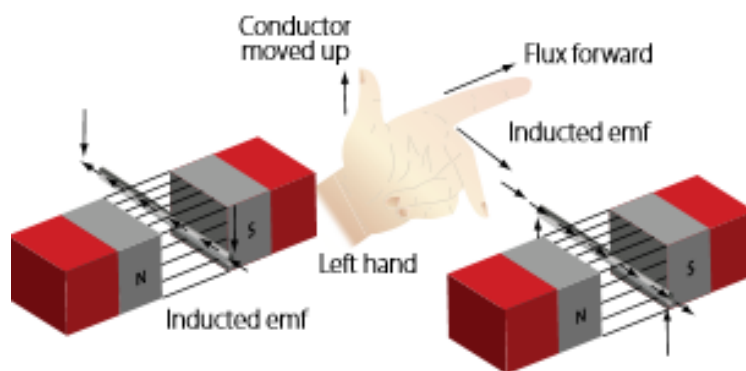




Power, Resistance, Capacitors and Inductance



6

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Table of Contents

Power and Energy	21
Types of Resistors	25
Circuit Protection Devices	30
Series DC Circuits	34
Parallel DC Circuits	40
Alternating Current and Voltage	44
Series-Parallel DC Circuits	42
Generator Principles	44
Capacitance	51
Inductance	57

List of Figures

Figure 10-43. Ohm's law formula.	23
Figure 10-44. Unconnected crossover wires.	24
Figure 10-45. Connected wires.	24
Figure 10-46. Common wire types.	25
Figure 10-47. Fixed resistor schematic.	25
Figure 10-48. Resistor color code.	26
Figure 10-49. End-to-center band marking.	26
Figure 10-50. Resistor color code example.	27
Figure 10-51. Resistor color code example.	27
Figure 10-52. Resistor with two percent tolerance.	27
Figure 10-53. Resistor with black third color band.	27
Figure 10-54. Resistor with gold third band.	27
Figure 10-56. Wire-wound resistors.	27
Figure 10-57. Rheostat schematic symbol.	28
Figure 10-58. Rheostat connected in series.	28
Figure 10-59. Potentiometer schematic symbol.	28
Figure 10-60. Potentiometer and schematic symbol.	28
Figure 10-61. Potentiometer wired to function as rheostat.	29
Figure 10-62. Linear potentiometer schematic.	29
Figure 10-63. Tapered potentiometer.	29
Figure 10-64. Schematic symbol for thermistor.	29
Figure 10-65. Photoconductive cell schematic symbol component.	29
Figure 10-66. Schematic symbol for fuse.	30
Figure 10-67. Schematic symbol for circuit breaker.	30
Figure 10-68. Single-pole, single-throw switch schematic symbol.	31
Figure 10-69. Single-pole, double-throw switch schematic symbol.	32
Figure 10-70. Double-pole, single-throw switch schematic symbol.	32
Figure 10-71. Double-pole, double-throw switch schematic symbol.	32
Figure 10-72. Cross-section of a microswitch.	33
Figure 10-73. Rotary selector switch.	33
Figure 10-74. Basic relay.	34
Figure 10-75. Simple DC circuit.	34
Figure 10-76. Inducing minimum voltage in an elementary generator.	35
Figure 10-77. Example of three resistors in series.	35
Figure 10-78. Voltage sources in series add algebraically.	36
Figure 10-79. Voltage sources add algebraically; one source reversed.	36

Figure 10-80. Kirchhoff's voltage law.	37
Figure 10-81. Determine the unknown voltage drop.	37
Figure 10-82. Determine the unknown voltage drop.	37
Figure 10-83. A voltage divider circuit.	38
Figure 10-84. A typical voltage divider.	38
Figure 10-85. Positive and negative voltage on a voltage divider.	38
Figure 10-86. Current flow through a voltage divider.	39
Figure 10-87. Voltage divider with changed ground.	39
Figure 10-88. Four resistor voltage divider.	39
Figure 10-89. Network of three resistors and one voltage source.	40
Figure 10-90. Basic parallel circuit.	40
Figure 10-91. Kirchhoff's current law.	41
Figure 10-92. Individual branch currents.	42
Figure 10-93. Determining an unknown circuit in branch 2.	42
Figure 10-94. Series-parallel circuits.	43
Figure 10-95. Equivalent circuit with three series connected resistors.	43
Figure 10-96. Determining total resistance.	43
Figure 10-97. DC and AC voltage curves.	44
Figure 10-98. Inducing a current flow.	45
Figure 10-99. Inducing an emf in a conductor.	45
Figure 10-100. An application of the generator left-hand rule.	45
Figure 10-101. Voltage induced in a loop.	46
Figure 10-102. Simple generator.	46
Figure 10-103. Generation of a sine wave.	47
Figure 10-104. Cycle of voltage.	48
Figure 10-105. Frequency in cycles per second.	48
Figure 10-106. In phase and out of phase conditions.	49
Figure 10-107. Sine wave effective value.	50
Figure 10-108. Capacitors in direct current.	51
Figure 10-109. Capacitance discharge curve.	51
Figure 10-110. Strength of some dielectric materials.	52
Figure 10-111. Schematic symbols for a fixed and variable capacitor.	53
Figure 10-112. Electrolytic capacitors.	54
Figure 10-113. Oil capacitor.	54
Figure 10-114. Simple series circuit.	54
Figure 10-115. Simplified parallel circuit.	55
Figure 10-116. Capacitor in an AC circuit.	55
Figure 10-117. Phase of current and voltage.	57
Figure 10-118. Many loops of a coil.	57
Figure 10-119. Inductor curve.	58
Figure 10-120. Typical symbol for an inductor.	59
Figure 10-121. Two inductors in series.	59
Figure 10-122. Two inductors in parallel.	59
Figure 10-123. AC circuit containing inductance.	60
Figure 10-124. Inductances in series.	60
Figure 10-125. Inductances in parallel.	61

Power and Energy

Power in an Electrical Circuit

This section covers power in the DC circuit and energy consumption. Whether referring to mechanical or electrical systems, power is defined as the rate of energy consumption or conversion within that system — that is, the amount of energy used or converted in a given amount of time.

From the scientific discipline of physics, the fundamental expression for power is:

$$P = \frac{\mathcal{E}}{t}$$

Where

P = Power measured in Watts (W)

\mathcal{E} = Energy (\mathcal{E} is a script E) measured in Joules (J)

And

t = Time measured in Seconds (s)

The unit measurement for power is the watt (W), which refers to a rate of energy conversion of 1 joule/second. Therefore, the number of joules consumed in 1 second is equal to the number of watts. A simple example is given below.

Suppose 300 J of energy is consumed in 10 seconds. What would be the power in watts?

$$\begin{aligned}\text{General formula } P &= \frac{\text{energy}}{\text{time}} \\ P &= \frac{300 \text{ J}}{10 \text{ s}} \\ P &= 30 \text{ W}\end{aligned}$$

The watt is named for James Watt, the inventor of the steam engine. Watt devised an experiment to measure the power of a horse in order to find a means of measuring the mechanical power of his steam engine. One horsepower is required to move 33,000 pounds 1 foot in 1 minute. Since power is the rate of doing work, it is equivalent to the work divided by time. Stated as a formula, this is:

$$\begin{aligned}\text{Power} &= \frac{33,000 \text{ ft-lb}}{60 \text{ sec}} \\ P &= 550 \text{ ft-lb/sec}\end{aligned}$$

Electrical power can be rated in a similar manner. For example, an electric motor rated as a 1 horsepower motor requires 746 watts of electrical energy.

Power Formulas Used in the Study of Electricity

When current flows through a resistive circuit, energy is dissipated in the form of heat. Recall that voltage can be expressed in the terms of energy and charge as given in the expression:

$$E = \frac{\mathcal{E}}{Q}$$

Where

E = potential difference in volts

W = energy expanded or absorbed in joules (J)

Q = Charge measured in coulombs

Current I, can also be expressed in terms of charge and time as given by the expression:

$$\text{Current} = \frac{\text{Charge}}{\text{Time}}$$

Or

$$I = \frac{Q}{t}$$

Where:

I = Current in Amperes (A)

Q = Charge in Coulombs (C)

t = time

When voltage \mathcal{E}/Q and current Q/t are multiplied, the charge Q is divided out leaving the basic expression from physics:

$$E \times I = \frac{\mathcal{E}}{Q} \times \frac{Q}{t} = \frac{\mathcal{E}}{t} = \text{power}$$

For a simple DC electrical system, power dissipation can then be given by the equation:

$$\text{General Power Formula } P = I (E)$$

Where

P = Power

I = Current

E = Volts

If a circuit has a known voltage of 24 volts and a current of 2 amps, then the power in the circuit will be:

$$P = I (E)$$

$$P = 2\text{A} (24\text{V})$$

$$P = 48 \text{ W}$$

Now recall Ohm's laws which states that $E = I(R)$. If we now substitute IR for E in the general formula, we get a formula that uses only current I and resistance R to determine the power in a circuit.

$$P = I (IR)$$

Second Form of Power Equation

$$P = I^2 R$$

If a circuit has a known current of 2 amps and a resistance of 100 Ω , then the power in the circuit will be:

$$P = I^2 R$$

$$P = (2\text{A})^2 100 \Omega$$

$$P = 400 \text{ W}$$

Using Ohm's law again, which can be stated as $I = E/R$, we can again make a substitution such that power can

be determined by knowing only the voltage (E) and resistance (R) of the circuit.

$$P = \left(\frac{E}{R} \right) (E)$$

Third Form of Power Equation

$$P = \frac{E^2}{R}$$

If a circuit has a known voltage of 24 volts and a resistance of 20 Ω , then the power in the circuit will be:

$$P = \frac{E^2}{R}$$

$$P = \frac{(24V)^2}{20 \Omega}$$

$$P = 28.8 \text{ W}$$

Power in a Series and Parallel Circuit

The total power dissipated in both a series and parallel circuit is equal to the sum of the power dissipated in each resistor in the circuit. Power is simply additive and can be stated as:

$$P_T = P_1 + P_2 + P_3 + \dots P_N$$

Figure 10-43 provides a summary of all the possible transpositions of the Ohm's law formula and the power formula.

Energy in an Electrical Circuit

Energy is defined as the ability to do work. Because power is the rate of energy usage, power used over a

span of time is actually energy consumption. If power and time are multiplied together, we will get energy.

The joule is defined as a unit of energy. There is another unit of measure which is perhaps more familiar. Because power is expressed in watts and time in seconds, a unit of energy can be called a watt-second (Ws) or more recognizable from the electric bill, a kilowatt-hour (kWh). Refer to Page 3-3 for further discussion on energy.

Sources of Electricity

Electrical energy can be produced in a number of methods. The four most common are pressure, chemical, thermal, and light.

Pressure Source

This form of electrical generation is commonly known as piezoelectric (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. The most common piezoelectric materials used today are crystalline quartz and Rochelle salt. However, Rochelle salt is being superseded by other materials, such as barium titanate.

The application of a mechanical stress produces an electric polarization, which is proportional to this stress. This polarization establishes a voltage across the crystal. If a circuit is connected across the crystal a flow of current can be observed when the crystal is loaded (pressure is applied). An opposite condition can occur, where an application of a voltage between certain faces of the crystal can produce a mechanical distortion. This effect is commonly referred to as the piezoelectric effect.

Piezoelectric materials are used extensively in transducers for converting a mechanical strain into an electrical signal. Such devices include microphones, phonograph pickups and vibration-sensing elements. The opposite effect, in which a mechanical output is derived from an electrical signal input, is also widely used in headphones and loudspeakers.

Chemical Source

Chemical energy can be converted into electricity; the most common form of this is the battery. A primary battery produces electricity using two different metals in a chemical solution like alkaline electrolyte, where a chemical reaction between the metals and the chemicals frees more electrons in one metal than in the other. One terminal of the battery is attached to one of the metals such as zinc; the other terminal is

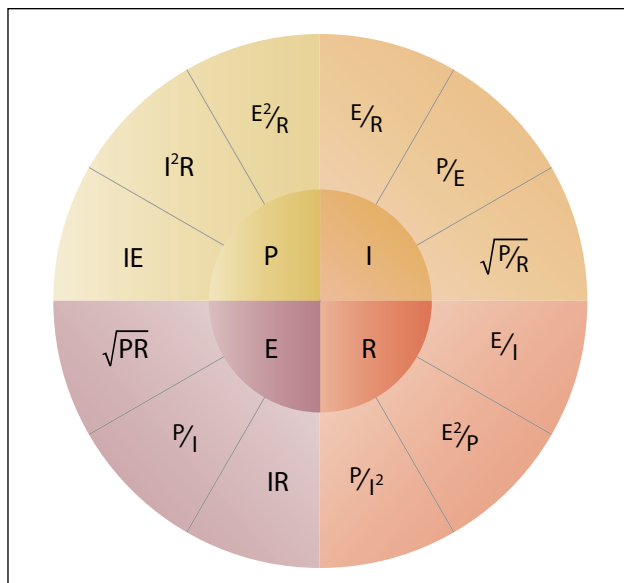


Figure 10-43. Ohm's law formula.

attached to the other metal such as manganese oxide. The end that frees more electrons develops a positive charge and the other end develops a negative charge. If a wire is attached from one end of the battery to the other, electrons flow through the wire to balance the electrical charge.

Thermal Sources

The most common source of thermal electricity found in the aviation industry comes from thermocouples. Thermocouples are widely used as temperature sensors. They are cheap and interchangeable, have standard connectors, and can measure a wide range of temperatures. Thermocouples are pairs of dissimilar metal wires joined at least at one end, which generate a voltage between the two wires that is proportional to the temperature at the junction. This is called the Seebeck effect, in honor of Thomas Seebeck who first noticed the phenomena in 1821. It was also noticed that different metal combinations have a different voltage difference.

Thermocouples are usually pressed into service as ways to measure cylinder head temperatures and inter-turbine temperature.

Light Sources

A solar cell or a photovoltaic cell is a device that converts light energy into electricity. Fundamentally, the device contains certain chemical elements that when exposed to light energy, they release electrons.

Photons in sunlight are taken in by the solar panel or cell, where they are then absorbed by semiconducting materials, such as silicon. Electrons in the cell are broken loose from their atoms, allowing them to flow through the material to produce electricity. The complementary positive charges that are also created are called holes (absence of electron) and flow in the direction opposite of the electrons in a silicon solar panel.

Solar cells have many applications and have historically been used in earth orbiting satellites or space probes, handheld calculators, and wrist watches.

Schematic Representation of Electrical Components

The schematic is the most common place where the technician will find electronic symbols. The schematic is a diagram that depicts the interconnection and logic of an electronic or electrical circuit. Many symbols are employed for use in the schematic drawings, blueprints, and illustrations. This section briefly outlines some

of the more common symbols and explains how to interpret them.

Conductors

The schematic depiction of a conductor is simple enough. This is generally shown as a solid line. However, the line types may vary depending on who drew the schematics and what exactly the line represents. While the solid line is used to depict the wire or conductor, schematics used for aircraft modifications can also use other line types such as a dashed to represent “existing” wires prior to modification and solid lines for “new” wires.

There are two methods employed to show wire cross-overs and wire connections. Figure 10-44 shows the two methods of drawing wires that cross, version A and version B. Figure 10-45 shows the two methods for drawing wire that connect version A and version B. If version A in Figure 10-44 is used to depict crossovers, then version A for wire connections in Figure 10-45 will be used. The same can then be said about the use of version B methods. The technician will encounter both in common use.

Figure 10-46 shows a few examples of the more common wire types that the technician will encounter in schematics. They are the single wire, single shielded, shielded twisted pair or double and the shielded triple. This is not an exhaustive list of wire types but a fair

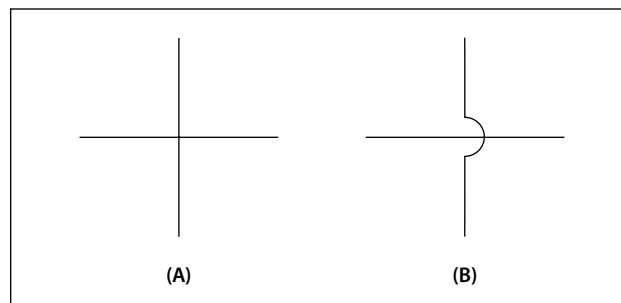


Figure 10-44. Unconnected crossover wires.

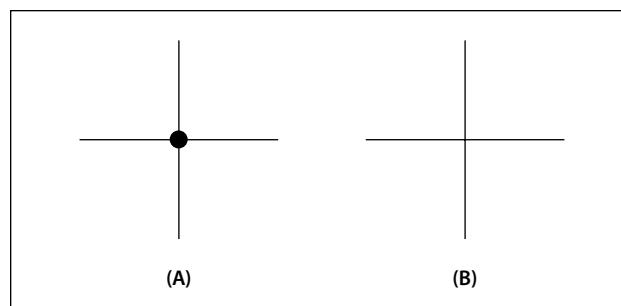


Figure 10-45. Connected wires.

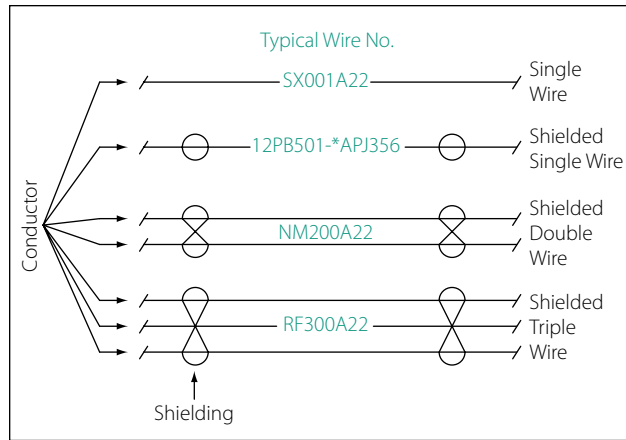


Figure 10-46. Common wire types.

representation of how they are depicted. Figure 10-46 also shows the wires having a wire number. These are shown for the sake of illustration and will vary from one installation agency to another. For further understanding of a wire numbering system, consult the appropriate wiring guide published by the agency that drew the prints. Regardless of the specifics of the wire numbering system, organizations that exercise professional wiring practices will have the installed wire marked in some manner. This will be an aid to the technician who has to troubleshoot or modify the system at a later date.

Types of Resistors

Fixed Resistor

Figure 10-47 is a schematic representation of a fixed resistor. Fixed resistors have built into the design a means of opposing current. The general use of a resistor in a circuit is to limit the amount of current flow. There are a number of methods used in construction and sizing of a resistor that control properties such as resistance value, the precision of the resistance value, and the ability to dissipate heat. While in some applications the purpose of the resistive element is used to generate heat, such as in propeller anti-ice boots, heat typically is the unwanted loss of energy.

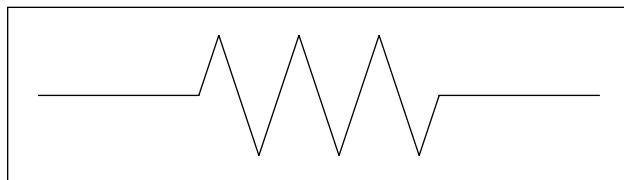


Figure 10-47. Fixed resistor schematic.

Carbon Composition

The carbon composed resistor is constructed from a mixture of finely grouped carbon/graphite, an insulation material for filler, and a substance for binding the material together. The amount of graphite in relation to the insulation material will determine the ohmic or resistive value of the resistor. This mixture is compressed into a rod, which is then fitted with axial leads or “pigtailed.” The finished product is then sealed in an insulating coating for isolation and physical protection.

There are other types of fixed resistors in common use. Included in this group are:

- Carbon film
- Metal oxide
- Metal film
- Metal glaze

The construction of a film resistor is accomplished by depositing a resistive material evenly on a ceramic rod. This resistive material can be graphite for the carbon film resistor, nickel chromium for the metal film resistor, metal and glass for the metal glaze resistor and last, metal and an insulating oxide for the metal oxide resistor.

Resistor Ratings

It is very difficult to manufacture a resistor to an exact standard of ohmic values. Fortunately, most circuit requirements are not extremely critical. For many uses, the actual resistance in ohms can be 20 percent higher or lower than the value marked on the resistor without causing difficulty. The percentage variation between the marked value and the actual value of a resistor is known as the “tolerance” of a resistor. A resistor coded for a 5 percent tolerance will not be more than 5 percent higher or lower than the value indicated by the color code.

The resistor color code is made up of a group of colors, numbers, and tolerance values. Each color is represented by a number, and in most cases, by a tolerance value. [Figure 10-48]

When the color code is used with the end-to-center band marking system, the resistor is normally marked with bands of color at one end of the resistor. The body or base color of the resistor has nothing to do with the color code, and in no way indicates a resistance value. To prevent confusion, this body will never be the same color as any of the bands indicating resistance value.

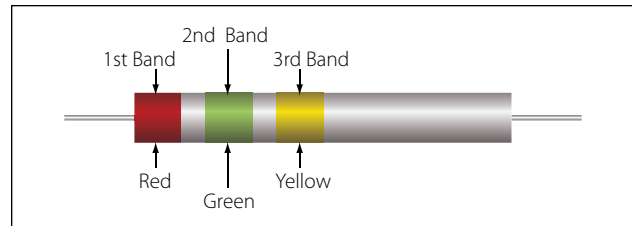
Resistor color code		
Color	Number	Tolerance
Black	0	—
Brown	1	1%
Red	2	2%
Orange	3	3%
Yellow	4	4%
Green	5	5%
Blue	6	6%
Violet	7	7%
Gray	8	8%
White	9	9%
Gold	—	5%
Silver	—	10%
No color	—	20%

Figure 10-48. Resistor color code.

When the end-to-center band marking system is used, either three or four bands will mark the resistor.

1. The first color band (nearest the end of the resistor) will indicate the first digit in the numerical resistance value. This band will never be gold or silver in color.
2. The second color band will always indicate the second digit of ohmic value. It will never be gold or silver in color. [Figure 10-49]
3. The third color band indicates the number of zeros to be added to the two digits derived from the first and second bands, except in the following two cases:
 - (a) If the third band is gold in color, the first two digits must be multiplied by 10 percent.
 - (b) If the third band is silver in color, the first two digits must be multiplied by 1 percent.
4. If there is a fourth color band, it is used as a multiplier for percentage of tolerance, as indicated in the color code chart in Figure 10-48. If there is no fourth band, the tolerance is understood to be 20 percent.

Figure 10-49 provides an example, which illustrates the rules for reading the resistance value of a resistor marked with the end-to-center band system. This resistor is marked with three bands of color, which must be read from the end toward the center.



Color	Numerical Value	Significance
1st band — Red	2	1st digit
2nd band — Green	5	2nd digit
3rd band — Yellow	4	No. of zeroes to add

Figure 10-49. End-to-center band marking.

There is no fourth color band; therefore, the tolerance is understood to be 20 percent. 20 percent of 250,000 Ω , equals 50,000 Ω .

Since the 20 percent tolerance is plus or minus,

$$\begin{aligned}
 \text{Maximum resistance} \\
 &= 250,000 \Omega + 50,000 \Omega \\
 &= 300,000 \Omega
 \end{aligned}$$

$$\begin{aligned}
 \text{Minimum resistance} \\
 &= 250,000 \Omega - 50,000 \Omega \\
 &= 200,000 \Omega
 \end{aligned}$$

The following paragraphs provide a few extra examples of resistor color band decoding. Figure 10-50 contains a resistor with another set of colors. This resistor code should be read as follows:

The resistance of this resistor is 86,000 \pm 10 percent ohms. The maximum resistance is 94,600 ohms, and the minimum resistance is 77,400 ohms.

As another example, the resistance of the resistor in Figure 10-51 is 960 \pm 5 percent ohms. The maximum resistance is 1,008 ohms, and the minimum resistance is 912 ohms.

Sometimes circuit considerations dictate that the tolerance must be smaller than 20 percent. Figure 10-52 shows an example of a resistor with a 2 percent tolerance. The resistance value of this resistor is 2,500 \pm 2 percent ohms. The maximum resistance is 2,550 ohms, and the minimum resistance is 2,450 ohms.

Figure 10-53 contains an example of a resistor with a black third color band. The color code value of black is zero, and the third band indicates the number of zeros to be added to the first two digits.

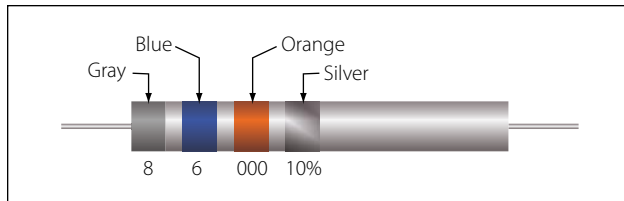


Figure 10-50. Resistor color code example.

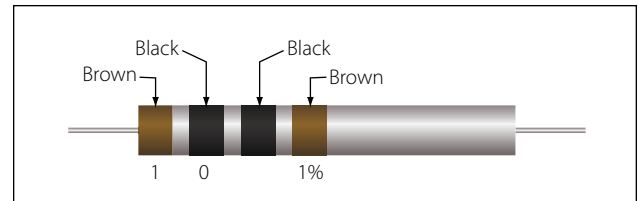


Figure 10-53. Resistor with black third color band.

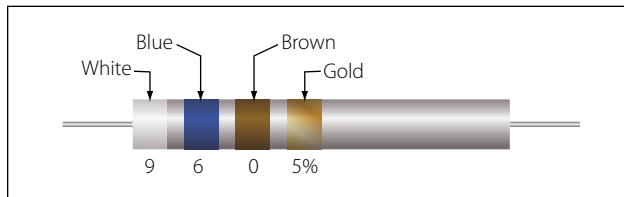


Figure 10-51. Resistor color code example.

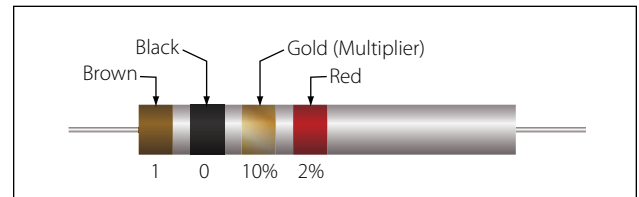


Figure 10-54. Resistor with gold third band.

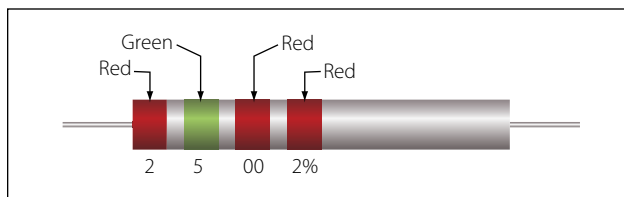


Figure 10-52. Resistor with two percent tolerance.

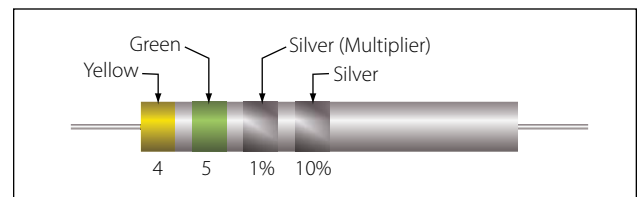


Figure 10-55. Resistor with a silver third band.

In this case, a zero number of zeros must be added to the first two digits; therefore, no zeros are added. Thus, the resistance value is 10 ± 1 percent ohms. The maximum resistance is 10.1 ohms, and the minimum resistance is 9.9 ohms. There are two exceptions to the rule stating the third color band indicates the number of zeros. The first of these exceptions is illustrated in Figure 10-54. When the third band is gold in color, it indicates that the first two digits must be multiplied by 10 percent. The value of this resistor in this case is:

$$10 \times 0.10 \pm 2\% = 1 = 0.02 \text{ ohms}$$

When the third band is silver, as is the case in Figure 10-55, the first two digits must be multiplied by 1 percent. The value of the resistor is 0.45 ± 10 percent ohms.

Wire-Wound

Wire-wound resistors typically control large amounts of current and have high power ratings. Resistors of this type are constructed by winding a resistance wire around an insulating rod, usually made of porcelain. The windings are then coated with an insulation material for physical protection and heat conduction. Both ends of the windings are then connected to terminals, which are used to connect the resistor to a circuit. [Figure 10-56]

A wire-wound resistor with tap is a special type of fixed resistor that can be adjusted. These adjustments can be made by moving a slide bar tap or by moving the tap to a preset incremental position. While the tap may be adjustable, the adjustments are usually set at the time of installation to a specific value and then operated in service as a fixed resistor. Another type of wire-wound resistor is that constructed of Manganin wire, used where high precision is needed.

Variable Resistors

Variable resistors are constructed so that the resistive value can be changed easily. This adjustment can be manual or automatic, and the adjustments can be made while the system that it is connected to is in operation. There are two basic types of manual adjusters. One is the rheostat and the second is the potentiometer.

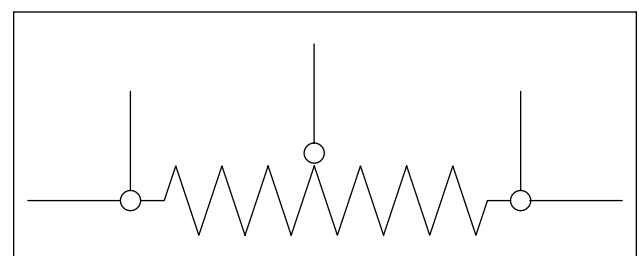


Figure 10-56. Wire-wound resistors.

Rheostat

The schematic symbol for the rheostat is shown in Figure 10-57. A rheostat is a variable resistor used to vary the amount of current flowing in a circuit. Figure 10-58 shows a rheostat connected in series with an ordinary resistance in a series circuit. As the slider arm moves from point A to B, the amount of rheostat resistance (AB) is increased. Since the rheostat resistance and the fixed resistance are in series, the total resistance in the circuit also increases, and the current in the circuit decreases. On the other hand, if the slider arm is moved toward point A, the total resistance decreases and the current in the circuit increases.

Potentiometer

The schematic symbol for the potentiometer is shown in Figure 10-59. The potentiometer is considered a three terminal device. As illustrated, terminals 1 and 2 have the entire value of the potentiometer resistance

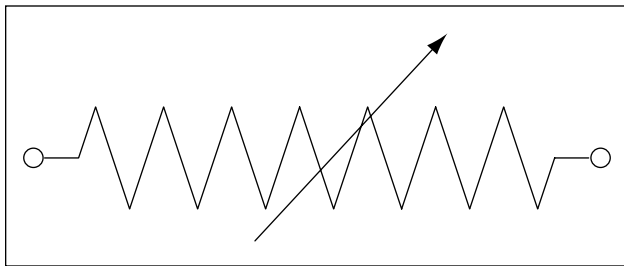


Figure 10-57. Rheostat schematic symbol.

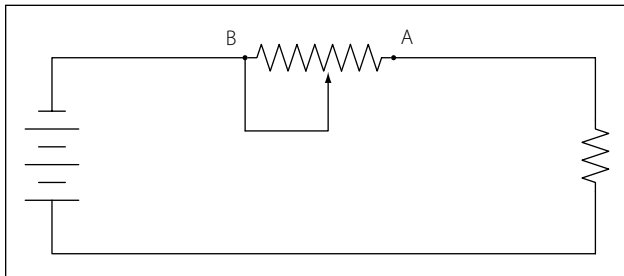


Figure 10-58. Rheostat connected in series.

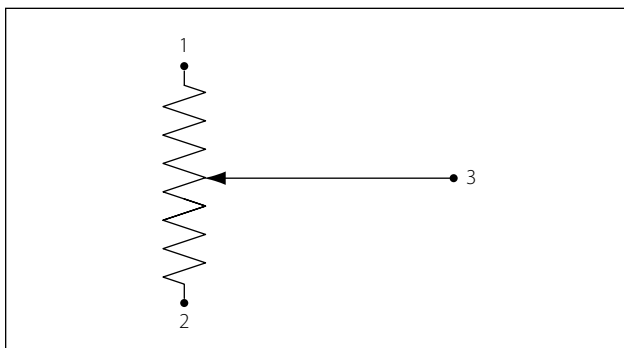


Figure 10-59. Potentiometer schematic symbol.

between them. Terminal 3 is the wiper or moving contact. Through this wiper, the resistance between terminals 1 and 3 or terminals 2 and 3 can be varied. While the rheostat is used to vary the current in a circuit, the potentiometer is used to vary the voltage in a circuit. A typical use for this component can be found in the volume controls on an audio panel and input devices for flight data recorders, among many other applications.

In Figure 10-60A, a potentiometer is used to obtain a variable voltage from a fixed voltage source to apply to an electrical load. The voltage applied to the load is the voltage between points 2 and 3. When the slider arm is moved to point 1, the entire voltage is applied to the electrical device (load); when the arm is moved to point 3, the voltage applied to the load is zero. The potentiometer makes possible the application of any voltage between zero and full voltage to the load.

The current flowing through the circuit of Figure 10-60 leaves the negative terminal electron flow of the battery and divides, one part flowing through the lower portion of the potentiometer (points 3 to 2) and the other part through the load. Both parts combine at point 2 and flow through the upper portion of the potentiometer (points 2 to 1) back to the positive terminal of the battery. In View B of Figure 10-60, a potentiometer and its schematic symbol are shown.

In choosing a potentiometer resistance, the amount of current drawn by the load should be considered as well

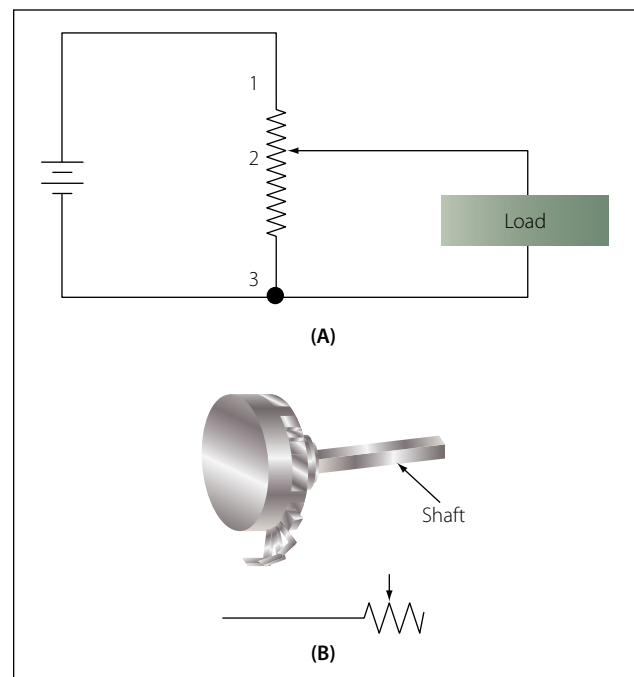


Figure 10-60. Potentiometer and schematic symbol.

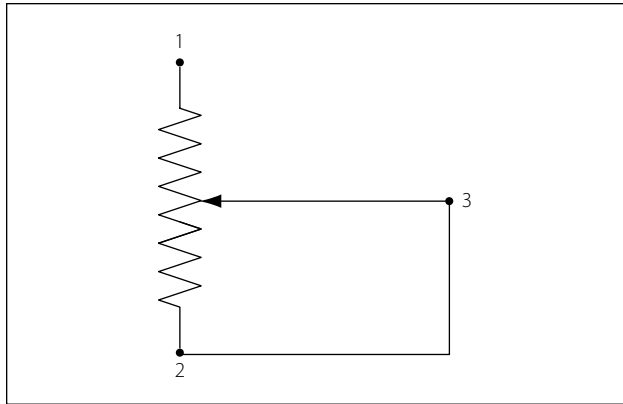


Figure 10-61. Potentiometer wired to function as rheostat.

as the current flow through the potentiometer at all settings of the slider arm. The energy of the current through the potentiometer is dissipated in the form of heat.

It is important to keep this wasted current as small as possible by making the resistance of the potentiometer as large as practicable. In most cases, the resistance of the potentiometer can be several times the resistance of the load. Figure 10-61 shows how a potentiometer can be wired to function as a rheostat.

Linear Potentiometers

In a linear potentiometer, the resistance between both terminal and the wiper varies linearly with the position of the wiper. To illustrate, one quarter of a turn on the potentiometer will result in one quarter of the total resistance. The same relationship exists when one-half or three-quarters of potentiometer movement. Figure 10-62 schematically depicts this.

Tapered Potentiometers

Resistance varies in a nonlinear manner in the case of the tapered potentiometer. Figure 10-63 illustrates this. Keep in mind that one-half of full potentiometer travel doesn't necessarily correspond to one-half the total resistance of the potentiometer.

Thermistors

Figure 10-64 shows the schematic symbol for the thermistor. The thermistor is a type of a variable resistor, which is temperature sensitive. This component has what is known as a negative temperature coefficient, which means that as the sensed temperature increases, the resistance of the thermistor decreases.

Photoconductive Cells

The photoconductive cell is similar to the thermistor. Like the thermistor, it has a negative temperature coefficient. Unlike the thermistor, the resistance is con-

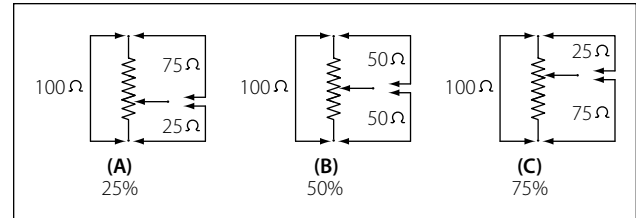


Figure 10-62. Linear potentiometer schematic.

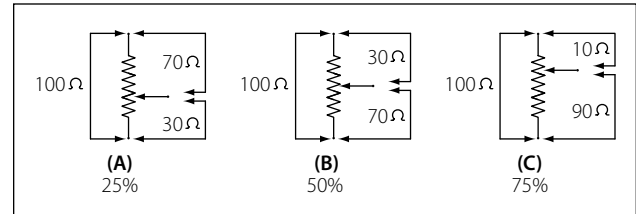


Figure 10-63. Tapered potentiometer.

trolled by light intensity. This kind of component can be found in radio control heads where the intensity of the ambient light is sensed through the photoconductive cell resulting in the backlighting of the control heads to adjust to the cockpit lighting conditions. Figure 10-65 shows the schematic symbol component.

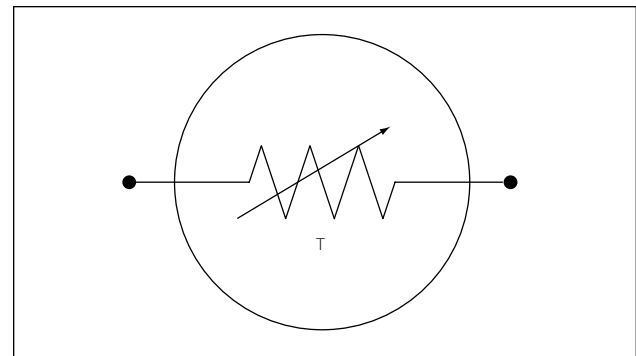


Figure 10-64. Schematic symbol for thermistor.

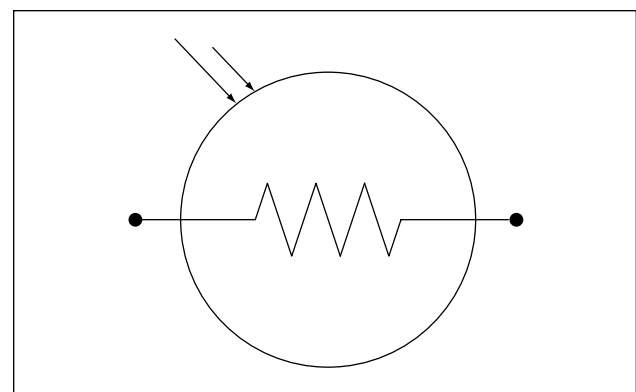


Figure 10-65. Photoconductive cell schematic symbol component.

Circuit Protection Devices

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

Most wires used in aircraft electrical circuits are small gauge, and their current carrying capacity is quite limited. The size of the wires used in any given circuit is determined by the amount of current the wires are expected to carry under normal operating conditions. Any current flow in excess of normal, such as the case of a direct short, would cause a rapid generation of heat. If the excessive current flow caused by the short is left unchecked, the heat in the wire will continue causing perhaps a portion of the wire to melt and at the very least, open the circuit.

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

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

Fuse

Figure 10-66 shows the schematic symbol for the fuse. Fuses are used to protect the circuit from over current conditions. The fuse is installed in the circuit so that

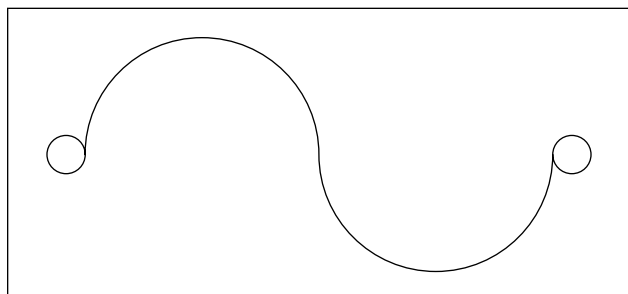


Figure 10-66. Schematic symbol for fuse.

all the current in the circuit passes through it. In most fuses, the strip of metal is made of an alloy of tin and bismuth, which will melt and open the circuit when the current exceeds the rated capacity of the fuse. For example, if a 5-amp fuse is placed into a circuit, the fuse will allow currents up to 5 amps to pass. Because the fuse is intended to protect the circuit, it is quite important that its capacity match the needs of the circuit in which it is used.

When replacing a fuse, consult the applicable manufacturer’s instructions to be sure a fuse of the correct type and capacity is installed. Fuses are installed in two types of fuse holders in aircraft. “Plug-in holders” or in-line holders are used for small and low capacity fuses. “Clip” type holders are used for heavy high capacity fuses and current limiters.

Current Limiter

The current limiter is very much like the fuse. However, the current limiter link is usually made of copper and will stand a considerable overload for a short period of time. Like the fuse it will open up in an over current condition in heavy current circuits such as 30 amp or greater. These are used primarily to sectionalize an aircraft circuit or bus. Once the limiter is opened, it must be replaced. The schematic symbol for the current limiter is the same as that for the fuse.

Circuit Breaker

The circuit breaker is commonly used in place of a fuse and is designed to break the circuit and stop the current flow when the current exceeds a predetermined value. Unlike the fuse, the circuit breaker can be reset; whereas the fuse or current limiter must be replaced. Figure 10-67 shows the schematic symbol for a circuit breaker.

There are several types of circuit breakers in general use in aircraft systems. One is a magnetic type. When excessive current flows in the circuit, it makes an elec-

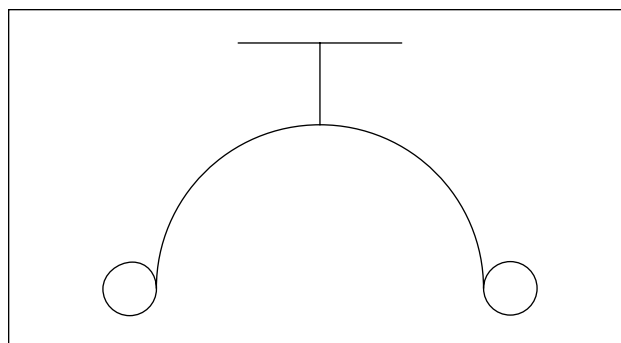


Figure 10-67. Schematic symbol for circuit breaker.

tromagnet strong enough to move a small armature, which trips the breaker. Another type is the thermal overload switch or breaker. This consists of a bimetallic strip which, when it becomes overheated from excessive current, bends away from a catch on the switch lever and permits the switch to trip open.

Most circuit breakers must be reset by hand. If the overload condition still exists, the circuit breaker will trip again to prevent damage to the circuit. At this point, it is usually not advisable to continue resetting the circuit breaker, but to initiate troubleshooting to determine the cause. Repeated resetting of a circuit breaker can lead to circuit or component damage or worse, the possibility of a fire or explosion.

Arc Fault Circuit Breaker

In recent years, the arc fault circuit breaker has begun to provide an additional layer of protection beyond that of the thermal protection already provided by conventional circuit breakers. The arc fault circuit breaker monitors the circuit for an electrical arcing signature, which can indicate possible wiring faults and unsafe conditions. These conditions can lead to fires or loss of power to critical systems. The arc fault circuit breaker is only beginning to make an appearance in the aircraft industry and is not widely used like the thermal type of circuit breaker.

Thermal Protectors

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

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

Control Devices

Components in the electrical circuits are typically not all intended to operate continuously or automatically. Most of them are meant to operate at certain times, under certain conditions, to perform very definite functions. There must be some means of controlling their

operation. Either a switch, or a relay, or both may be included in the circuit for this purpose.

Switches

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

An understanding of some basic definitions of the switch is necessary before any of the switch types are discussed. The number of poles, throws, and positions they have designates toggle switches, as well as some other type of switches.

Pole: the switch's movable blade or contactor. The number of poles is equal to the number of circuits, or paths for current flow, that can be completed through the switch at any one time.

Throw: indicates the number of circuits, or paths for current, that it is possible to complete through the switch with each pole or contactor.

Positions: indicates the number of places at which the operating device (toggle, plunger, and so forth) will come to rest and at the same time open or close one or more circuits.

Toggle Switch

Single-Pole, Single-Throw (SPST)

The single-pole, single-throw switch allows a connection between two contacts. One of two conditions will exist. Either the circuit is open in one position or closed in the other position. The schematic symbol for this switch is shown in Figure 10-68.

Single-Pole, Double-Throw (SPDT)

The single-pole, double-throw switch is shown in Figure 10-69. With this switch, contact between one contact can be made between one contact and the other.

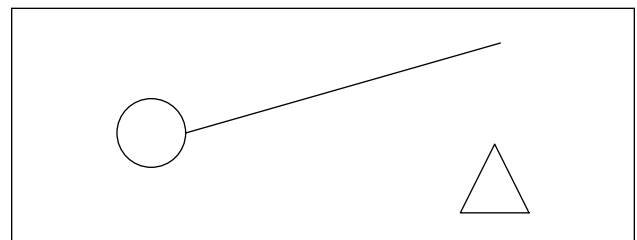


Figure 10-68. Single-pole, single-throw switch schematic symbol.

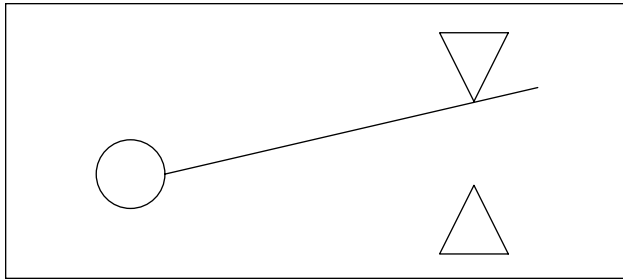


Figure 10-69. Single-pole, double-throw switch schematic symbol.

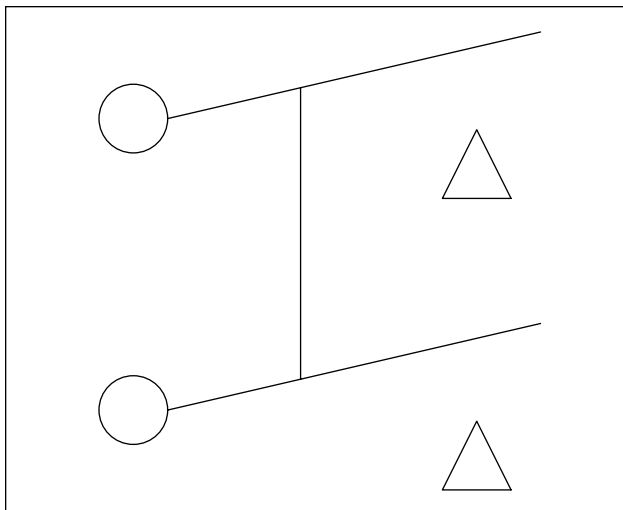


Figure 10-70. Double-pole, single-throw switch schematic symbol.

Double-Pole, Single-Throw (DPST)

The double-pole, single-throw switch connection can be made between one set of contacts and either of two other sets of contacts. The schematic symbol for this switch is shown in Figure 10-70.

Double-Pole, Double-Throw (DPDT)

The schematic symbol for the double-pole, double-throw switch is shown in Figure 10-71. This type of switch makes a connection from one set of contacts to either of two other sets of contacts.

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

A switch that stays open, except when it is held in the closed position, is a normally open switch (usually

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

Locking toggles require the operator to pull out on the switch toggle before moving it in to another position. Once in the new position, the switch toggle is release back into a lock, which then prevents the switch from inadvertently being moved.

Pushbutton Switches

Pushbutton switches have one stationary contact and one movable contact. The movable contact is attached to the pushbutton. The pushbutton is either an insulator itself or is insulated from the contact. This switch is spring loaded and designed for momentary contact.

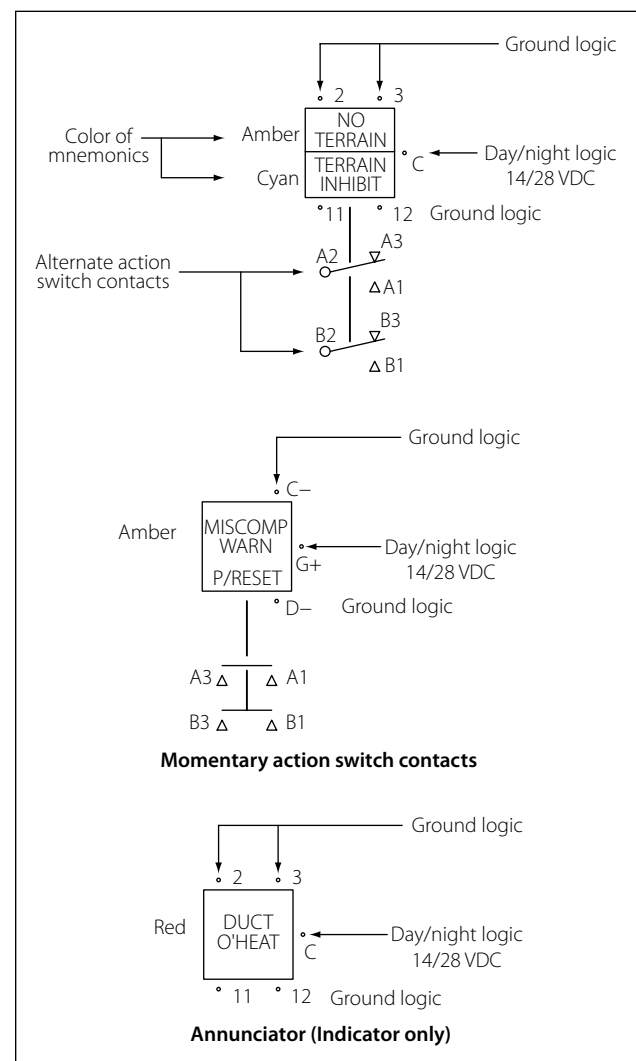


Figure 10-71. Double-pole, double-throw switch schematic symbol.

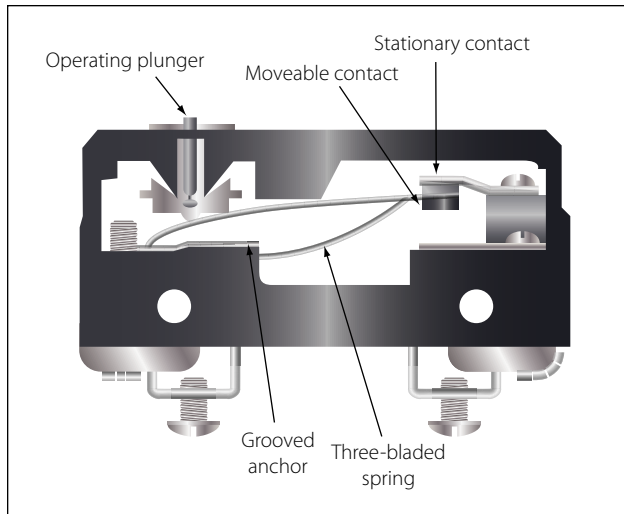


Figure 10-72. Cross-section of a microswitch.

Microswitches

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

Microswitches are usually pushbutton switches. They are used primarily as limit switches to provide automatic control of landing gears, actuator motors, and the like. The diagram in Figure 10-72 shows a normally closed microswitch in cross-section and illustrates how these switches operate. When the operating plunger is pressed in, the spring and the movable contact are pushed, opening the contacts and the circuit.

Rotary Selector Switches

A rotary selector switch takes the place of several switches. When the knob of the switch is rotated, the switch opens one circuit and closes another. Ignition

switches and voltmeter selector switches are typical examples of this kind of switch. [Figure 10-73]

Lighted Pushbutton Switches

Another more common switch found in today's aircraft is the lighted pushbutton switch. This type of switch takes the form of a 5/8-inch to 1-inch cube with incandescent or LED lights to indicate the function of the switch. Switch designs come in a number of configurations; the two most common are the alternate action and momentary action and will usually have a two-pole or four-pole switch body. Other less common switch actions are the alternate and momentary holding coil configurations. The less known holding or latching coil switch bodies are designed to have a magnetic coil inside the switch body that is energized through two contacts in the base of the switch. When the coil is energized and the switch is pressed, the switch contacts will remain latched until power is removed from the coil. This type of design allows for some degree of remote control over the switch body. Figure 10-71 illustrates a schematic representation of this switch design.

The display optics of the lighted pushbutton switch provide the crew with a clear message that is visible under a wide range of lighting conditions with very high luminance and wide viewing angles. While some displays are simply a transparent screen that is backlit by an incandescent light, the higher quality and more reliable switches are available in sunlight readable displays and night vision (NVIS) versions. Due to the sunlight environment of the cockpit, displays utilizing standard lighting techniques will "washout" when viewed in direct sunlight. Sunlight readable displays are designed to minimize this effect.

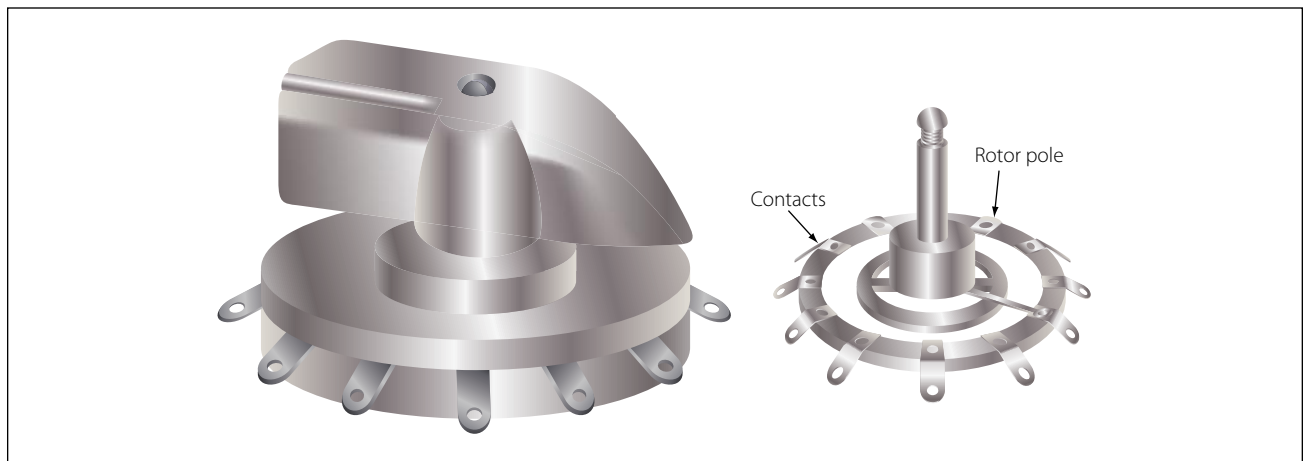


Figure 10-73. Rotary selector switch.

Lighted pushbutton switches can also be used in applications where a switch is not required and the optics are only for indications. This type of an indicator is commonly called an annunciator.

DIP Switches

The acronym “DIP” switch is defined as Dual In-Line Parallel switch in reference to the physical layout. DIP switches are commonly found in card cages, and line replaceable units (LRU) are used in most cases to adjust gains, control configurations, and so forth. Each one of the switches is generally an SPST slide or rocker switch. The technician may find this switch in packages ranging in size from DIP2 through DIP32. Some of the more common sizes are DIP4 and DIP8.

Switch Guards

Switch guards are covers that protect a switch from unintended operation. Prior to the operation of the switch, the guard is usually lifted. Switch guards are commonly found on systems such as fire suppression and override logics for various systems.

Relays

A relay is simply an electromechanical switch where a small amount of current can control a large amount of current. Figure 10-74 illustrates the basic relay in

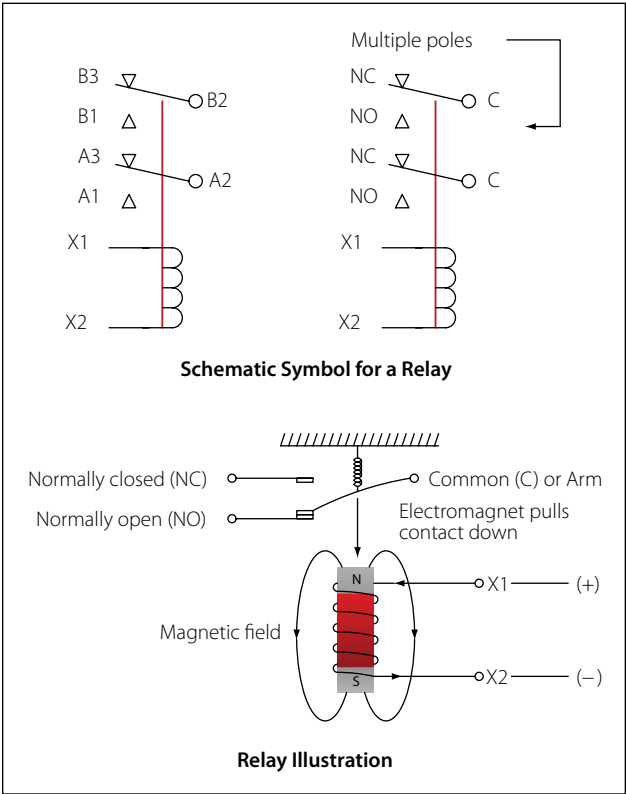


Figure 10-74. Basic relay.

both schematic and pictorial format. When a voltage is applied to the coil of the relay, the electromagnet will be energized due to the current. When energized, an electromagnetic field will pull the common (C) or arm of the relay down. When the arm or common is pulled down, the circuit between the arm and the normally closed (NC) contacts is opened and the circuit between the arm and the normally open (NO) contacts are closed. When the energizing voltage is removed, the spring will return the arm contacts back to the normally closed (NC) contacts. The relay usually has two connections for the coil. The (+) side is designated as X1 and the ground-side of the coil is designated as X2.

Series DC Circuits

Introduction

The series circuit is the most basic electrical circuit and provides a good introduction to basic circuit analysis. The series circuit represents the first building block for all of the circuits to be studied and analyzed. Figure 10-75 shows this simple circuit with nothing more than a voltage source or battery, a conductor, and a resistor. This is classified as a series circuit because the components are connected end-to-end, so that the same current flows through each component equally. There is only one path for the current to take and the battery and resistor are in series with each other. Next is to make a few additions to the simple circuit in Figure 10-75.

Figure 10-76 shows an additional resistor and a little more detail regarding the values. With these values, we can now begin to learn more about the nature of the circuit. In this configuration, there is a 12-volt DC source in series with two resistors, R1 = 10 Ω and R2 = 30 Ω. For resistors in a series configuration, the total resistance of the circuit is equal to the sum of the individual resistors. The basic formula is:

$$R_T = R_1 + R_2 + R_3 +R_N$$

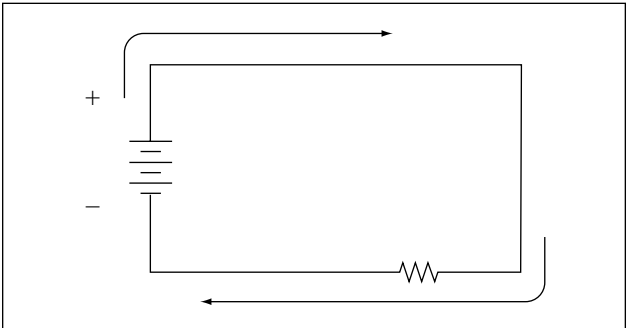


Figure 10-75. Simple DC circuit.

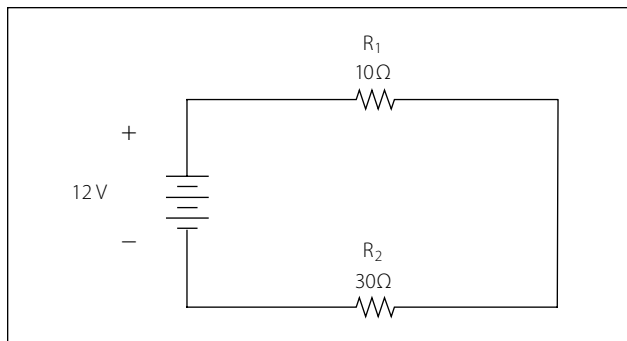


Figure 10-76. Inducing minimum voltage in an elementary generator.

For Figure 10-76, this will be:

$$R_T = 10\Omega + 30\Omega$$

$$R_T = 40\Omega$$

Now that the total resistance of the circuit is known, the current for the circuit can be determined. In a series circuit, the current cannot be different at different points within the circuit. The current through a series circuit will always be the same through each element and at any point. Therefore, the current in the simple circuit can now be determined using Ohm's law:

$$\text{Formula, } E = I (R)$$

$$\text{Solve for current, } I = \frac{E}{R}$$

$$\text{The variables, } E = 12\text{V and } R_T = 40\Omega$$

$$\text{Substitute variables, } I = \frac{12\text{V}}{40\Omega}$$

$$\text{Current in circuits, } I = 0.3\text{A}$$

Ohm's law describes a relationship between the variables of voltage, current, and resistance that is linear and easy to illustrate with a few extra calculations.

First will be the act of changing the total resistance of the circuit while the other two remain constant. In this example, the R_T of the circuit in Figure 10-76 will be doubled. The effects on the total current in the circuit are:

$$\text{Formula, } E = I (R)$$

$$\text{Solve for current, } I = \frac{E}{R}$$

$$\text{The variables, } E = 12\text{V and } R_T = 80\Omega$$

$$\text{Substitute variables, } I = \frac{12\text{V}}{80\Omega}$$

$$\text{Current in circuits, } I = 0.15\text{A}$$

It can be seen quantitatively and intuitively that when the resistance of the circuit is doubled, the current is reduced by half the original value.

Next, reduce the R_T of the circuit in Figure 10-76 to half of its original value. The effects on the total current are:

$$\text{Formula, } E = I (R)$$

$$\text{Solve for current, } I = \frac{E}{R}$$

$$\text{The variables, } E = 12\text{V and } R_T = 20\Omega$$

$$\text{Substitute variables, } I = \frac{12\text{V}}{20\Omega}$$

$$\text{Current in circuits, } I = 0.6\text{A}$$

Voltage Drops and Further Application of Ohm's Law

The example circuit in Figure 10-77 will be used to illustrate the idea of voltage drop. It is important to differentiate between voltage and voltage drop when discussing series circuits. Voltage drop refers to the loss in electrical pressure or emf caused by forcing electrons through a resistor. Because there are two resistors in the example, there will be separate voltage drops. Each drop is associated with each individual resistor. The amount of electrical pressure required to force a given number of electrons through a resistance is proportional to the size of the resistor.

In Figure 10-77, the values used to illustrate the idea of voltage drop are:

$$\text{Current, } I = 1\text{mA}$$

$$R_1 = 1\text{ k}\Omega$$

$$R_2 = 3\text{ k}\Omega$$

$$R_3 = 5\text{ k}\Omega$$

The voltage drop across each resistor will be calculated using Ohm's law. The drop for each resistor is the product of each resistance and the total current in the circuit. Keep in mind that the same current flows through series resistor.

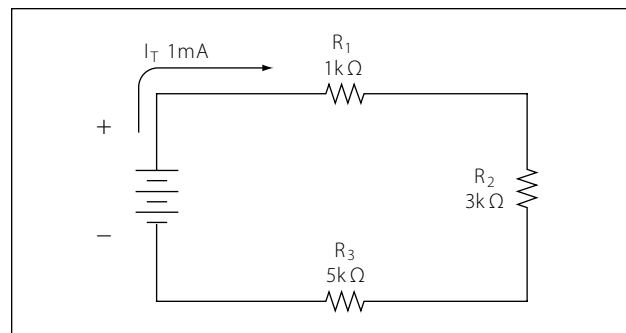


Figure 10-77. Example of three resistors in series.

Formula, $E = I (R)$
 Voltage across R_1 : $E_1 = I_T (R_1)$
 $E_1 = 1 \text{ mA} (1 \text{ k } \Omega) = 1 \text{ volt}$
 Voltage across R_2 : $E_2 = I_T (R_2)$
 $E_2 = 1 \text{ mA} (3 \text{ k } \Omega) = 3 \text{ volt}$
 Voltage across R_3 : $E_3 = I_T (R_3)$
 $E_3 = 1 \text{ mA} (5 \text{ k } \Omega) = 5 \text{ volt}$

The source voltage can now be determined, which can then be used to confirm the calculations for each voltage drop. Using Ohm's law:

Formula: $E = I (R)$
 Source voltage = current times the total resistance
 $E_S = I (R_T)$
 $R_T = 1 \text{ k } \Omega + 3 \text{ k } \Omega + 5 \text{ k } \Omega$
 $R_T = 9 \text{ k } \Omega$
 Now: $E_S = I (R_T)$
 Substitute $E_S = 1 \text{ mA} (9 \text{ k } \Omega)$
 $E_S = 9 \text{ volts}$

Simple checks to confirm the calculation and to illustrate the concept of the voltage drop add up the individual values of the voltage drops and compare them to the results of the above calculation.

$$1 \text{ volt} + 3 \text{ volts} + 5 \text{ volts} = 9 \text{ volts.}$$

Voltage Sources in Series

A voltage source is an energy source that provides a constant voltage to a load. Two or more of these sources in series will equal the algebraic sum of all the sources connected in series. The significance of pointing out the algebraic sum is to indicate that the polarity of the sources must be considered when adding up the sources. The polarity will be indicated by a plus or minus sign depending on the source's position in the circuit.

In Figure 10-78 all of the sources are in the same direction in terms of their polarity. All of the voltages have the same sign when added up. In the case of Figure 10-78, three cells of a value of 1.5 volts are in series

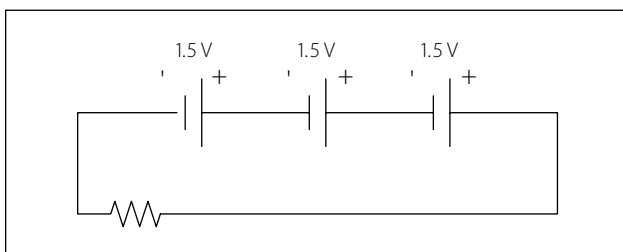


Figure 10-78. Voltage sources in series add algebraically.

with the polarity in the same direction. The addition is simple enough:

$$E_T = 1.5\text{v} + 1.5\text{v} + 1.5\text{v} = +4.5 \text{ volts}$$

However, in Figure 10-79, one of the three sources has been turned around, and the polarity opposes the other two sources. Again the addition is simple:

$$E_T = + 1.5\text{v} - 1.5\text{v} + 1.5\text{v} = +1.5 \text{ volts}$$

Kirchhoff's Voltage Law

A law of basic importance to the analysis of an electrical circuit is Kirchhoff's voltage law. This law simply states that the algebraic sum of all voltages around a closed path or loop is zero. Another way of saying it: The sum of all the voltage drops equals the total source voltage. A simplified formula showing this law is shown below:

With three resistors in the circuit:
 $E_S - E_1 - E_2 - E_3 \dots - E_N = 0 \text{ volts}$

Notice that the sign of the source is opposite that of the individual voltage drops. Therefore, the algebraic sum equals zero. Written another way:

$$E_S = E_1 + E_2 + E_3 \dots + E_N$$

The source voltage equals the sum of the voltage drops.

The polarity of the voltage drop is determined by the direction of the current flow. When going around the circuit, notice that the polarity of the resistor is opposite that of the source voltage. The positive on the resistor is facing the positive on the source and the negative towards the negative.

Figure 10-80 illustrates the very basic idea of Kirchhoff's voltage law. There are two resistors in this example. One has a drop of 14 volts and the other has a drop of 10 volts. The source voltage must equal the sum of the voltage drops around the circuit. By inspection it is easy to determine the source voltage as 24 volts.

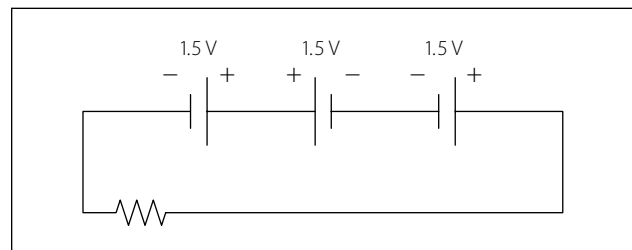


Figure 10-79. Voltage sources add algebraically; one source reversed.

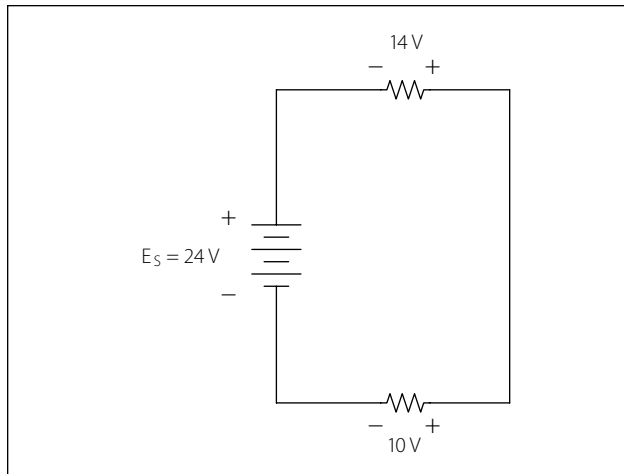


Figure 10-80. Kirchhoff's voltage law.

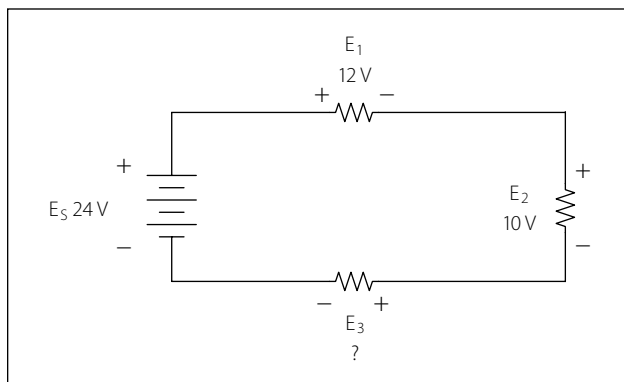


Figure 10-81. Determine the unknown voltage drop.

Figure 10-81 shows a series circuit with three voltage drops and one voltage source rated at 50 volts. Two of the voltage drops are known. However, the third is not known. Using Kirchhoff's voltage law, the third voltage drop can be determined.

With three resistors in the circuit:

$$E_S - E_1 - E_2 - E_3 = 0 \text{ volts}$$

Substitute the known values:

$$24\text{v} - 12\text{v} - 10\text{v} - E_3 = 0$$

Collect known values: $2\text{v} - E_3 = 0$

Solve for the unknown: $E_3 = 2 \text{ volts}$

Determine the value of E_4 in Figure 10-82. For this example, $I = 200 \text{ mA}$.

First, the voltage drop across each of the individual resistors must be determined.

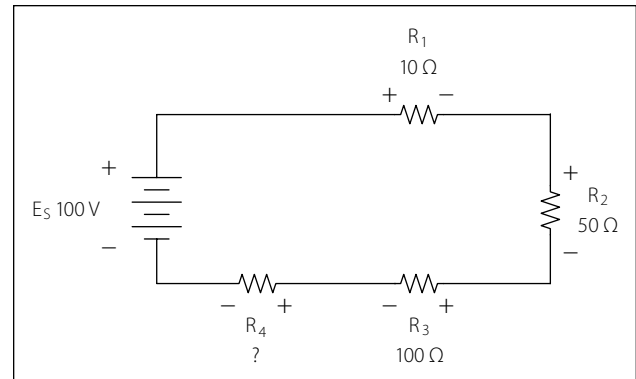


Figure 10-82. Determine the unknown voltage drop.

$$E_1 = I (R_1)$$

$$E_1 = (200 \text{ mA}) (10 \Omega)$$

Voltage drop across R_1 $E_1 = 2 \text{ volts}$

$$E_2 = I (R_2)$$

$$E_2 = (200 \text{ mA}) (50 \Omega)$$

Voltage drop across R_2 $E_2 = 10 \text{ volts}$

$$E_3 = I (R_3)$$

$$E_3 = (200 \text{ mA}) (100 \Omega)$$

Voltage drop across R_3 $E_3 = 20 \text{ volts}$

Kirchhoff's voltage law is now employed to determine the voltage drop across E_4 .

With four resistors in the circuit:

$$E_S - E_1 - E_2 - E_3 - E_4 = 0 \text{ volts}$$

Substituting values:

$$100\text{v} - 2\text{v} - 10\text{v} - 20\text{v} - E_4 = 0$$

Combine: $68\text{v} - E_4 = 0$

Solve for unknown: $E_4 = 68 \text{ v}$

Using Ohm's law and substituting in E_4 , the value for R_4 can now be determined.

$$\text{Ohm's law: } R = \frac{E}{I}$$

$$\text{Specific application: } R_4 = \frac{E_4}{I}$$

$$\text{Substitute values: } R_4 = \frac{68\text{V}}{200 \text{ mA}}$$

$$\text{Value for } R_4: R_4 = 340 \Omega$$

Voltage Dividers

Voltage dividers are devices that make it possible to obtain more than one voltage from a single power source. A voltage divider usually consists of a resistor, or resistors connected in series, with fixed or movable contacts and two fixed terminal contacts. As current

flows through the resistor, different voltages can be obtained between the contacts.

Series circuits are used for voltage dividers. The voltage divider rule allows the technician to calculate the voltage across one or a combination of series resistors without having to first calculate the current in the circuit. Because the current flows through each resistor, the voltage drops are proportional to the ohmic values of the constituent resistors.

A typical voltage divider is shown in Figure 10-83.

To understand how a voltage divider works, examine Figure 10-84 carefully and observe the following:

Each load draws a given amount of current: I_1 , I_2 , I_3 . In addition to the load currents, some bleeder current (I_B) flows. The current (I_T) is drawn from the power source and is equal to the sum of all currents.

The voltage at each point is measured with respect to a common point. Note that the common point is the

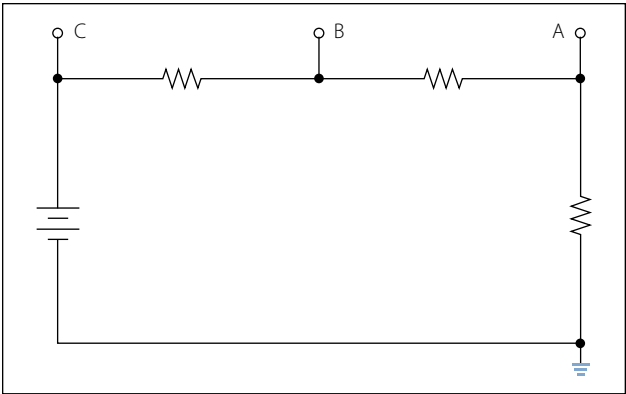


Figure 10-83. A voltage divider circuit.

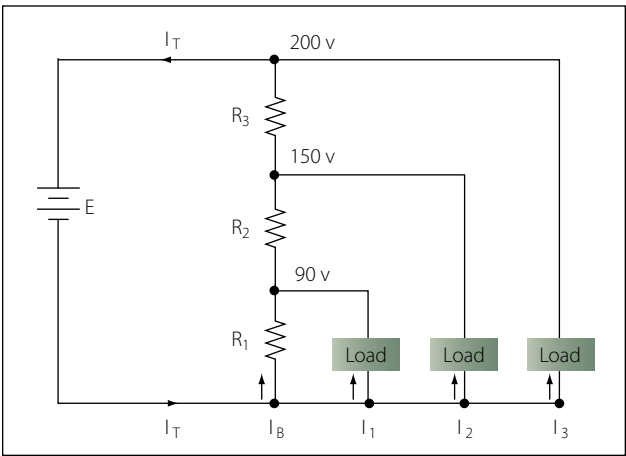


Figure 10-84. A typical voltage divider.

point at which the total current (I_T) divides into separate currents (I_1 , I_2 , I_3).

Each part of the voltage divider has a different current flowing in it. The current distribution is as follows:

- Through R_1 — bleeder current (I_B)
- Through R_2 — I_B plus I_1
- Through R_3 — I_B plus I_1 , plus I_2

The voltage across each resistor of the voltage divider is:

- 90 volts across R_1
- 60 volts across R_2
- 50 volts across R_3

The voltage divider circuit discussed up to this point has had one side of the power supply (battery) at ground potential. In Figure 10-85 the common reference point (ground symbol) has been moved to a different point on the voltage divider. The voltage drop across R_1 is 20 volts; however, since tap A is connected to a point in the circuit that is at the same potential as the negative side of the battery, the voltage between tap A and the reference point is a negative (–) 20 volts. Since resistors R_2 and R_3 are connected to the positive side of the battery, the voltages between the reference point and tap B or C are positive.

The following rules provide a simple method of determining negative and positive voltages: (1) If current enters a resistance flowing away from the reference point, the voltage drop across that resistance is positive in respect to the reference point; (2) if current flows out of a resistance toward the reference point, the voltage drop across that resistance is negative in respect to the reference point. It is the location of the reference point that determines whether a voltage is negative or positive.

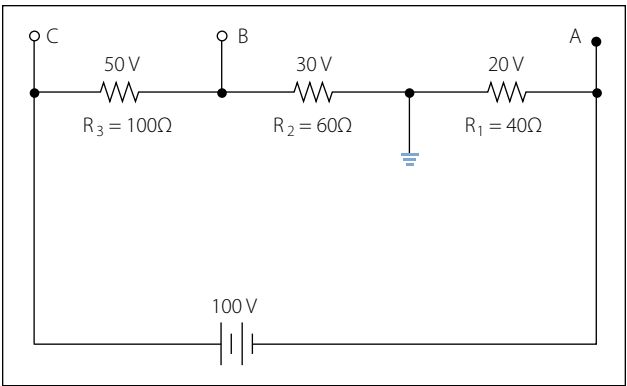


Figure 10-85. Positive and negative voltage on a voltage divider.

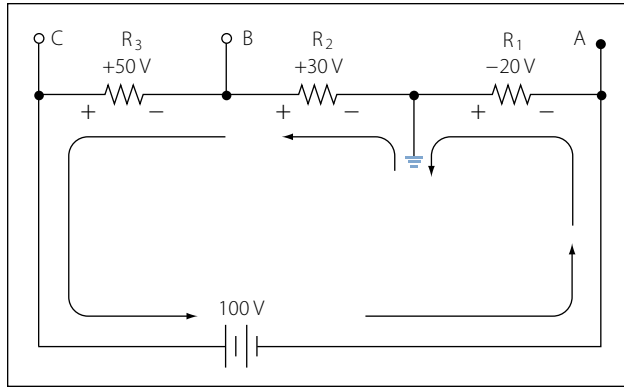


Figure 10-86. Current flow through a voltage divider.

Tracing the current flow provides a means for determining the voltage polarity. Figure 10-86 shows the same circuit with the polarities of the voltage drops and the direction of current flow indicated.

The current flows from the negative side of the battery to R_1 . Tap A is at the same potential as the negative terminal of the battery since the slight voltage drop caused by the resistance of the conductor is disregarded; however, 20 volts of the source voltage are required to force the current through R_1 and this 20-volt drop has the polarity indicated. Stated another way, there are only 80 volts of electrical pressure left in the circuit on the ground side of R_1 .

When the current reaches tap B, 30 more volts have been used to move the electrons through R_2 , and in a similar manner the remaining 50 volts are used for R_3 . But the voltages across R_2 and R_3 are positive voltages, since they are above ground potential.

Figure 10-87 shows the voltage divider used previously. The voltage drops across the resistances are the same; however, the reference point (ground) has been changed. The voltage between ground and tap A is now a negative 100 volts, or the applied voltage.

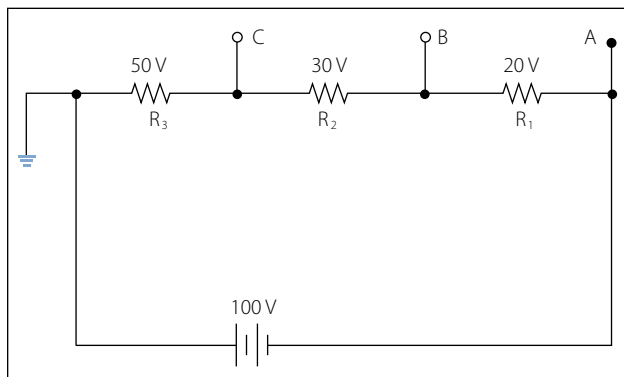


Figure 10-87. Voltage divider with changed ground.

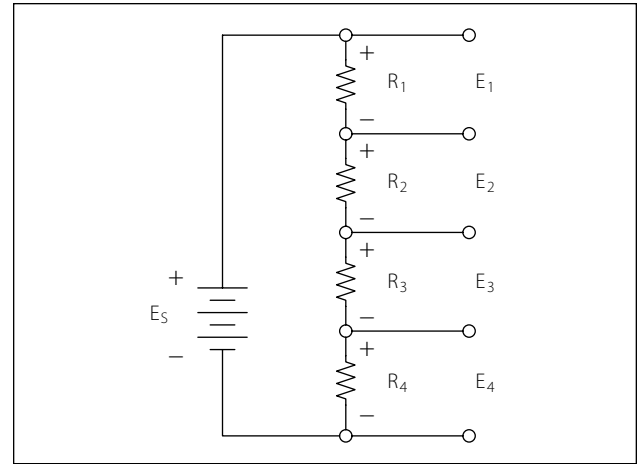


Figure 10-88. Four resistor voltage divider.

The voltage between ground and tap B is a negative 80 volts, and the voltage between ground and tap C is a negative 50 volts.

Determining the Voltage Divider Formula

Figure 10-88 shows the example network of four resistors and a voltage source. With a few simple calculations, a formula for determining the voltage divisions in a series circuit can be determined.

The voltage drop across any particular resistor shall be called E_X , where the subscript x is the value of a particular resistor (1, 2, 3, or 4). Using Ohm's law, the voltage drop across any resistor can be determined.

$$\text{Ohm's law: } E_X = I (R_X)$$

As seen earlier in the text, the current is equal to the source voltage divided by the total resistance of the series circuit.

$$\text{Current: } I = \frac{E_S}{R_T}$$

The current equation can now be substituted into the equation for Ohm's law.

$$\text{Substitute: } E_X = \left(\frac{E_S}{R_T} \right) (R_X)$$

$$\text{Algebraic rearrange: } E_X = \left(\frac{R_X}{R_T} \right) (E_S)$$

This equation is the general voltage divider formula. The explanation of this formula is that the voltage drop across any resistor or combination of resistors in a series circuit is equal to the ratio of the resistance value to the total resistance, divided by the value of the source voltage. Figure 10-89 illustrates this with a network of three resistors and one voltage source.

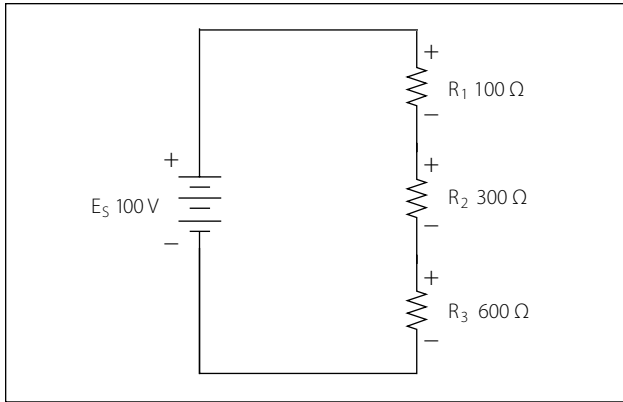


Figure 10-89. Network of three resistors and one voltage source.

$$E_X = \left(\frac{R_X}{R_T} \right) E_S$$

$$R_T = 100 \, \Omega + 300 \, \Omega + 600 \, \Omega = 1000 \, \Omega$$

$$E_S = 100 \text{ volts}$$

Voltage drop over 100 Ω resistor is:

$$E_X = \left(\frac{100 \, \Omega}{1000 \, \Omega} \right) 100 \text{ V}$$

$$E_{100 \, \Omega} = 10 \text{ V}$$

Voltage drop over 300 Ω resistor is:

$$E_X = \left(\frac{300 \, \Omega}{1000 \, \Omega} \right) 100 \text{ V}$$

$$E_{100 \, \Omega} = 30 \text{ V}$$

Voltage drop over 600 Ω resistor is:

$$E_X = \left(\frac{600 \, \Omega}{1000 \, \Omega} \right) 100 \text{ V}$$

$$E_{100 \, \Omega} = 60 \text{ V}$$

Checking work

$$E_T = 10 \text{ V} + 30 \text{ V} + 60 \text{ V} = 100 \text{ V}$$

Parallel DC Circuits

Overview

A circuit in which two or more electrical resistances or loads are connected across the same voltage source is called a parallel circuit. The primary difference between the series circuit and the parallel circuit is that more than one path is provided for the current in the parallel circuit. Each of these parallel paths is called a branch. The minimum requirements for a parallel circuit are the following:

- A power source.
- Conductors.

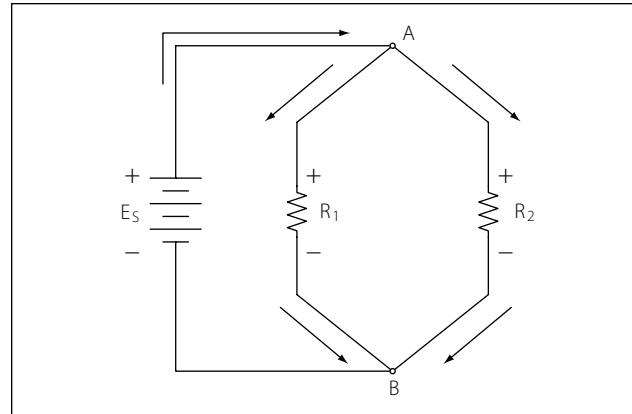


Figure 10-90. Basic parallel circuit.

- A resistance or load for each current path.
- Two or more paths for current flow.

Figure 10-90 depicts the most basic parallel circuit. Current flowing out of the source divides at point A in the diagram and goes through R_1 and R_2 . As more branches are added to the circuit, more paths for the source current are provided.

Voltage Drops

The first point to understand is that the voltage across any branch is equal to the voltage across all of the other branches.

Total Parallel Resistance

The voltage across any branch is equal to the voltage across all of the other branches.

The parallel circuit consists of two or more resistors connected in such a way as to allow current flow to pass through all of the resistors at once. This eliminates the need for current to pass one resistor before passing through the next. When resistors are connected in parallel, the total resistance of the circuit decreases. The total resistance of a parallel combination is always less than the value of the smallest resistor in the circuit. In the series circuit, the current has to pass through the resistors one at a time. This gave a resistance to the current equal the sum of all the resistors. In the parallel circuit, the current has several resistors that it can pass through, actually reducing the total resistance of the circuit in relation to any one resistor value.

The amount of current passing through each resistor will vary according to its individual resistance. The total current of the circuit will then be the sum of the current in all branches. It can be determined by inspection that the total current will be greater than that of any given branch. Using Ohm's law to calculate the

resistance based on the applied voltage and the total current, it can be determined that the total resistance is less than any individual branch.

An example of this is if there was a circuit with a 100 Ω resistor and a 5 Ω resistor; while the exact value must be calculated, it still can be said that the combined resistance between the two will be less than the 5 Ω .

Resistors in Parallel

The formula for the total parallel resistance is as follows:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots \frac{1}{R_N}$$

If the reciprocal of both sides is taken, then the general formula for the total parallel resistance is:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots \frac{1}{R_N}}$$

Two Resistors in Parallel

Typically, it is more convenient to consider only two resistors at a time because this setup occurs in common practice. Any number of resistors in a circuit can be broken down into pairs. Therefore, the most common method is to use the formula for two resistors in parallel.

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

Combining the terms in the denominator and rewriting

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

Put in words, this states that the total resistance for two resistors in parallel is equal to the product of both resistors divided by the sum of the two resistors. In the formula below, calculate the total resistance.

General formula $R_T = \frac{R_1 R_2}{R_1 + R_2}$

Known values $R_1 = 500 \Omega$

$R_2 = 400 \Omega$

$$R_T = \frac{500 \Omega \cdot 400 \Omega}{500 \Omega + 400 \Omega}$$

$$R_T = \frac{200000 \Omega}{900 \Omega}$$

$$R_T = 222.22 \Omega$$

Current Source

A current source is an energy source that provides a constant value of current to a load even when the load changes in resistive value. The general rule to remember is that the total current produced by current sources in parallel is equal to the algebraic sum of the individual sources.

Kirchhoff's Current Law

Kirchhoff's current law can be stated as: The sum of the currents into a junction or node is equal to the sum of the currents flowing out of that same junction or node. A junction can be defined as a point in the circuit where two or more circuit paths come together. In the case of the parallel circuit, it is the point in the circuit where the individual branches join.

General formula $I_T = I_1 + I_2 + I_3$

Refer to Figure 10-91 for an illustration. Point A and point B represent two junctions or nodes in the circuit with three resistive branches in between. The voltage source provides a total current I_T into node A. At this point, the current must divide, flowing out of node A into each of the branches according to the resistive value of each branch. Kirchhoff's current law states that the current going in must equal that going out. Following the current through the three branches and back into node B, the total current I_T entering node B and leaving node B is the same as that which entered node A. The current then continues back to the voltage source.

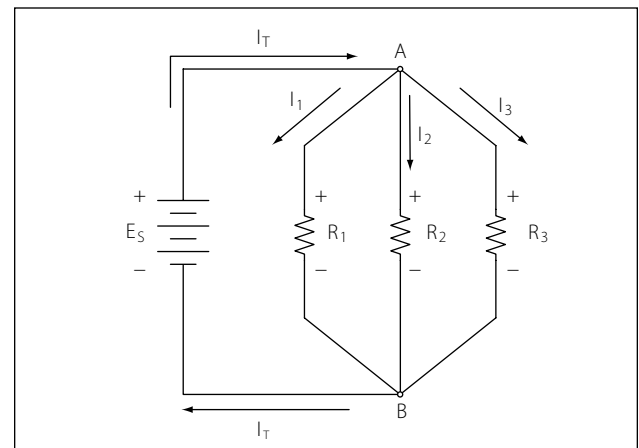


Figure 10-91. Kirchhoff's current law.

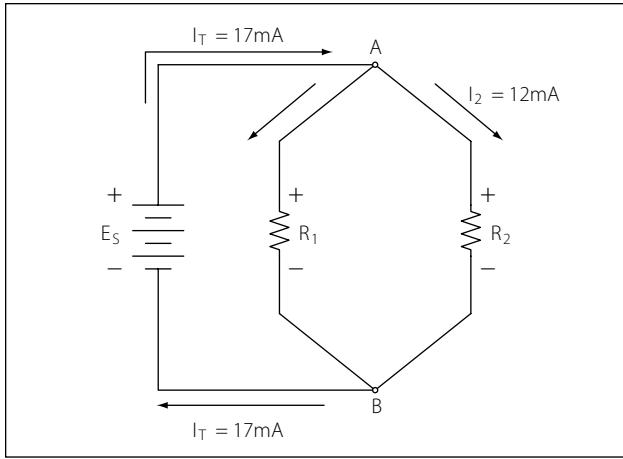


Figure 10-92. Individual branch currents.

Figure 10-92 shows that the individual branch currents are:

$$I_1 = 5 \text{ mA}$$

$$I_2 = 12 \text{ mA}$$

The total current flow into the node A equals the sum of the branch currents, which is:

$$I_T = I_1 + I_2$$

Substitute $I_T = 5\text{mA} + 12\text{mA}$

$$I_T = 17\text{mA}$$

The total current entering node B is also the same.

Figure 10-93 illustrates how to determine an unknown current in one branch. Note that the total current into a junction of the three branches is known. Two of the branch currents are known. By rearranging the general formula, the current in branch two can be determined.

General formula $I_T = I_1 + I_2 + I_3$

Substitute $75\text{mA} = 30\text{mA} + I_2 + 20\text{mA}$

Solve I_2 $I_2 = 75\text{mA} - 30\text{mA} - 20\text{mA}$

$$I_2 = 25\text{mA}$$

Current Dividers

It can now be easily seen that the parallel circuit is a current divider. As could be seen in Figure 10-90, there is a current through each of the two resistors. Because the same voltage is applied across both resistors in parallel, the branch currents are inversely proportional to the ohmic values of the resistors. Branches with higher resistance have less current than those with lower resistance. For example, if the resistive value of R_2 is twice as high as that of R_1 , the current in R_2 will be half of that of R_1 . All of this can be determined with Ohm's law.

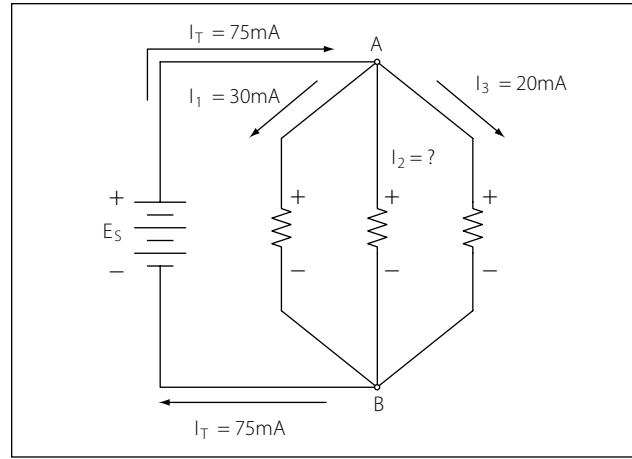


Figure 10-93. Determining an unknown circuit in branch 2.

By Ohm's law, the current through any one of the branches can be written as:

$$I_X = E_S / R_X$$

The voltage source appears across each of the parallel resistors and R_X represents any one the resistors. The source voltage is equal to the total current times the total parallel resistance.

$$E_S = I_T R_T$$

Substituting $I_T R_T$ for E_S $I_X = \frac{I_T R_T}{R_X}$

Rearranging $I_X = \left(\frac{R_T}{R_X} \right) I_T$

$$I_2 = \left(\frac{R_T}{R_2} \right) I_T$$

And $I_1 = \left(\frac{R_T}{R_1} \right) I_T$

This formula is the general current divider formula. The current through any branch equals the total parallel resistance divided by the individual branch resistance, multiplied by the total current.

Series-Parallel DC Circuits

Overview

Most of the circuits that the technician will encounter will not be a simple series or parallel circuit. Circuits are usually a combination of both, known as series-parallel circuits, which are groups consisting of resistors in parallel and in series. An example of this type of circuit can be seen in Figure 10-94. While the series-parallel circuit can initially appear to be complex, the same rules that have been used for the series and parallel circuits can be applied to these circuits.

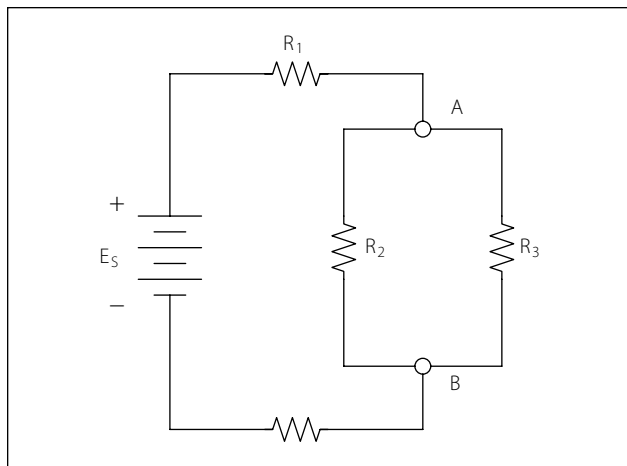


Figure 10-94. Series-parallel circuits.

The voltage source will provide a current out to resistor R_1 , then to the group of resistors R_2 and R_3 and then to the next resistor R_4 before returning to the voltage source. The first step in the simplification process is to isolate the group R_2 and R_3 and recognize that they are a parallel network that can be reduced to an equivalent resistor. Using the formula for parallel resistance,

$$R_{23} = \frac{R_2 R_3}{R_2 + R_3}$$

R_2 and R_3 can be reduced to R_{23} . Figure 10-95 now shows an equivalent circuit with three series connected resistors. The total resistance of the circuit can now be simply determined by adding up the values of resistors R_1 , R_{23} , and R_4 .

Determining the Total Resistance

A more quantitative example for determining total resistance and the current in each branch in a combina-

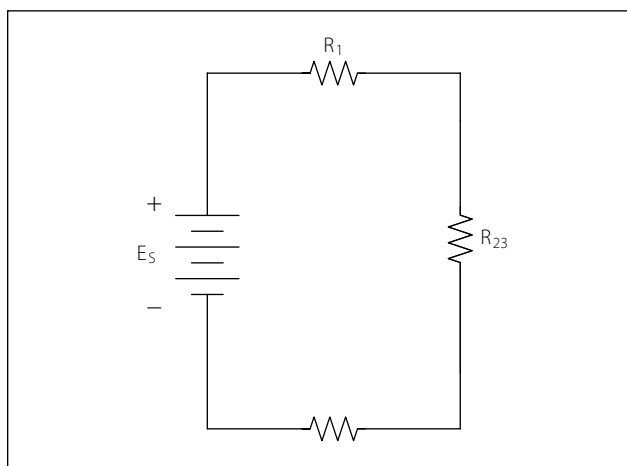


Figure 10-95. Equivalent circuit with three series connected resistors.

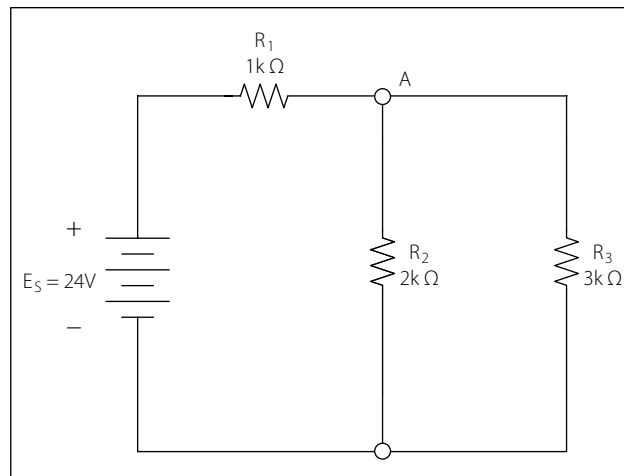


Figure 10-96. Determining total resistance.

tion circuit is shown in the following example. Also refer to Figure 10-96.

The first step is to determine the current at junction A, leading into the parallel branch. To determine the I_T , the total resistance R_T of the entire circuit must be known. The total resistance of the circuit is given as:

$$R_T = R_1 + R_{23}$$

Where $R_{23} = \left(\frac{R_2 R_3}{R_2 + R_3} \right)$ Parallel network

Find R_{EQ} $R_{23} = \frac{2k\Omega \cdot 3k\Omega}{2k\Omega + 3k\Omega}$

Solve for R_{EQ} $R_{23} = \frac{6000k\Omega}{5k\Omega}$

$$R_{23} = 1.2k\Omega$$

Solve for R_T $R_T = 1k\Omega + 1.2k\Omega$

$$R_T = 2.2k\Omega$$

With the total resistance R_T now determined, the total I_T can be determined. Using Ohm's law:

$$I_T = \frac{E_S}{R_T}$$

Substitute values $I_T = \frac{24V}{2.2k\Omega}$

$$I_T = 10.9mA$$

The current through the parallel branches of R_2 and R_3 can be determined using the current divider rule discussed earlier in the text. Recall that:

Current divider rule $I_2 = \left(\frac{R_T}{R_2}\right)(I_T)$

And $I_3 = \left(\frac{R_T}{R_3}\right)(I_T)$

Substitute values for I_2

$$I_2 = \left(\frac{R_2 + R_3}{R_2}\right)(I_T)$$

$$I_2 = \left(\frac{2k\ \Omega + 3k\ \Omega}{2k\ \Omega}\right)(10.9mA)$$

$$I_2 = \left(\frac{5k\ \Omega}{2k\ \Omega}\right)(10.9mA)$$

$$I_2 = 2.5\ \Omega (10.9mA)$$

$$I_2 = 1.25mA$$

Now using Kirchhoff's current law, the current in branch with R_3 can be determined.

$$I_T = I_2 + I_3$$

$$I_3 = I_T - I_2$$

$$I_3 = 10.9mA - 1.25mA$$

$$I_3 = 9.65mA$$

Alternating Current and Voltage

Alternating current has largely replaced direct current in commercial power systems for a number of reasons. It can be transmitted over long distances more readily and more economically than direct current, since 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. 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 commutation trouble at high altitude is eliminated. Circuit breakers will operate satisfactorily under load 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.

AC and DC Compared

"AC" stands for Alternating Current. Many of the principles, characteristics, and effects of AC are similar to those of direct current. Similarly, there are a number of differences, which will be explained. Direct current flows constantly in only one direction with a constant polarity. It changes magnitude only when the circuit is opened or closed, as shown in the DC waveform in Figure 10-97. Alternating current changes direction at regular intervals, increases in value at a definite rate from zero to a maximum positive strength, and decreases back to zero; then it flows in the opposite direction, similarly increasing to a maximum negative value, and again decreasing to zero. DC and AC waveforms are compared in Figure 10-97.

Since alternating current constantly changes direction and intensity, the following two effects (to be discussed later) take place in AC circuits that do not occur in DC circuits:

1. Inductive reactance.
2. Capacitive reactance.

Generator Principles

After the discovery that an electric current flowing through a conductor creates a magnetic field around the conductor, there was considerable scientific speculation about whether a magnetic field could create a current flow in a conductor. In 1831, it was demonstrated this could be accomplished.

To show how an electric current can be created by a magnetic field, a demonstration similar to that illustrated in Figure 10-98 can be used. Several turns of

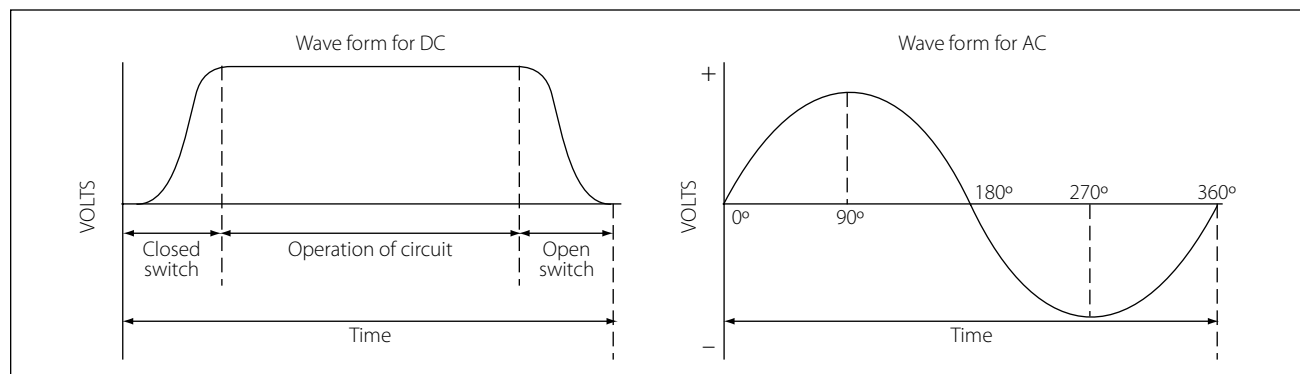


Figure 10-97. DC and AC voltage curves.

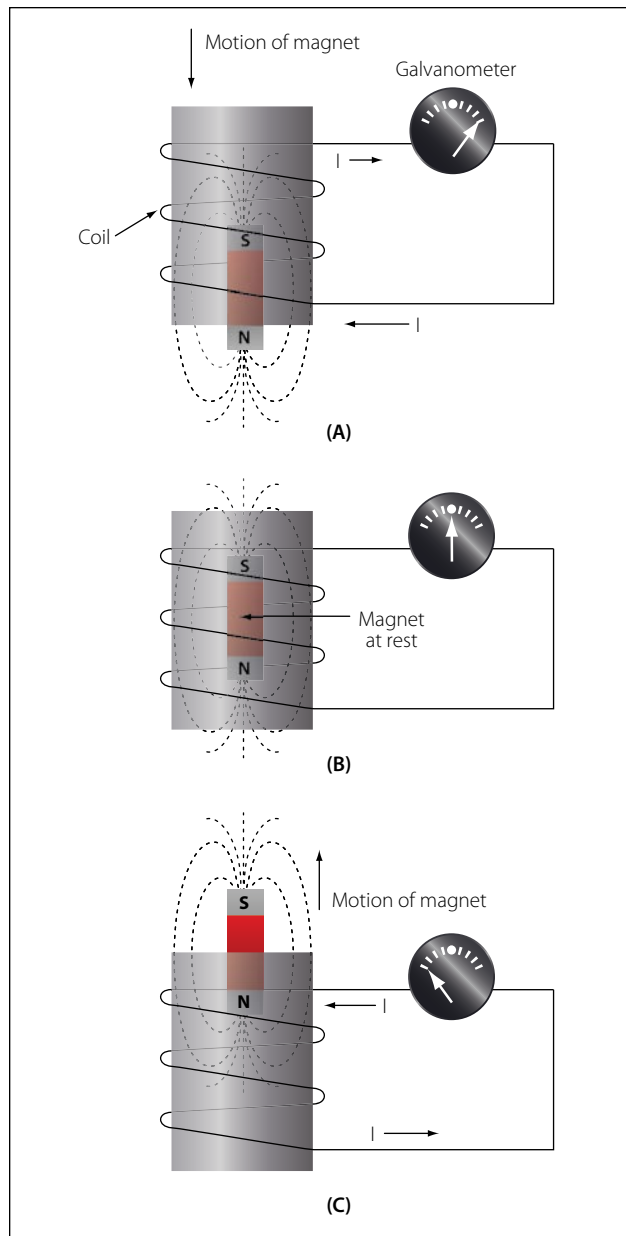


Figure 10-98. Inducing a current flow.

a conductor are wrapped around a cylindrical form, and the ends of the conductor are connected together to form a complete circuit, which includes a galvanometer. If a simple bar magnet is plunged into the cylinder, the galvanometer can be observed to deflect in one direction from its zero (center) position (Figure 10-98A).

When the magnet is at rest inside the cylinder, the galvanometer shows a reading of zero, indicating that no current is flowing (Figure 10-98B).

In Figure 10-98C, the galvanometer indicates a current flow in the opposite direction when the magnet is pulled from the cylinder.

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

The induced current caused by the relative motion of a conductor and a magnetic field always flows in such a direction that its magnetic field opposes the motion.

When a conductor is moved through a magnetic field, an electromotive force (emf) is induced in the conductor. [Figure 10-99] The direction (polarity) of the induced emf is determined by the magnetic lines of force and the direction the conductor is moved through the magnetic field. The generator left-hand rule (not to be confused with the left-hand rules used with a coil) can be used to determine the direction of the induced emf. [Figure 10-100] The left-hand rule is summed up as follows:

The first finger of the left hand is pointed in the direction of the magnetic lines of force (north to south), the

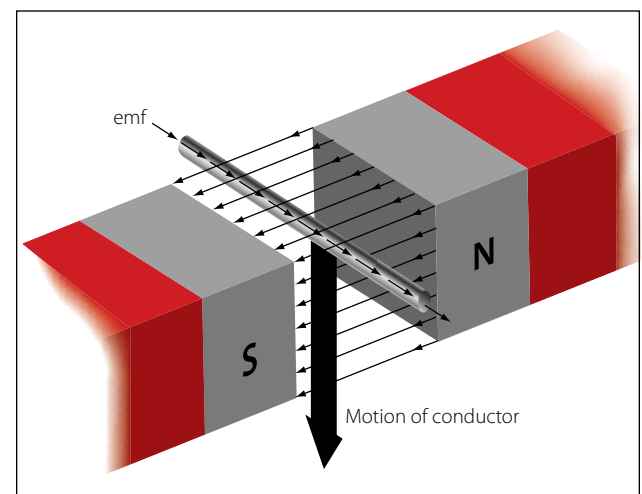


Figure 10-99. Inducing an emf in a conductor.

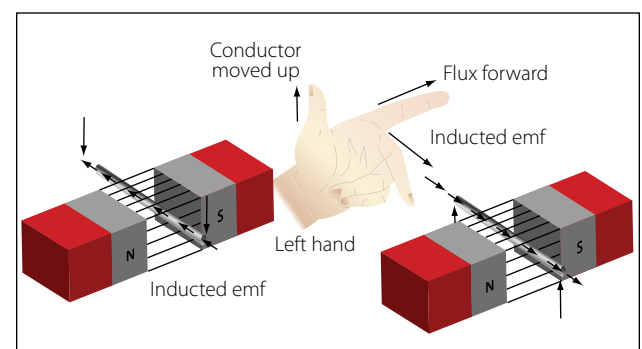


Figure 10-100. An application of the generator left-hand rule.

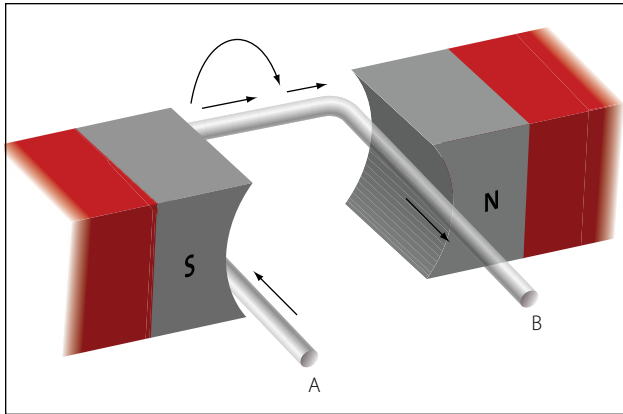


Figure 10-101. Voltage induced in a loop.

thumb is pointed in the direction of movement of the conductor through the magnetic field, and the second finger points in the direction of the induced emf.

When a loop conductor is rotated in a magnetic field, a voltage is induced in each side of the loop. [Figure 10-101] The two sides cut the magnetic field in opposite directions, and although the current flow is continuous, it moves in opposite directions with respect to the two sides of the loop. If sides A and B and the loop are rotated half a turn and the sides of the conductor have exchanged positions, the induced emf in each wire reverses its direction, since the wire formerly cutting the lines of force in an upward direction is now moving downward.

The value of an induced emf depends on three factors:

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

Generators of Alternating Current

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

The simple generator constitutes one method of generating an alternating voltage. [Figure 10-102] It consists of a rotating loop, marked A and B, placed between two magnetic poles, N and S. The ends of the loop are connected to two metal slip rings (collector rings), 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 A moves up across the field, a voltage is induced which causes the current to flow inward. As wire B moves down across the field, a voltage is induced which causes the current to flow outward. When the wires are formed into a loop, the voltages induced in the two sides of the loop are combined. Therefore, for explanatory purposes, the action of either conductor, A or B, while rotating in the magnetic field is similar to the action of the loop.

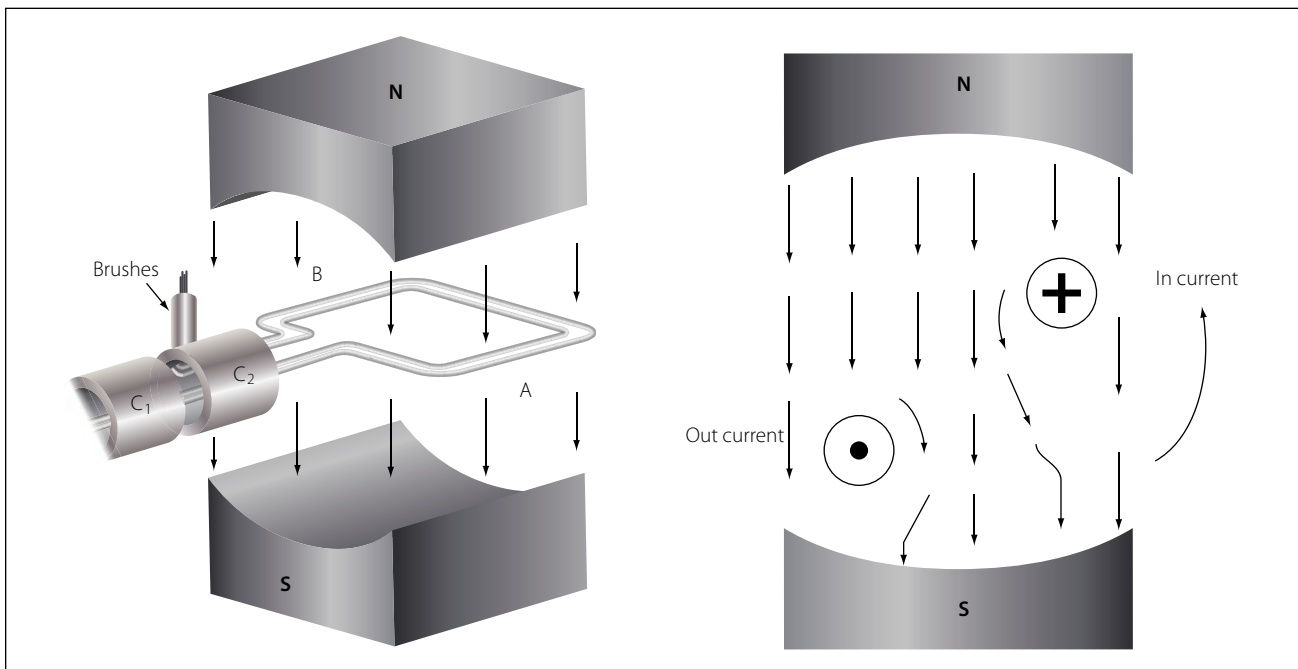


Figure 10-102. Simple generator.

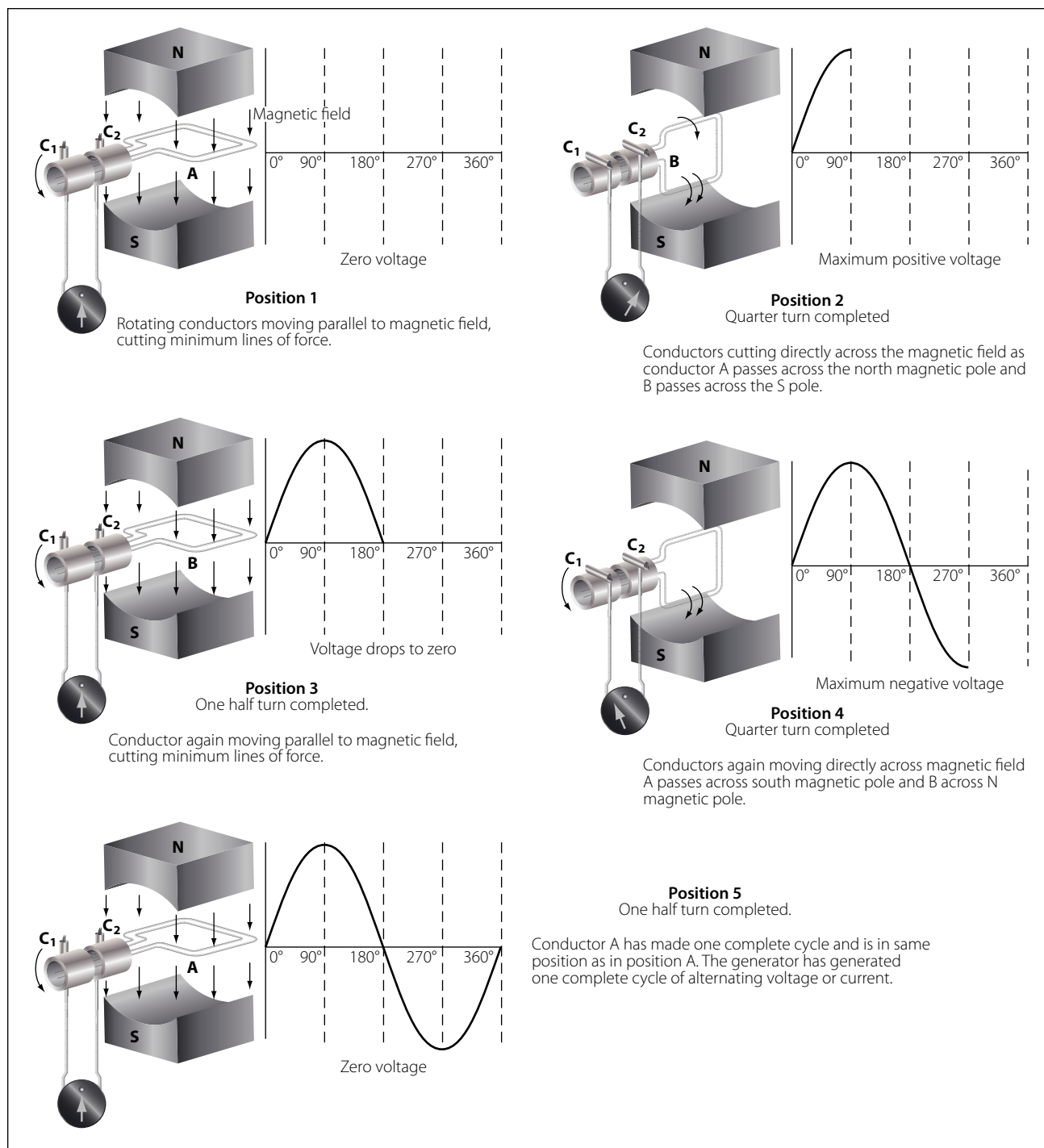


Figure 10-103. Generation of a sine wave.

Figure 10-103 illustrates the generation of alternating current with a simple loop conductor rotating in a magnetic field. As it is rotated in a counterclockwise direction, varying values of voltages are induced in it.

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 voltage induced gradually increases.

Position 2

The conductor is now moving 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 at each instant, and the induced voltage decreases.

Position 3

At this point, the conductor has made one-half of 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 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 values of the voltages generated. The horizontal base line is divided into degrees, or time, and the vertical distance above or below the base line represents the value of voltage at each particular point in the rotation of the loop.

Cycle and Frequency

Cycle Defined

A cycle is a repetition of a pattern. Whenever a voltage or current passes through a series of changes, returns to the starting point, and then again starts the same series of changes, the series is called a cycle. The cycle is represented by the symbol of a wavy line in a circle (Ⓢ). In the cycle of voltage shown in Figure 10-104, the voltage increases from zero to a maximum positive value, decreases to zero; then increases to a maximum negative value, and again decreases to zero. At this point, it is ready to go through the same series of changes. There are two alternations in a complete cycle: the positive alternation and the negative. Each is half a cycle.

Frequency Defined

The frequency is the number of cycles of alternating current per second (1 second). The standard unit of frequency measurement is the hertz (Hz). [Figure 10-105]

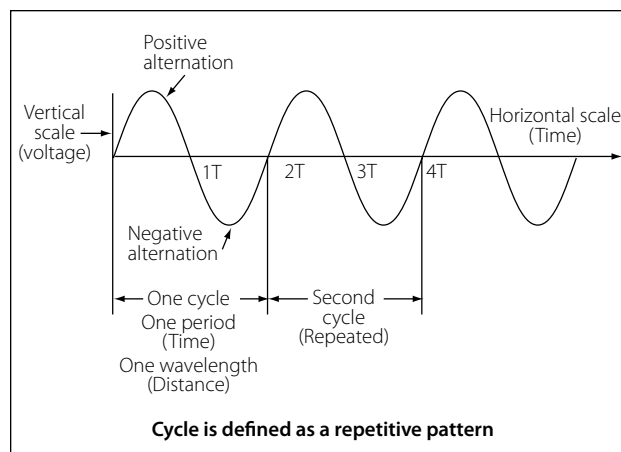


Figure 10-104. Cycle of voltage.

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

$$F = \frac{\text{Number of poles}}{2} \times \frac{\text{rpm}}{60}$$

where $P/2$ is the number of pairs of poles, and rpm/60 the number of revolutions per second. If in a 2 pole generator, the conductor is turning at 3,600 rpm, the revolutions per second are

$$\text{rps} = \frac{3600}{60} = 60 \text{ revolutions per second}$$

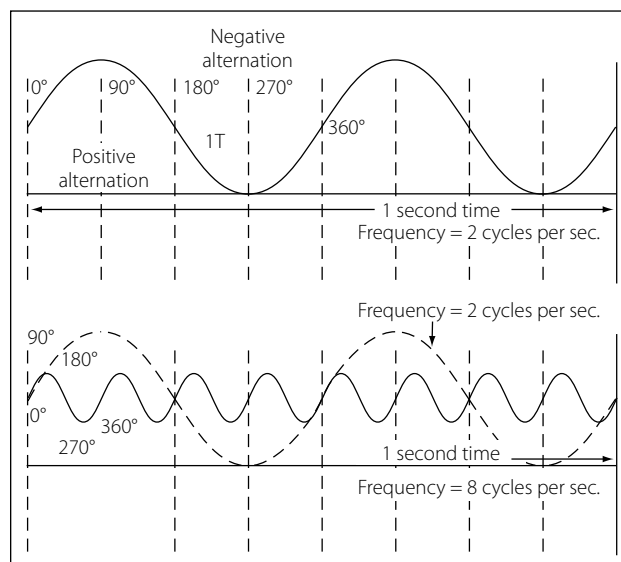


Figure 10-105. Frequency in cycles per second.

Since there are 2 poles, $P/2$ is 1, and the frequency is 60 cycles per second (cps). In a 4 pole generator with an armature speed of 1,800 rpm, substitute in the equation,

$$F = \frac{P}{2} \times \frac{\text{rpm}}{60} \text{ as follows}$$

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

$$F = 2 \times 30$$

$$F = 60 \text{ cps}$$

Period Defined

The time required for a sine wave to complete one full cycle is called a period. [Figure 10-104] 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 will be. The mathematical relationship between frequency and period is given as:

$$\text{Period is } t = \frac{1}{f}$$

$$\text{Frequency is } f = \frac{1}{t}$$

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). The measurement of wavelength is taken from one point on the waveform to a corresponding point on the next waveform. [Figure 10-104]

Phase Relationships

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

In Phase Condition

Figure 10-106A, 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 volt-

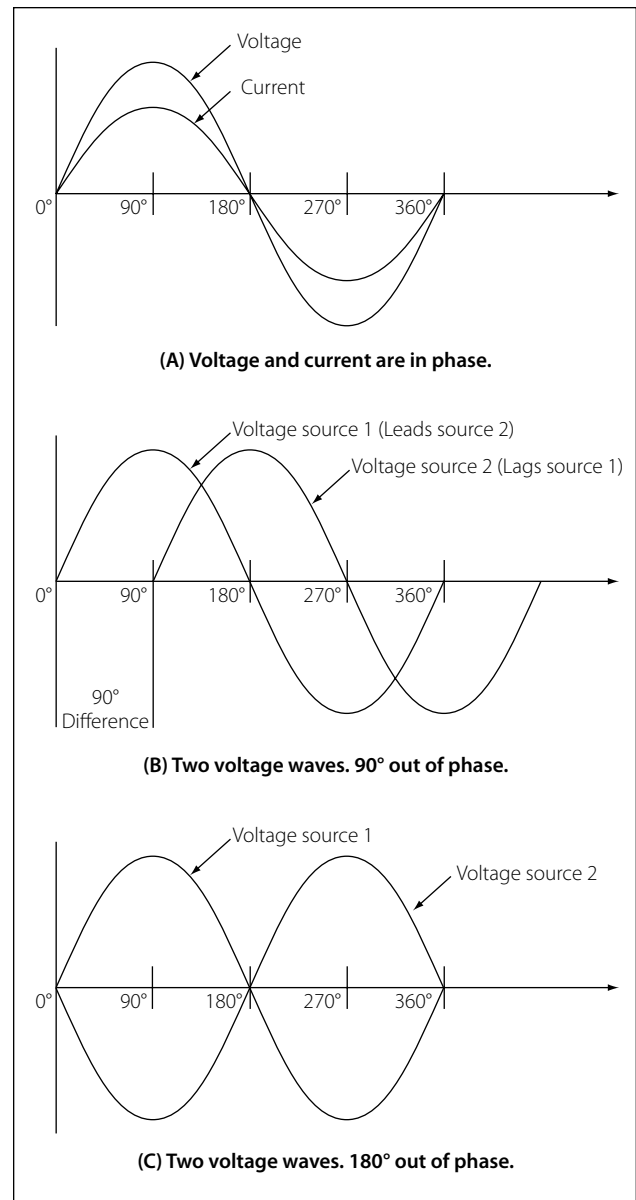


Figure 10-106. In phase and out of phase conditions.

age 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, such as these in Figure 10-106A, 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.

Out of Phase Condition

When two waveforms go through their maximum and minimum points at different times, a phase difference will exist 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 10-106B shows this relationship. Voltage source one starts to rise at the 0° position and voltage source two starts to rise at the 90° position. Because voltage source one begins its rise earlier in time (90°) in relation to the second voltage source, it is said to be leading the second source. On the other hand, the second source 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 10-106]

A practical note of caution: *When encountering an aircraft that has two or more AC busses in use, it is possible that they may be split and not synchronized to be in phase with each other. When two signals that are not locked in phase are mixed, much damage can occur to aircraft systems or avionics.*

Values of Alternating Current

There are three values of alternating current, which are instantaneous, peak, and effective (root mean square, RMS).

Instantaneous Value

An instantaneous value of voltage or current is the induced voltage or current flowing at any instant during a cycle. 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 Value

The peak value is the largest instantaneous value. The largest single positive value occurs when the sine wave of voltage is at 90° , and the largest single negative value occurs when it is at 270° . Maximum value is 1.41 times the effective value. These are called peak values.

Effective Value

The effective value is also known as the RMS value or root mean square, which refers to the mathematical process by which the value is derived. Most AC voltmeters will display the effective or RMS value when used. The

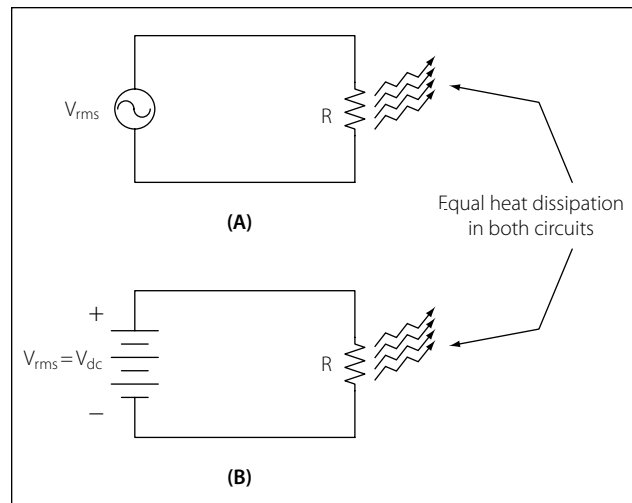


Figure 10-107. Sine wave effective value.

effective value is less than the maximum value, being equal to .707 times the maximum value.

The effective value of a sine wave is actually a measure of the heating effect of the sine wave. Figure 10-107 illustrates what happens when a resistor is connected across an AC voltage source. In illustration A, a certain amount of heat is generated by the power in the resistor. Illustration B shows the same resistor now inserted into a DC voltage source. The value of the DC voltage source can now be adjusted so that the resistor dissipates the same amount of heat as it did when it was in the AC circuit. The RMS or effective value of a sine wave is equal to the DC voltage that produces the same amount of heat as the sinusoidal voltage.

The peak value of a sine wave can be converted to the corresponding RMS value using the following relationship.

$$V_{rms} = (\sqrt{0.5}) \times V_p$$

$$V_{rms} = 0.707 \times V_p$$

This can be applied to either voltage or current.

Algebraically rearranging the formula and solving for V_p can also determine the peak voltage. The resulting formula is:

$$V_p = 1.414 \times V_{rms}$$

Thus, the 110 volt value given for alternating current supplied to homes is only 0.707 of the maximum voltage of this supply. The maximum voltage is approximately 155 volts ($110 \times 1.41 = 155$ volts maximum).

In the study of alternating current, any values given for current or voltage are assumed to be effective values unless otherwise specified, and in practice, only the effective values of voltage and current are used. Similarly, alternating current voltmeters and ammeters measure the effective value.

Capacitance

Another important property in AC circuits, besides resistance and inductance, is capacitance. While inductance is represented in a circuit by a coil, capacitance is represented by a capacitor. In its most basic form the capacitor is constructed of two parallel plates separated by a nonconductor, called a dielectric. In an electrical circuit, a capacitor serves as a reservoir or storehouse for electricity.

Capacitors in Direct Current

When a capacitor is connected across a source of direct current, such as a storage battery in the circuit shown in Figure 10-108A, and the switch is then closed, the plate marked B becomes positively charged, and the A plate negatively charged. Current flows in the external circuit during the time the electrons are moving from B to A. The current flow in the circuit is at a maxi-

mum the instant the switch is closed, but continually decreases thereafter until it reaches zero. The current becomes zero as soon as the difference in voltage of A and B becomes the same as the voltage of the battery. If the switch is opened as shown in Figure 10-108B, the plates remain charged. Once the capacitor is shorted, it will discharge quickly as shown Figure 10-108C.

It should be clear that during the time the capacitor is being charged or discharged, there is current in the circuit, even though the circuit is broken by the gap between the capacitor plates. Current is present only during the time of charge and discharge, and this period of time is usually short.

The RC Time Constant

The time required for a capacitor to attain a full charge is proportional to the capacitance and the resistance of the circuit. The resistance of the circuit introduces the element of time into the charging and discharging of a capacitor.

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 will not change instantaneously. The rate of charging or discharging is determined by the time constant of the circuit. The time constant of a series RC (resistor/capacitor) circuit is a time interval that equals the product of the resistance in ohms and the capacitance in farad and is symbolized by the greek letter tau (τ).

$$\tau = RC$$

The time in the formula is that required to charge to 63% of the voltage of the source. The time required to bring the charge to about 99% of the source voltage is approximately 5τ . Figure 10-109 illustrates this relationship of a time constant characteristics of charging.

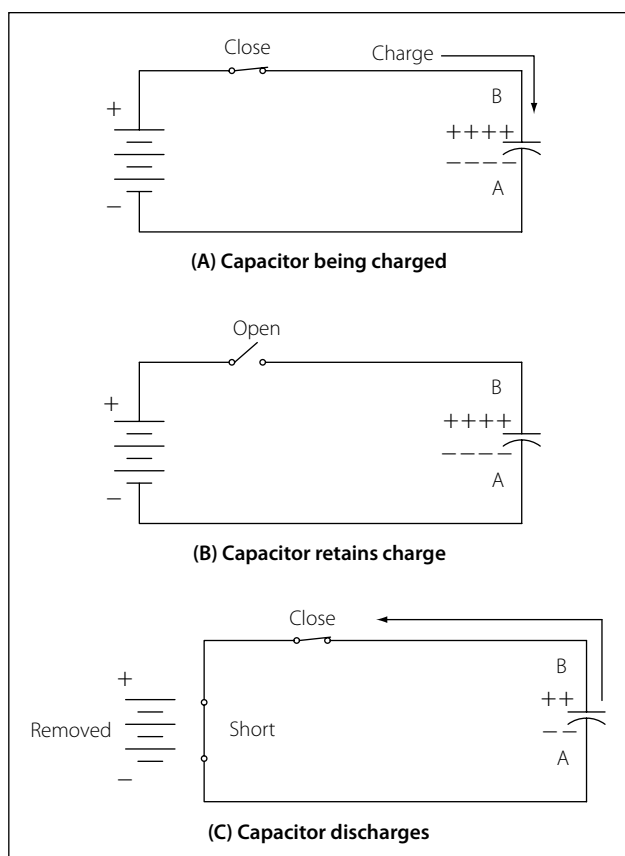


Figure 10-108. Capacitors in direct current.

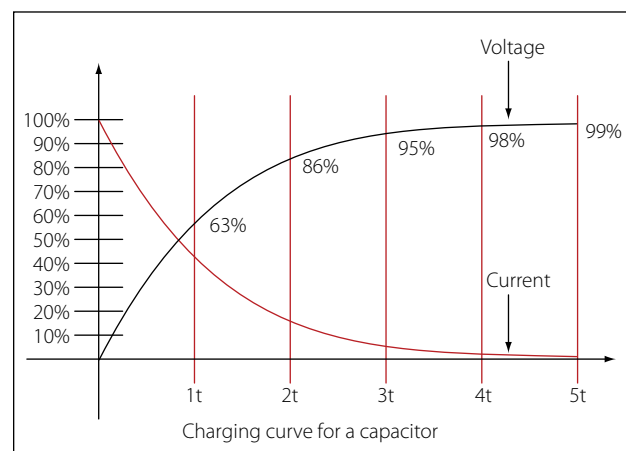


Figure 10-109. Capacitance discharge curve.

The measure of a capacitor’s ability to store charge is its capacitance. The symbol used for capacitance is the letter C.

As can be seen from the time constant illustration there can be no continuous movement of direct current through a capacitor. A good capacitor will block direct current and will pass the effects of pulsing DC or alternating current.

Units of Capacitance

Electrical charge, which is symbolized by the letter Q, is measured in units of coulombs. The coulomb is given by the letter C, as with capacitance. Unfortunately this can be confusing. One coulomb of charge is defined as a charge having 6.28×10^{18} electrons. 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. The general formula for capacitance in terms of charge and voltage is:

Where $C = \frac{Q}{E}$
C = Capacitance measured in farads.
E = Applied voltage measured in volts.
Q = Charge measured in coulombs.

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.

Voltage Rating of a Capacitor

Capacitors have their limits as to how much voltage can be applied across the plates. The aircraft technician must be aware of the voltage rating, which specifies the maximum DC voltage that can be applied without the risk of damage to the device. This voltage rating is typically called the breakdown voltage, the working voltage, or simply the voltage rating. If the voltage applied across the plates is too great, the dielectric will break down and arcing will occur between the plates. The capacitor is then short circuited, and the possible flow of direct current through it can cause damage to other parts of the equipment.

A capacitor that can be safely charged to 500 volts DC cannot be safely subjected to AC or pulsating DC whose effective values are 500 volts. An alternating voltage of 500 volts (RMS) has a peak voltage of 707 volts, and a capacitor to which it is applied should have a working voltage of at least 750 volts. The capacitor

should be selected so that its working voltage is at least 50 percent greater than the highest voltage to be applied.

The voltage rating of the capacitor is a factor in determining the actual capacitance because capacitance decreases as the thickness of the dielectric increases. A high voltage capacitor that has a thick dielectric must have a larger plate area in order to have the same capacitance as a similar low voltage capacitor having a thin dielectric.

Factors Affecting Capacitance

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. The charge that a capacitor can hold at a given potential difference is doubled, and since $C = Q/E$, the capacitance is doubled.
2. The capacitance of parallel plates is inversely proportional to their spacing.
3. The dielectric material affects 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 specified in relation to air (vacuum).

The strength of some commonly used dielectric materials is listed in Figure 10-110. The voltage rating also depends on frequency because the losses, and the resultant heating effect, increase as the frequency increases.

Dielectric	K	Dielectric Strength (volts per .001 inch)
Air	1.0	80
Paper		
(1) Paraffined	2.2	1,200
(2) Beeswaxed	3.1	1,800
Glass	4.2	200
Castor Oil	4.7	380
Bakelite	6.0	500
Mica	6.0	2,000
Fiber	6.5	50

Figure 10-110. Strength of some dielectric materials.

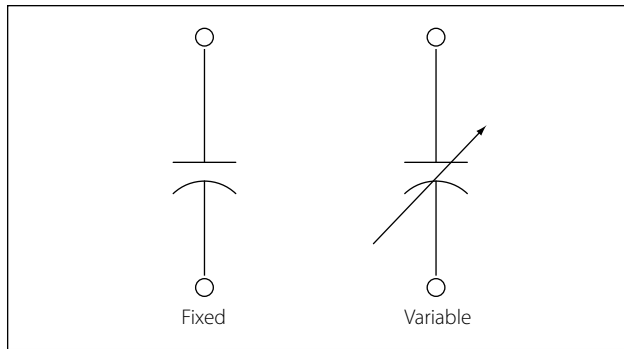


Figure 10-111. Schematic symbols for a fixed and variable capacitor.

Types of Capacitors

Capacitors come in all shapes and sizes and are usually marked with their value in farads. They may also be divided into two groups: fixed and variable. The fixed capacitors, which have approximately constant capacitance, may then be further divided according to the type of dielectric used. Some varieties are: paper, oil, mica, electrolytic and ceramic capacitors. Figure 10-111 shows the schematic symbols for a fixed and variable capacitor.

Fixed Capacitors

Mica Capacitors

The fixed mica capacitor is made of metal foil plates that are separated by sheets of mica, which form the dielectric. The whole assembly is covered in molded plastic, which keeps out moisture. Mica is an excellent dielectric and will withstand higher voltages than paper without allowing arcing between the plates. Common values of mica capacitors range from approximately 50 micromicrofarads, to about 0.02 microfarads.

Ceramic

The ceramic capacitor is constructed with materials, such as titanium acid barium for a dielectric. Internally these capacitors are not constructed as a coil, so they are well suited for use in high frequency applications. They are shaped like a disk, available in very small capacitance values and very small sizes. This type is fairly small, inexpensive, and reliable. Both the ceramic and the electrolytic are the most widely available and used capacitor.

Electrolytic

Two kinds of electrolytic capacitors are in use: (1) wet electrolytic and (2) dry electrolytic.

The wet electrolytic capacitor is designed of two metal plates separated by an electrolyte with an electrolyte

dielectric, which is basically conductive salt in solvent. For capacitances greater than a few microfarads, the plate areas of paper or mica capacitors must become very large; thus, electrolytic capacitors are usually used instead. These units provide large capacitance in small physical sizes. Their values range from 1 to about 1,500 microfarads. Unlike the other types, electrolytic capacitors are generally polarized, with the positive lead marked with a “+” and the negative lead marked with a “-” and should only be subjected to direct voltage or pulsating direct voltage only.

The electrolyte in contact with the negative terminal, either in paste or liquid form, comprises the negative electrode. The dielectric is an exceedingly thin film of oxide deposited on the positive electrode of the capacitor. The positive electrode, which is an aluminum sheet, is folded to achieve maximum area. The capacitor is subjected to a forming process during manufacture, in which current is passed through it. The flow of current results in the deposit of the thin coating of oxide on the aluminum plate.

The close spacing of the negative and positive electrodes gives rise to the comparatively high capacitance value, but allows greater possibility of voltage breakdown and leakage of electrons from one electrode to the other.

The electrolyte of the dry electrolytic unit is a paste contained in a separator made of an absorbent material, such as gauze or paper. The separator not only holds the electrolyte in place but also prevents it from short circuiting the plates. Dry electrolytic capacitors are made in both cylindrical and rectangular block form and may be contained either within cardboard or metal covers. Since the electrolyte cannot spill, the dry capacitor may be mounted in any convenient position. Electrolytic capacitors are shown in Figure 10-112.

Tantalum

Similar to the electrolytic, these capacitors are constructed with a material called tantalum, which is used for the electrodes. They are superior to electrolytic capacitors, having better temperature and frequency characteristics. When tantalum powder is baked in order to solidify it, a crack forms inside. This crack is used to store an electrical charge. Like electrolytic capacitors, the tantalum capacitors are also polarized and are indicated with the “+” and “-” symbols.

Polyester Film

In this capacitor, a thin polyester film is used as a dielectric. These components are inexpensive, tem-



Figure 10-112. Electrolytic capacitors.

perature stable, and widely used. Tolerance is approximately 5–10 percent. It can be quite large depending on capacity or rated voltage.

Oil Capacitors

In radio and radar transmitters, voltages high enough to cause arcing, or breakdown, of paper dielectrics are often used. Consequently, in these applications capacitors that use oil or oil impregnated paper for the dielectric material are preferred. Capacitors of this type are considerably more expensive than ordinary paper capacitors, and their use is generally restricted to radio and radar transmitting equipment. [Figure 10-113]

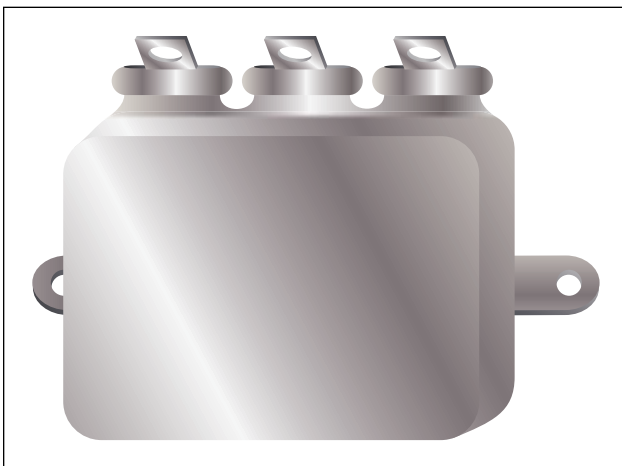


Figure 10-113. Oil capacitor.

Variable Capacitors

Variable capacitors are mostly used in radio tuning circuits, and they are sometimes called “tuning capacitors.” They have very small capacitance values, typically between 100pF and 500pF.

Trimmers

The trimmer is actually an adjustable or variable capacitor, which uses ceramic or plastic as a dielectric. Most of them are color coded to easily recognize their tunable size. The ceramic type has the value printed on them. Colors are: yellow (5pF), blue (7pF), white (10pF), green (30pF), and brown (60pF).

Varactors

A voltage-variable capacitor or varactor is also known as a variable capacitance diode or a varicap. This device utilizes the variation of the barrier width in a reversed-biased diode. Because the barrier width of a diode acts as a non-conductor, a diode forms a capacitor when reversed biased. Essentially the N-type material becomes one plate and the junctions are the dielectric. If the reversed-bias voltage is increased, then the barrier width widens, effectively separating the two capacitor plates and reducing the capacitance.

Capacitors in Series

When capacitors are placed in series, the effective plate separation is increased and the total capacitance is less than that of the smallest capacitor. Additionally, the series combination is capable of withstanding a higher total potential difference than any of the individual capacitors. Figure 10-114 is a simple series circuit. The bottom plate of C_1 and the top plate of C_2 will be charged by electrostatic induction. The capacitors

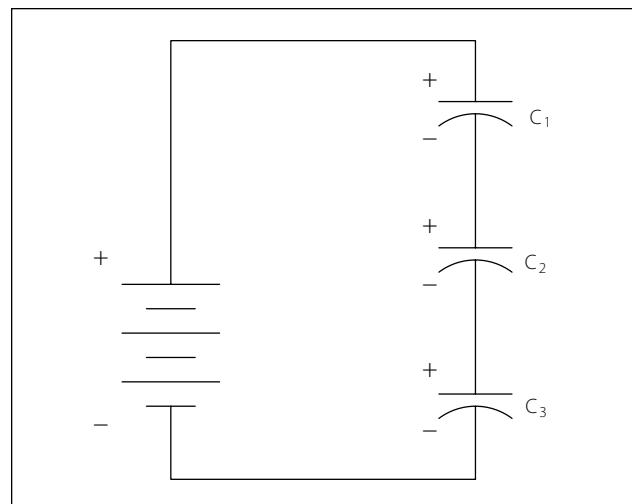


Figure 10-114. Simple series circuit.

charge as current is established through the circuit. Since this is a series circuit, the current must be the same at all points. Since the current is the rate of flow of charge, the amount of charge (Q) stored by each capacitor is equal to the total charge.

$$Q_T = Q_1 + Q_2 + Q_3$$

According to Kirchhoff's voltage law, the sum of the voltages across the charged capacitors must equal the total voltage, E_T . This is expressed as:

$$E_T = E_1 + E_2 + E_3$$

Equation $E = Q/C$ can now be substituted into the voltage equation where we now get:

$$\frac{Q_T}{C_T} = \frac{Q_1}{C_1} + \frac{Q_2}{C_2} + \frac{Q_3}{C_3}$$

Since the charge on all capacitors is equal, the Q terms can be factored out, leaving us with the equation:

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

Consider the following example:

If $C_1 = 10\mu\text{F}$, $C_2 = 5\mu\text{F}$ and $C_3 = 8\mu\text{F}$

$$\text{Then } \frac{1}{C_T} = \frac{1}{10\mu\text{F}} + \frac{1}{5\mu\text{F}} + \frac{1}{8\mu\text{F}}$$

$$C_T = \frac{1}{0.425\mu\text{F}} = 2.35\mu\text{F}$$

Capacitors in Parallel

When capacitors are connected in parallel, the effective plate area increases, and the total capacitance is the sum of the individual capacitances. Figure 10-115 shows a simplified parallel circuit. The total charging current from the source divides at the junction of the parallel branches. There is a separate charging current through each branch so that a different charge can be stored by each capacitor. Using Kirchhoff's current law, the sum

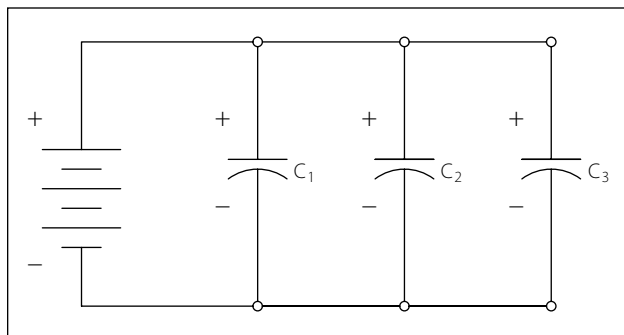


Figure 10-115. Simplified parallel circuit.

of all of the charging currents is then equal to the total current. The sum of the charges (Q) on the capacitors is equal to the total charge. The voltages (E) across all of the parallel branches are equal. With all of this in mind, a general equation for capacitors in parallel can be determined as:

$$Q_T = Q_1 + Q_2 + Q_3$$

$$\text{Because } Q = CE: C_T E_T = C_1 E_1 + C_2 E_2 + C_3 E_3$$

Voltages can be factored out because:

$$E_T = E_1 + E_2 + E_3$$

Leaving us with the equation for capacitors in parallel:

$$C_T = C_1 + C_2 + C_3$$

Consider the following example:

If $C_1 = 330\mu\text{F}$, $C_2 = 220\mu\text{F}$

Then $C_T = 330\mu\text{F} + 220\mu\text{F} = 550\mu\text{F}$

Capacitors in Alternating Current

If a source of alternating current is substituted for the battery, the capacitor acts quite differently than it does with direct current. When an alternating current is applied in the circuit, the charge on the plates constantly changes. [Figure 10-116] 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. In a circuit in which there is only capacitance, current leads the applied voltage as contrasted with a circuit in which there is inductance, where the current lags the voltage.

Capacitive Reactance X_C

The effectiveness of a capacitor in allowing an AC flow to pass depends upon the capacitance of the circuit and the applied frequency. To what degree a

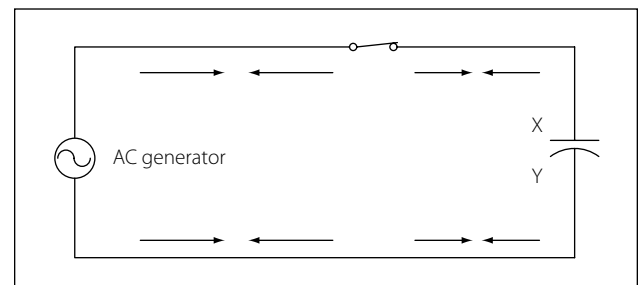


Figure 10-116. Capacitor in an AC circuit.

capacitor allows an AC flow to pass depends largely upon the capacitive value of the capacitor given in farads (f). The greater the capacitance of the capacitor, the greater the number of electrons, measured in Coulombs, necessary to bring the capacitor to a fully charged state. Once the capacitor approaches or actually reaches a fully charged condition, the polarity of the capacitor will oppose the polarity of the applied voltage, essentially acting then as an open circuit. To further illustrate this characteristic and how it manifests itself in an AC circuit, consider the following. If a capacitor has a large capacitive value, meaning that it requires a relatively large number of electrons to bring it to a fully charged state, then a rather high frequency current can alternate through the capacitor without the capacitor ever reaching a full charge. In this case, if the frequency is high enough and the capacitance large enough that there is never enough time for the capacitor to ever reach a full charge, it is possible that the capacitor may offer very little or no resistance to the current. However, the smaller the capacitance, the fewer electrons are required to bring it up to a full charge and it is more likely that the capacitor will build up enough of an opposing charge that it can present a great deal of resistance to the current if not to the point of behaving like an open circuit. In between these two extreme conditions lies a continuum of possibilities of current opposition depending on the combination of applied frequency and the selected capacitance. Current in an AC circuit can be controlled by changing the circuit capacitance in a similar manner that resistance can control the current. The actual AC reactance X_c , which just like resistance, is measured in ohms (Ω). Capacitive reactance X_c is determined by the following:

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

Where X_c = Capacitive Reactance
 f = frequency in cps
 C = capacity in farads
 $2\pi = 6.28$

Sample Problem:

A series circuit is assumed in which the impressed voltage is 110 volts at 60 cps, and the capacitance of a condenser is 80 Mf. Find the capacitive reactance and the current flow.

Solution:

To find capacitive reactance, the equation $X_c = 1/(2\pi fC)$ is used. First, the capacitance, 80 Mf, 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 and

$$X_c = \frac{1}{6.28 \times 60 \times 0.000080}$$

$$X_c = 33.2 \text{ ohms reactance}$$

Once the reactance has been determined, ohm's law can then be used in the same manner as it is used in DC circuits to determine the current.

$$\text{Current} = \frac{\text{Voltage}}{\text{Capacitive reactance}}, \text{ or}$$

$$I = \frac{E}{X_c},$$

Find the current flow:

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

$$I = \frac{110}{33.2}$$

$$I = 3.31 \text{ amperes}$$

Capacitive Reactances in Series and in Parallel

When capacitors are connected in series, the total reactance is equal to the sum of the individual reactances. Thus,

$$X_{ct} = (X_c)_1 + (X_c)_2$$

The total reactance of capacitors connected in parallel is found in the same way total resistance is computed in a parallel circuit:

$$(X_c)_t = \frac{1}{\frac{1}{(X_c)_1} + \frac{1}{(X_c)_2} + \frac{1}{(X_c)_3}}$$

Phase of Current and Voltage in Reactive Circuits

Unlike a purely resistive circuit, the capacitive and inductive reactance has a significant effect on the phase relationship between the applied AC voltage and the corresponding current in the circuit.

In review, when current and voltage pass through zero and reach maximum value at the same time, the current and voltage are said to be in phase. [Figure 10-117A] If the current and voltage pass through zero and reach the maximum values at different times, the current and voltage are said to be out of phase. In a circuit containing only inductance, the current reaches a maximum value later than the voltage, lagging the voltage by 90° , or one-fourth cycle. [Figure 10-117B]

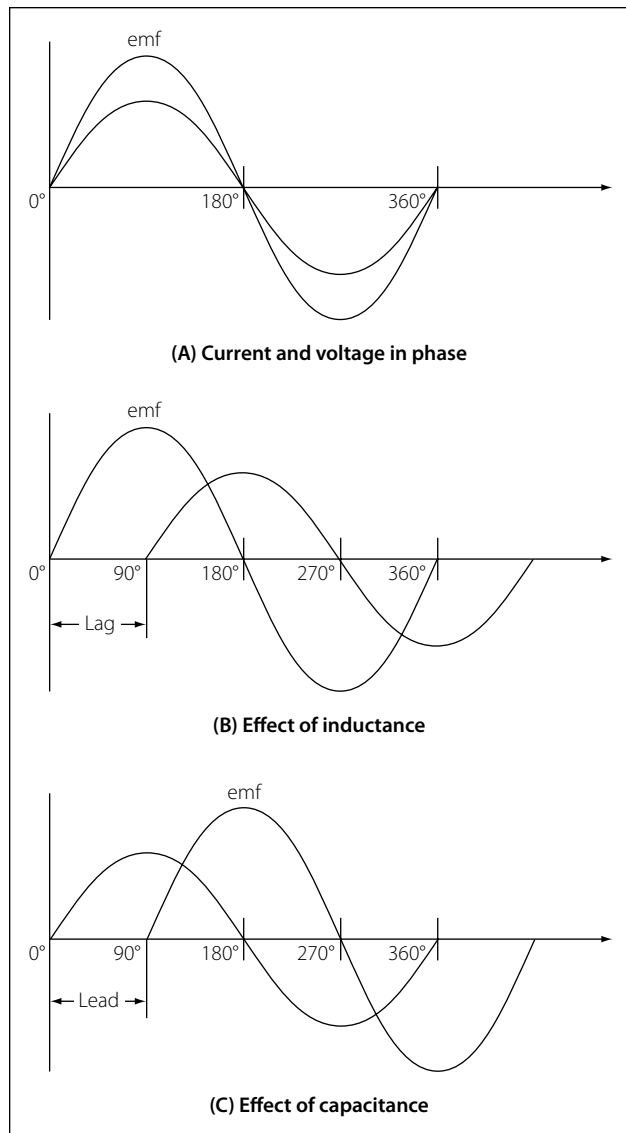


Figure 10-117. Phase of current and voltage.

In a circuit containing only capacitance, the current reaches its maximum value ahead of the voltage and the current leads the voltage by 90°, or one-fourth cycle. [Figure 10-117C] The amount the current lags or leads the voltage in a circuit depends on the relative amounts of resistance, inductance, and capacitance in the circuit.

Inductance

Characteristics of Inductance

Michael Faraday discovered that by moving a magnet through a coil of wire, a voltage was induced across the coil. If a complete circuit was provided, then a current was also induced. The amount of induced voltage is directly proportional to the rate of change of the magnetic field with respect to the coil. The simplest

of experiments can prove that when a bar magnet is moved through a coil of wire, a voltage is induced and can be measured on a voltmeter. This is commonly known as Faraday's Law or the law of electromagnetic induction, which states:

The induced emf or electromagnetic force in a closed loop of wire is proportional to the rate of change of the magnetic flux through a coil of wire.

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 magnetic lines of force around each loop or turn in the coil effectively add to the lines of force around the adjoining loops. This forms a strong magnetic field within and around the coil. Figure 10-118A, illustrates this idea of a coil of wire strengthening a magnetic field. The magnetic lines of force around adjacent loops are deflected into an outer path when the loops are brought close together. This happens because the magnetic lines of force between adjacent loops are in opposition with each other. The total magnetic field for the two loops

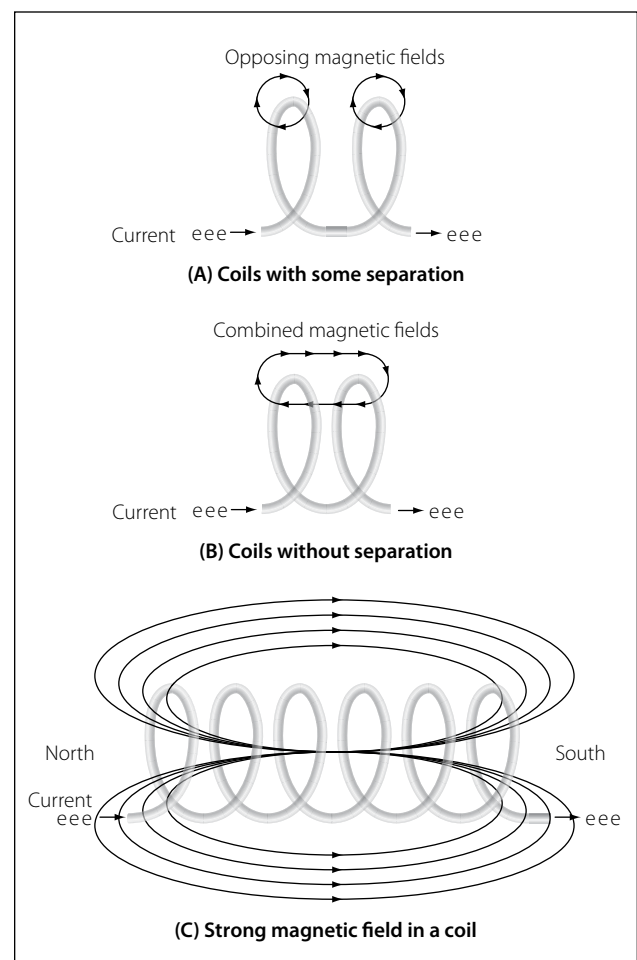


Figure 10-118. Many loops of a coil.

is shown in Figure 10-118B. As more loops are added close together, the strength of the magnetic field will increase. Figure 10-118C illustrates the combined effects of many loops of a coil. The result is a strong electromagnet.

The primary aspect of the operation 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 current flow. The effects of this countering emf are to oppose the immediate establishment of the maximum current. This effect is only a temporary condition. Once the current reaches a steady value in the conductor, the lines of magnetic force will no longer be expanding and the countering emf will no longer be present.

At the starting instant, the countering emf nearly equals the applied voltage, resulting in a small current flow. However, as the lines of force move outward, the number of lines cutting the conductor per second becomes progressively smaller, resulting in a diminished counter emf. Eventually, the counter emf drops to zero and the only voltage in the circuit is the applied voltage and the current is at its maximum value.

The RL Time Constant

Because the inductors basic action is to oppose a change in its current, it then follows that the current cannot change instantaneously in the inductor. A certain time is required for the current to make a change from one value to another. The rate at which the current changes is determined by a time constant represented by the greek letter tau (τ). The time constant for the RL circuit is:

$$\tau = \frac{L}{R}$$

Where τ = seconds

L = inductance (H)

R = Resistance (Ω)

In a series RL circuit, the current will increase to 63% of its full value in 1 time constant after the circuit is closed. This build up of course is similar to the build up of voltage in a capacitor when charging an RC circuit. Both follow an exponential curve and reach 99% value after the 5th time constant. Figure 10-119 illustrates this characteristic.

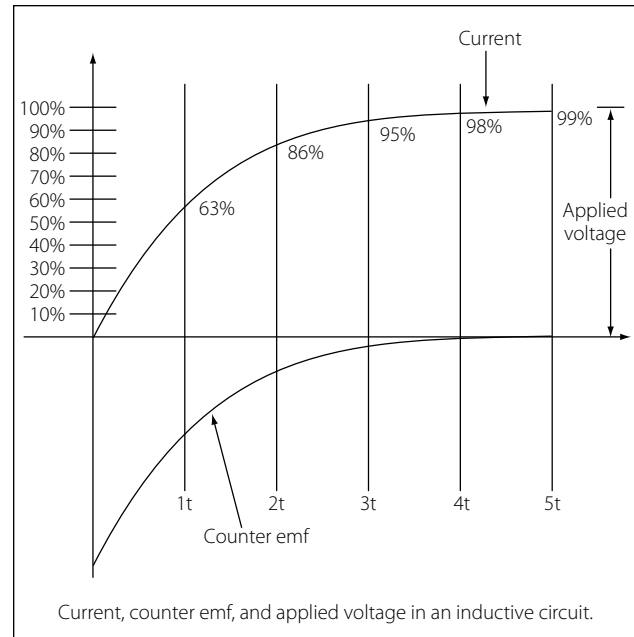


Figure 10-119. Inductor curve.

Physical Parameters

Some of the physical factors that affect inductance are:

1. The number of turns: Doubling the number of turns in a coil will produce a field twice as strong, if the same current is used. As a general rule, the inductance varies as the square of the number of turns.
2. The 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. The length of a coil: Doubling the length of a coil, while keeping the same number of turns, halves the value of inductance.
4. The 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, or cobalt, which have a permeability that provides a better path for the magnetic lines of force and permit a stronger magnetic field.

Self-Inductance

The characteristic of self-inductance was summarized by German physicist Heinrich Lenz in 1833 and gives the direction of the induced electromotive force (emf) resulting from electromagnetic induction. This is commonly known as Lenz's Law, which states:

The emf induced in an electric circuit always acts in such a direction that the current it drives around a closed circuit produces a magnetic field which opposes the change in magnetic flux.

Self inductance is the generation of a voltage in an electric circuit by a changing current in the same circuit. Even a straight piece of wire will have some degree of inductance because current in a conductor produces a magnetic field. When the current in a conductor changes direction, there will be a corresponding change in the polarity of the magnetic field around the conductor. Therefore, a changing current produces a changing magnetic field around the wire. To further intensify the magnetic field, the wire can be rolled into a coil, which is called an inductor. The changing magnetic field around the inductor induces a voltage across the coil. This induced electromotive force is called self-inductance and tends to oppose any change in current within the circuit. This property is usually called inductance and symbolized with the letter L.

Types of Inductors

Inductors used in radio can range from a straight wire at UHF to large chokes and transformers used for filtering the ripple from the output of power supplies and in audio amplifiers. Figure 10-69 shows the schematic symbols for common inductors. Values of inductors range from nano-henries to tens of henries.

Inductors are classified by the type of core and the method of winding them. The number of turns in the inductor winding and the core material determine the capacity of the inductor. Cores made of dielectric material like ceramics, wood, paper provide small amounts of stored energy while cores made of ferrite substances have a much higher degree of stored energy. The core material is usually the most important aspect of the inductors construction. The conductors typically used in the construction of an inductor offer little resistance to the flow of current. However, with the introduction of a core, resistance is introduced in the circuit and the current now builds up in the windings until the resistance of the core is overcome. This buildup is stored as magnetic energy in the core. Depending on the core resistance, the buildup soon reaches a point of magnetic saturation and it can be released when necessary. The most common core materials are: Air, solid ferrite, powdered ferrite, steel, toroid and ferrite toroid.

Units of Inductance

The henry is the basic unit of inductance and is symbolized with the letter H. An electric circuit has an inductance of one henry when current changing at the

rate of one ampere per second induces a voltage of one volt into the circuit. In many practical applications, millihenries (mH) and microhenries (μH) are more common units. The typical symbol for an inductor is shown in Figure 10-120.

Inductors in Series

If we connect two inductors in series as shown in Figure 10-121, the same current flows through both inductors and, therefore, both will be subject to the same rate of change of current. When inductors are connected in series, the total inductance L_T is the sum of the individual inductors. The general equation for n number of inductors in series is:

$$L_T = L_1 + L_2 + L_3 + \dots L_N$$

Inductors in Parallel

When two inductors are connected in parallel as shown in Figure 10-122, each must have the same potential difference between the terminals. When inductors are connected in parallel, the total inductance is less than

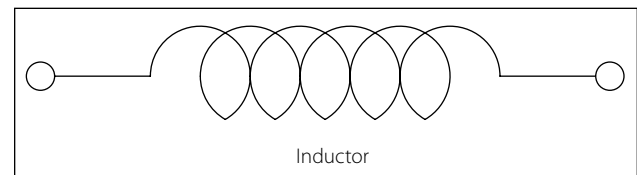


Figure 10-120. Typical symbol for an inductor.

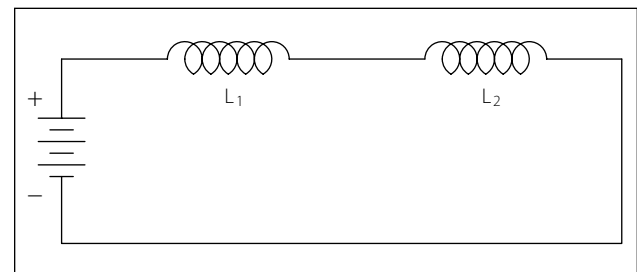


Figure 10-121. Two inductors in series.

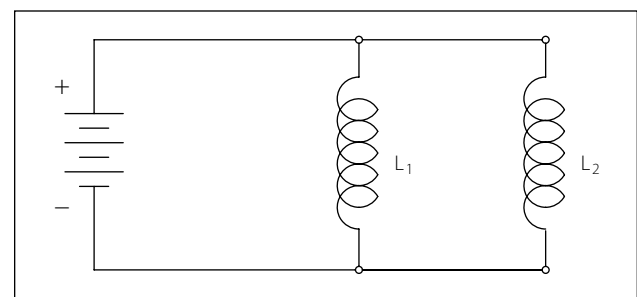


Figure 10-122. Two inductors in parallel.

the smallest inductance. The general equation for n number of inductors in parallel is:

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

A simple example would be:

$$L_1 = 10\text{mH}, L_2 = 5\text{mH}, L_3 = 2\text{mH}$$

$$L_T = \frac{1}{\frac{1}{10\text{mH}} + \frac{1}{5\text{mH}} + \frac{1}{2\text{mH}}}$$

$$L_T = \frac{1}{0.8\text{mH}}$$

$$L_T = 1.25\text{mH}$$

Inductive Reactance

Alternating current is in a constant state of change; the effects of the magnetic fields are a continuously induced voltage opposition to the current in the circuit. This opposition is called inductive reactance, symbolized by X_L , and is measured in ohms just as resistance is measured. 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 will oppose current variations.

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 will likewise increase and present more opposition to current in the circuit. This relationship is given as:

$$X_L = 2\pi fL$$

Where: X_L = inductive reactance in ohms
 f = frequency in cycles per second
 $\pi = 3.1416$

In Figure 10-123, 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.

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

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

To find current:

In any circuit where there is only resistance, the expression for the relationship of voltage and current is given by Ohm's law: $I = E/R$. Similarly, when there

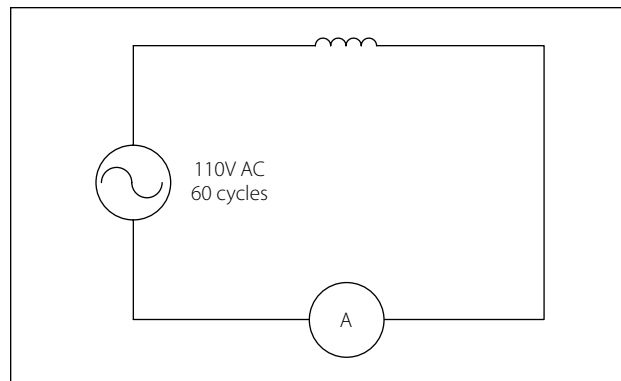


Figure 10-123. AC circuit containing inductance.

is inductance in an AC circuit, the relationship between voltage and current can be expressed as:

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

Where:

X_L = inductive reactance of the circuit in ohms.

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

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

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

In AC series circuits, inductive reactances are added like resistances in series in a DC circuit. [Figure 10-124] Thus, the total reactance in the illustrated circuit equals the sum of the individual reactances.

The total reactance of inductors connected in parallel is found the same way as the total resistance in a parallel circuit. [Figure 10-125] Thus, the total reactance of inductances connected in parallel, as shown, is expressed as

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

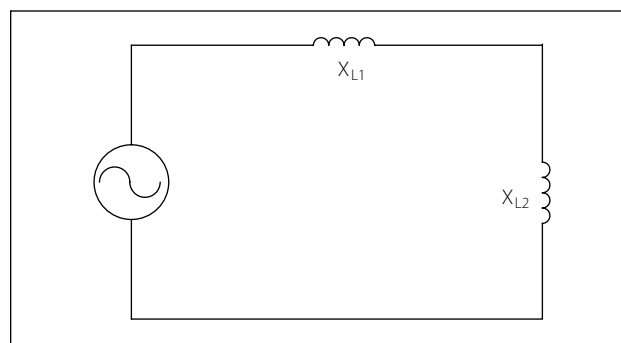


Figure 10-124. Inductances in series.

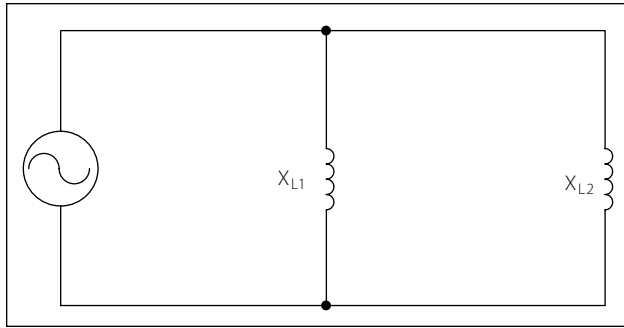


Figure 10-125. Inductances in parallel.