DC Theory and Resistive Components

5

Glossary

Alternating current — A flow of charged particles through a conductor, first in one direction, then in the other direction.

Ampere — A measure of flow of charged particles per unit time. One ampere represents one coulomb of charge flowing past a point in one second.

Atom — The smallest particle of matter that makes up an element. Consists of protons and neutrons in the central area called the nucleus, with electrons surrounding this central region.

Coulomb — A unit of measure of a quantity of electrically charged particles. One coulomb is equal to 6.25×10^{18} electrons.

Direct current — A flow of charged particles through a conductor in one direction only.

EMF — Electromotive Force is the term used to define the force of attraction between two points of different charge potential. Also called voltage.

Energy — Capability of doing work. It is usually measured in electrical terms as the number of watts of power consumed during a specific period of time, such as watt-seconds or kilowatt-hours.

Joule — Measure of a quantity of energy. One joule is defined as one newton (a measure of force) acting over a distance of one meter.

Ohm — Unit of resistance. One ohm is defined as the resistance that will allow one ampere of current when one volt of EMF is impressed across the resistance.

Power — Power is the rate at which work is done. One watt of power is equal to one volt of EMF, causing a current of one ampere.

Volt — A measure of electromotive force.

Introduction

This chapter was written by Roger Taylor, K9ALD.

The atom is the primary building block of the universe. The main parts of the atom include protons, electrons and neutrons. Protons have a positive electrical charge, electrons a negative charge and neutrons have no electrical charge. All atoms are electrically neutral, so they have the same number of electrons as protons. If an atom loses electrons, so it has more protons than electrons, it has a net positive charge. If an atom gains electrons, so it has more electrons than protons, it has a negative charge. Particles with a positive or negative charge are called ions. Free electrons are also called ions, because they have a negative charge.

When there are a surplus number of positive ions in one location and a surplus number of negative ions (or electrons) in another location, there is an attractive force between the two collections of particles. That force tries to pull the collections together. This attraction is called electromotive force, or EMF.

If there is no path (conductor) to allow electric charge to flow between the two locations, the charges cannot move together and neutralize one another. If a conductor is provided, then electric current (usually electrons) will flow through the conductor.

Electrons move from the negative to the positive side of the voltage, or EMF source. *Conventional current* has the opposite direction, from positive to negative. This comes from an arbitrary decision made by Benjamin Franklin in the 18th century. The conventional current direction is important in establishing the proper polarity sign for many electronics calculations. Conventional current is used in much of the technical literature. The arrows in semiconductor schematic symbols point in the direction of conventional current, for example.

To measure the quantities of charge, current and force, certain definitions have been adopted. Charge is measured in *coulombs*. One coulomb is equal to 6.25×10^{18} electrons (or protons). Charge flow is measured in *amperes*. One ampere represents one coulomb of charge flowing past a point in one second. Electromotive force is measured in *volts*. One volt is defined as the potential force (electrical) between two points for which one ampere of current will do one *joule* (measure of energy) of work flowing from one point to another. (A joule of work per second represents a power of one watt. See the **Mathematics for Amateur Radio** chapter for more information about these unit definitions.)

Voltage can be generated in a variety of ways. Chemicals with certain characteristics can be combined to form a battery. Mechanical motion such as friction (static electricity, lightning) and rotating conductors in a magnetic field (generators) can also produce voltage.

Any conductor between points at different voltages will allow current to pass between the points. No conductor is perfect or lossless, however, at least not at normal temperatures. Charged particles such as electrons resist being moved and it requires energy to move them. The amount of resistance to current is measured in *ohms*.

OHM'S LAW

One ohm is defined as the amount of resistance that allows one ampere of current to flow between two points that have a potential difference of one volt. Thus, we get Ohm's Law, which is:

$$R = \frac{E}{I} \tag{1}$$

where:

R = resistance in ohms,
E = potential or EMF in volts and
I = current in amperes.

Transposing the equation gives the other common expressions of Ohm's Law as:

$$E = I \times R \qquad (2)$$

and

$$I = \frac{E}{R} \qquad (3)$$

All three forms of the equation are used often in radio work. You must remember that the quantities are in volts, ohms and amperes; other units cannot be used in the equations without first being converted. For example, if the current is in milliamperes you must first change it to the equivalent fraction of an ampere before substituting the value into the equations.

The following examples illustrate the use of Ohm's Law. The current through a 20000-Ω resistance is 150 mA. See **Fig 5.1**. What is the voltage? To find voltage, use equation 2 (E = I × R). Convert the current from milliamperes to amperes. Divide by 1000 mA / A (or multiply by 10^{-3} A / mA) to make this conversion. If you are uncertain how to do these conversions, see the **Mathematics for Amateur Radio** chapter. (Notice the conversion factor of 1000 does not limit the number of significant figures in the calculated answer.)

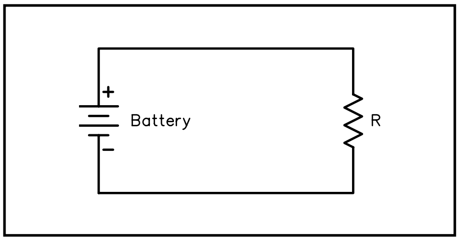

Fig 5.1 — A simple circuit consisting of a battery and a resistor.

$$I = \frac{150\ \text{mA}}{1000\ \frac{\text{mA}}{\text{A}}} = 0.150\ \text{A}$$

Then:

$$E = 0.150\ \text{A} \times 20000\ \Omega = 3000\ \text{V}$$

If you are unfamiliar with the use of significant figures and rounding off calculated values, see the **Mathematics for Amateur Radio** chapter.

When 150 V is applied to a circuit, the current is measured at 2.5 A. What is the resistance of the circuit? In this case R is the unknown, so we will use equation 1:

$$R = \frac{E}{I} = \frac{150\text{V}}{2.5\text{A}} = 60.\ \Omega$$

No conversion was necessary because the voltage and current were given in volts and amperes.

How much current will flow if 250 V is applied to a 5000-Ω resistor? Since I is unknown,

$$I = \frac{E}{R} = \frac{250\ \text{V}}{5000\ \Omega} = 0.05\ \text{A}$$

It is more convenient to express the current in mA, and 0.05 A × 1000 mA / A = 50 mA.

RESISTANCE AND CONDUCTANCE

Suppose we have two conductors of the same size and shape, but of different materials. The amount of current that will flow when a given EMF is applied will vary with the resistance of the material. The lower the resistance, the greater the current for a given EMF. The *resistivity* of a material is the resistance, in ohms, of a cube of the material measuring one centimeter on each edge. One of the best conductors is copper, and in making resistance calculations it is frequently convenient to compare the resistance of the material under consideration with that of a copper conductor of the same size and shape. **Table 5.1** gives the ratio of the resistivity of various conductors to the resistivity of copper.

The longer the physical path, the higher the resistance of that conductor. For direct current and low-frequency alternating currents (up to a few thousand hertz) the resistance is inversely proportional to the cross-sectional area of the path the current must travel; that is, given two conductors of the same material and having the same length, but differing in cross-sectional area, the one with the larger area will have the lower resistance.

Table 5.1
Relative Resistivity of Metals

Material	*Resistivity Compared to Copper*
Aluminum (pure)	1.60
Brass	3.7-4.90
Cadmium	4.40
Chromium	1.80
Copper (hard-drawn)	1.03
Copper (annealed)	1.00
Gold	1.40
Iron (pure)	5.68
Lead	12.80
Nickel	5.10
Phosphor bronze	2.8-5.40
Silver	0.94
Steel	7.6-12.70
Tin	6.70
Zinc	3.40

RESISTANCE OF WIRES

The problem of determining the resistance of a round wire of given diameter and length—or its converse, finding a suitable size and length of wire to provide a desired amount of resistance—can easily be solved with the help of the copper wire table given in the **Component Data** chapter. This table gives the resistance, in ohms per 1000 ft, of each standard wire size. For example, suppose you need a resistance of 3.5 Ω, and some #28 wire is on hand. The wire table in the **Component Data** chapter shows that #28 wire has a resistance of 66.17 Ω / 1000 ft. Since the desired resistance is 3.5 Ω, the required wire length is:

$$\text{Length} = \frac{R_{DESIRED}}{\frac{R_{WIRE}}{1000\text{ ft}}} = \frac{3.5\,\Omega}{\frac{66.17\,\Omega}{1000\text{ ft}}} = \frac{3.5\,\Omega \times 1000\text{ ft}}{66.17\,\Omega} = 53\text{ ft} \qquad (4)$$

As another example, suppose that the resistance of wire in a circuit must not exceed 0.05 Ω and that the length of wire required for making the connections totals 14 ft. Then:

$$\frac{R_{WIRE}}{1000\text{ ft}} < \frac{R_{MAXIMUM}}{\text{Length}} = \frac{0.05\,\Omega}{14.0\text{ ft}} = 3.57\times10^{-3}\,\frac{\Omega}{\text{ft}} \times \frac{1000\text{ ft}}{1000\text{ ft}}$$

$$\frac{R_{WIRE}}{1000\text{ ft}} < \frac{3.57\,\Omega}{1000\text{ ft}} \qquad (5)$$

Find the value of R_{WIRE} / 1000 ft that is less than the calculated value. The wire table shows that #15 is the smallest size having a resistance less than this value. (The resistance of #15 wire is given as 3.1810 Ω / 1000 ft.) Select any wire size larger than this for the connections in your circuit, to ensure that the total wire resistance will be less than 0.05 Ω.

When the wire in question is not made of copper, the resistance values in the wire table should be multiplied by the ratios shown in Table 5.1 to obtain the resulting resistance. If the wire in the first example were made from nickel instead of copper, the length required for 3.5 Ω would be:

$$\text{Length} = \frac{R_{DESIRED}}{\frac{R_{WIRE}}{1000\text{ft}}} = \frac{3.5\,\Omega}{\frac{66.17\,\Omega}{1000\text{ ft}}\times 5.1} = \frac{3.5\,\Omega\times1000\text{ ft}}{66.17\,\Omega\times5.1}$$

$$\text{Length} = \frac{3500\text{ ft}}{337.5} = 10.37\text{ ft} \qquad (6)$$

TEMPERATURE EFFECTS

The resistance of a conductor changes with its temperature. The resistance of practically every metallic conductor increases with increasing temperature. Carbon, however, acts in the opposite way; its resistance decreases when its temperature rises. It is seldom necessary to consider temperature in making resistance calculations for amateur work. The temperature effect is important when it is necessary to maintain a constant resistance under all conditions, however. Special materials that have little or no change in resistance over a wide temperature range are used in that case.

RESISTORS

A package of material exhibiting a certain amount of resistance, made up into a single unit is called a resistor. Different resistors having the same resistance value may be considerably different in physical size and construction (see **Fig 5.2**). Current through a resistance causes the conductor to become heated; the higher the resistance and the larger the current, the greater the amount of heat developed. Resistors intended for carrying large currents must be physically large so the heat can be radiated quickly to the surrounding air. If the resistor does not dissipate the heat quickly, it may get hot enough to melt or burn.

The amount of heat a resistor can safely dissipate depends on the material, surface area and design. Typical carbon resistors used in amateur electronics ($^1/_8$ to 2-W resistors) depend primarily on the surface area of the case, with some heat also being carried off through the connecting leads. Wirewound resistors are usually used for higher power levels. Some have finned cases for better convection cooling and/or metal cases for better conductive cooling.

In some circuits, the resistor value may be critical. In this case, precision resistors are used. These are typically wirewound, or carbon-film devices whose values are carefully controlled during manufacture. In addition, special material or construction techniques may be used to provide temperature compensation, so the value does not change (or changes in a precise manner) as the resistor temperature changes. There is more information about the electrical characteristics of real resistors in the **Real-World Component Characteristics** chapter.

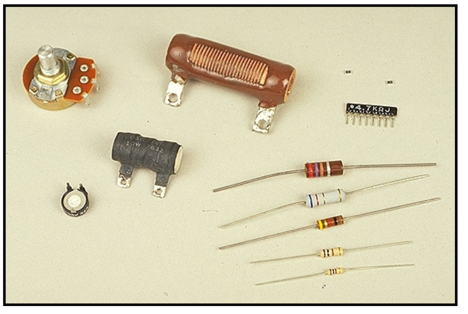

Fig 5.2 — Examples of various resistors. In the right foreground are $^1/_4$-, $^1/_2$- and 1-W composition resistors. The two larger cylindrical components at the center are wire-wound power resistors. A surface-mount, or chip resistor is shown at the top right. The remaining two parts are variable resistors; a PC-board-mount device at the lower left and a panel-mount unit at the upper left.

CONDUCTANCE

The reciprocal of resistance (1/R) is *conductance*. It is usually represented by the symbol G. A circuit having high conductance has low resistance, and vice versa. In radio work, the term is used chiefly in connection with electron-tube and field-effect transistor characteristics. The unit of conductance is the siemens, abbreviated S. A resistance of 1 Ω has a conductance of 1 S, a resistance of 1000 Ω has a conductance of 0.001 S, and so on. A unit frequently used in connection with electron devices is the µS or one millionth of a siemens. It is the conductance of a 1-MΩ resistance.

Series and Parallel Resistances

Very few actual electric circuits are as simple as Fig 5.1. Commonly, resistances are found connected in a variety of ways. The two fundamental methods of connecting resistances are shown in **Fig 5.3**. In part A, the current flows from the source of EMF (in the direction shown by the arrow) down through the first resistance, R1, then through the second, R2 and then back to the source. These resistors are connected in series. The current everywhere in the circuit has the same value.

In part B, the current flows to the common connection point at the top of the two resistors and then divides, one part of it flowing through R1 and the other through R2. At the lower connection point these two currents again combine; the total is the same as the current into the upper common connection. In this case, the two resistors are connected in parallel.

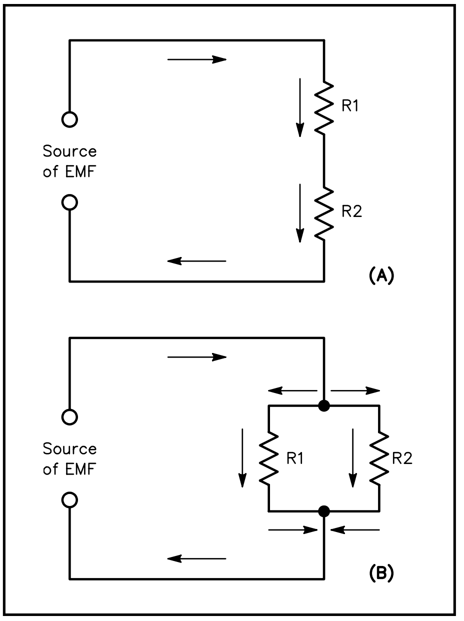

Fig 5.3 — Resistors connected in series at A, and in parallel at B.

RESISTORS IN PARALLEL

In a circuit with resistances in parallel, the total resistance is less than that of the lowest resistance value present. This is because the total current is always greater than the current in any individual resistor. The formula for finding the total resistance of resistances in parallel is

$$R = \frac{1}{\frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3} + \frac{1}{R4} + \cdots} \qquad (7)$$

where the dots indicate that any number of resistors can be combined by the same method. For only two resistances in parallel (a very common case) the formula becomes:

$$R = \frac{R1 \times R2}{R1 + R2} \qquad (8)$$

Example: If a 500-Ω resistor is connected in parallel with one of 1200 Ω, what is the total resistance?

$$R = \frac{R1 \times R2}{R1 + R2} = \frac{500\,\Omega \times 1200\,\Omega}{500\,\Omega + 1200\,\Omega}$$

$$R = \frac{600000\,\Omega^2}{1700\,\Omega} = 353\,\Omega$$

KIRCHHOFF'S FIRST LAW (KIRCHHOFF'S CURRENT LAW)

Suppose three resistors (5.00 kΩ, 20.0 kΩ and 8.00 kΩ) are connected in parallel as shown in **Fig 5.4**. The same EMF, 250 V, is applied to all three resistors. The current in each can be found from Ohm's Law, as shown below. The current through R1 is I1, I2 is the current through R2 and I3 is the current through R3.

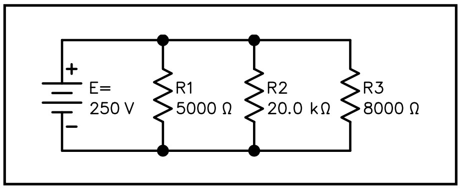

Fig 5.4 — An example of resistors in parallel. See text for calculations.

For convenience, we can use resistance in kΩ, which gives current in milliamperes.

$$I1 = \frac{E}{R1} = \frac{250\ V}{5.00\ k\Omega} = 50.0\ mA$$

$$I2 = \frac{E}{R2} = \frac{250\ V}{20.0\ k\Omega} = 12.5\ mA$$

$$I3 = \frac{E}{R3} = \frac{250\ V}{8.00\ k\Omega} = 31.2\ mA$$

Notice that the branch currents are inversely proportional to the resistances. The 20000-Ω resistor has a value four times larger than the 5000-Ω resistor, and has a current one quarter as large. If a resistor has a value twice as large as another, it will have half as much current through it when they are connected in parallel.

The total circuit current is:

$$I_{TOTAL} = I1 + I2 + I3 \quad (9)$$

$$I_{TOTAL} = 50.0\ mA + 12.5\ mA + 31.2\ mA$$

$$I_{TOTAL} = 93.7\ mA$$

This example illustrates Kirchhoff's Current Law: The current flowing into a node or branching point is equal to the sum of the individual currents leaving the node or branching point. The total resistance of the circuit is therefore:

$$R = \frac{E}{I} = \frac{250\ V}{93.7\ mA} = 2.67\ k\Omega$$

You can verify this calculation by combining the three resistor values in parallel, using equation 7.

RESISTORS IN SERIES

When a circuit has a number of resistances connected in series, the total resistance of the circuit is the sum of the individual resistances. If these are numbered R1, R2, R3 and so on, then:

$$R_{TOTAL} = R1 + R2 + R3 + R4 + ... \quad (10)$$

where the dots indicate that as many resistors as necessary may be added.

Example: Suppose that three resistors are connected to a source of EMF as shown in **Fig 5.5**. The EMF is 250 V, R1 is 5.00 kΩ, R2 is 20.0 kΩ and R3 is 8.00 kΩ. The total resistance is then

$$R_{TOTAL} = R1 + R2 + R3$$

$$R = 5.00\ k\Omega + 20.0\ k\Omega + 8.00\ k\Omega$$

$$R = 33.0\ k\Omega.$$

The current in the circuit is then

$$I = \frac{E}{R} = \frac{250\ V}{33.0\ k\Omega} = 7.58\ mA$$

(We need not carry calculations beyond three significant fig-

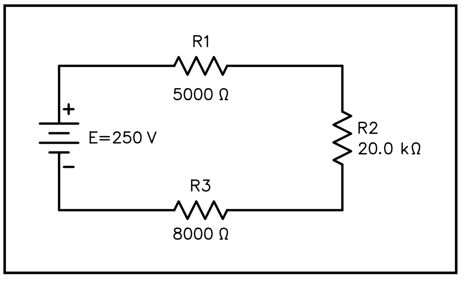

Fig 5.5 — An example of resistors in series. See text for calculations.

ures; often, two will suffice because the accuracy of measurements is seldom better than a few percent.)

KIRCHHOFF'S SECOND LAW (KIRCHHOFF'S VOLTAGE LAW)

Ohm's Law applies in any portion of a circuit as well as to the circuit as a whole. Although the current is the same in all three of the resistances in the example of Fig 5.5, the total voltage divides between them. The voltage appearing across each resistor (the voltage drop) can be found from Ohm's Law.

Example: If the voltage across R1 is called E1, that across R2 is called E2 and that across R3 is called E3, then

$$E1 = IR1 = 0.00758\,A \times 5000\,\Omega = 37.9\,V$$
$$E2 = IR2 = 0.00758\,A \times 20000\,\Omega = 152\,V$$
$$E3 = IR3 = 0.00758\,A \times 8000\,\Omega = 60.6\,V$$

Notice here that the voltage drop across each resistor is directly proportional to the resistance. The 20000-Ω resistor value is four times larger than the 5000-Ω resistor, and the voltage drop across the 20000-Ω resistor is four times larger. A resistor that has a value twice as large as another will have twice the voltage drop across it when they are connected in series.

Kirchhoff's Voltage Law accurately describes the situation in the circuit: The sum of the voltages in a closed current loop is zero. The resistors are power sinks, while the battery is a power source. It is common to assign a + sign to power sources and a – sign to power sinks. This means the voltages across the resistors have the opposite sign from the battery voltage. Adding all the voltages yields zero. In the case of a single voltage source, algebraic manipulation implies that the sum of the individual voltage drops in the circuit must be equal to the applied voltage.

$$E_{TOTAL} = E1 + E2 + E3 \quad (11)$$

$$E_{TOTAL} = 37.9\,V + 152\,V + 60.6\,V$$

$$E_{TOTAL} = 250\,V$$

(Remember the significant figures rule for addition.)

In problems such as this, when the current is small enough to be expressed in milliamperes, considerable time and trouble can be saved if the resistance is expressed in kilohms rather than in ohms. When the resistance in kilohms is substituted directly in Ohm's Law, the current will be milliamperes, if the EMF is in volts.

RESISTORS IN SERIES-PARALLEL

A circuit may have resistances both in parallel and in series, as shown in **Fig 5.6A**. The method for analyzing such a circuit is as follows: Consider R2 and R3 to be the equivalent of a single resistor, R_{EQ} whose value is equal to R2 and R3 in parallel.

$$R_{EQ} = \frac{R2 \times R3}{R2 + R3} = \frac{20000\,\Omega \times 8000\,\Omega}{20000\,\Omega + 8000\,\Omega}$$
$$= \frac{1.60 \times 10^8\,\Omega^2}{28000\,\Omega}$$
$$R_{EQ} = 5710\,\Omega = 5.71\,k\Omega$$

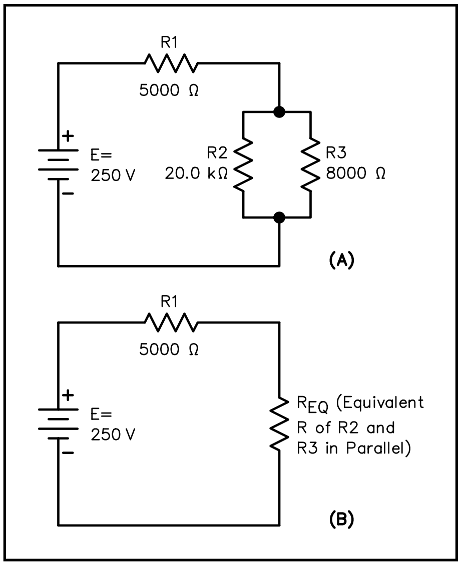

Fig 5.6 — At A, an example of resistors in series-parallel. The equivalent circuit is shown at B. See text for calculations.

This resistance in series with R1 forms a simple series circuit, as shown in Fig 5.6B. The total resistance in the circuit is:

$$R_{TOTAL} = R1 + R_{EQ} = 5.00\ k\Omega + 5.71\ k\Omega$$

$$R_{TOTAL} = 10.71\ k\Omega$$

The current is:

$$I = \frac{E}{R} = \frac{250\ V}{10.71\ k\Omega} = 23.3\ mA$$

The voltage drops across R1 and R_{EQ} are:

$$E1 = I \times R1 = 23.3\ mA \times 5.00\ k\Omega = 117\ V$$

$$E2 = I \times R_{EQ} = 23.3\ mA \times 5.71\ k\Omega = 133\ V$$

with sufficient accuracy. These two voltage drops total 250 V, as described by Kirchhoff's Current Law. E2 appears across both R2 and R3 so,

$$I2 = \frac{E2}{R2} = \frac{133\ V}{20.0\ k\Omega} = 6.65\ mA$$

$$I3 = \frac{E3}{R3} = \frac{133\ V}{8.00\ k\Omega} = 16.6\ mA$$

where:

I2 = current through R2 and

I3 = current through R3.

The sum of I2 and I3 is equal to 23.3 mA, conforming to Kirchhoff's Voltage Law.

THEVENIN'S THEOREM

Thevenin's Theorem is a useful tool for simplifying electrical networks. Thevenin's Theorem states that any two-terminal network of resistors and voltage or current sources can be replaced by a single voltage source and a series resistor. Such a transformation can simplify the calculation of current through a parallel branch. Thevenin's Theorem can be readily applied to the circuit of Fig 5.6A, to find the current through R3.

In this example, R1 and R2 form a voltage divider circuit, with R3 as the load (**Fig 5.7A**). The current drawn by the load (R3) is simply the voltage across R3, divided by its resistance. Unfortunately, the value of R2 affects the voltage across R3, just as the presence of R3 affects the potential appearing across R2. Some means of separating the two is needed; hence the Thevenin-equivalent circuit.

The voltage of the Thevenin-equivalent battery is the open-circuit voltage, measured when there is no current from either

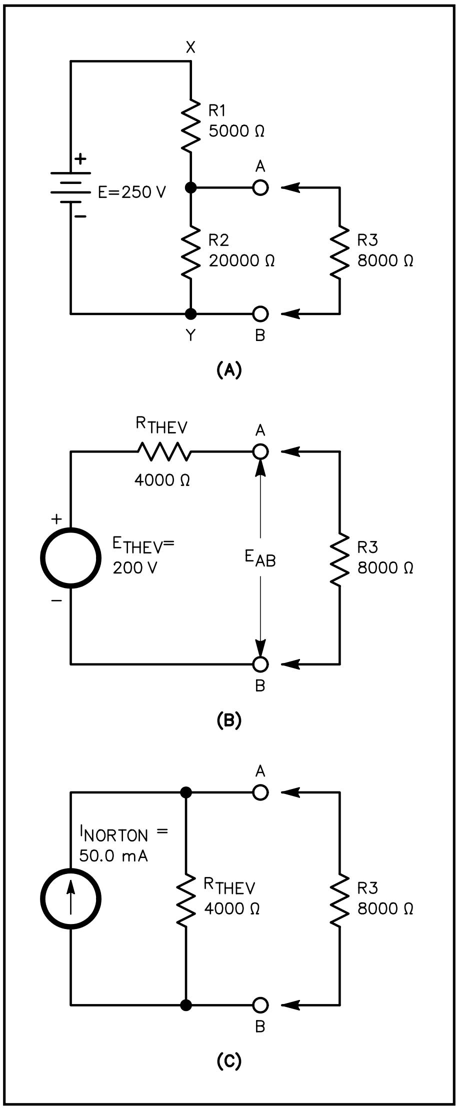

Fig 5.7 — Equivalent circuits for the circuit shown in Fig 5.6. A shows the load resistor (R3) looking into the circuit. B shows the Thevenin-equivalent circuit, with a resistor and a voltage source in series. C shows the Norton-equivalent circuit, with a resistor and current source in parallel.

terminal A or B. Without a load connected between A and B, the total current through the circuit is (from Ohm's Law):

$$I = \frac{E}{R1 + R2} \tag{12}$$

and the voltage between terminals A and B (E_{AB}) is:

$$E_{AB} = I \times R2 \tag{13}$$

By substituting the first equation into the second, we can find a simplified expression for E_{AB}:

$$E_{AB} = \frac{R2}{R1 + R2} \times E \tag{14}$$

Using the values in our example, this becomes:

$$E_{AB} = \frac{20.0\ k\Omega}{25.0\ k\Omega} \times 250\ V = 200\ V$$

when nothing is connected to terminals A or B. With no current drawn, E is equal to E_{AB}.

The Thevenin-equivalent resistance is the total resistance between terminals A and B. The ideal voltage source, by definition, has zero internal resistance. Assuming the battery to be a close approximation of an ideal source, put a short between points X and Y in the circuit of Fig 5.7A. R1 and R2 are then effectively placed in parallel, as viewed from terminals A and B. The Thevenin-equivalent resistance is then:

$$R_{THEV} = \frac{R1 \times R2}{R1 + R2}$$
$$R_{THEV} = \frac{5000\,\Omega \times 20000\,\Omega}{5000\,\Omega + 20000\,\Omega}$$
$$R_{THEV} = \frac{1.00 \times 10^8\ \Omega^2}{25000\,\Omega} = 4000\,\Omega \tag{15}$$

This gives the Thevenin-equivalent circuit as shown in Fig 5.7B. The circuits of Figs. 5.7A and 5.7B are equivalent as far as R3 is concerned.

Once R3 is connected to terminals A and B, there will be current through R_{THEV}, causing a voltage drop across R_{THEV} and reducing E_{AB}. The current through R3 is equal to

$$I3 = \frac{E_{THEV}}{R_{TOTAL}} = \frac{E_{THEV}}{R_{THEV} + R3} \tag{16}$$

Substituting the values from our example:

$$I3 = \frac{200\ V}{4000\,\Omega + 8000\,\Omega} = 16.7\ mA$$

This agrees with the value calculated earlier.

NORTON'S THEOREM

Norton's Theorem is another tool for analyzing electrical networks. Norton's Theorem states that any two-terminal network of resistors and current or voltage sources can be replaced by a single current source and a parallel resistor. Norton's Theorem is to current sources what Thevenin's Theorem is to voltage sources. In fact, the Thevenin resistance calculated previously is also used as the Norton equivalent resistance.

The circuit just analyzed by means of Thevenin's Theorem can be analyzed just as easily by Norton's Theorem. The equivalent Norton circuit is shown in Fig 5.7C. The current I_{SC} of the equivalent current source is the short-circuit current through terminals A and B. In the case of the voltage divider shown in Fig 5.7A, the short-circuit current is:

$$I_{SC} = \frac{E}{R1} \tag{17}$$

Substituting the values from our example, we have:

$$I_{SC} = \frac{E}{R1} = \frac{250\ V}{5000\ \Omega} = 50.0\ mA$$

The resulting Norton-equivalent circuit consists of a 50.0-mA current source placed in parallel with a 4000-Ω resistor. When R3 is connected to terminals A and B, one-third of the supply current flows through R3 and the remainder through R_{THEV}. This gives a current through R3 of 16.7 mA, again agreeing with previous conclusions.

A Norton-equivalent circuit can be transformed into a Thevenin-equivalent circuit and vice versa. The equivalent resistor stays the same in both cases; it is placed in series with the voltage source in the case of a Thevenin-equivalent circuit and in parallel with the current source in the case of a Norton-equivalent circuit. The voltage for a Thevenin-equivalent source is equal to the no-load voltage appearing across the resistor in the Norton-equivalent circuit. The current for a Norton-equivalent source is equal to the short-circuit current provided by the Thevenin source.

Power and Energy

Regardless of how voltage is generated, energy must be supplied if current is drawn from the voltage source. The energy supplied may be in the form of chemical energy or mechanical energy. This energy is measured in joules. One joule is defined from classical physics as the amount of energy or work done when a force of one newton (a measure of force) is applied to an object that is moved one meter in the direction of the force.

Power is another important concept. In the USA, power is often measured in horsepower in mechanical systems. We use the metric power unit of watts in electrical systems, however. In metric countries, mechanical power is usually expressed in watts also. One watt is defined as the use (or generation) of one joule of energy per second. One watt is also defined as one volt of potential pushing one ampere of current through a resistance. Thus,

$$P = I \times E \qquad (18)$$

where:

P = power in watts
I = current in amperes
E = EMF in volts.

When current flows through a resistance, the electrical energy is turned into heat. Common fractional and multiple units for power are the milliwatt (one thousandth of a watt) and the kilowatt (1000 W).

Example: The plate voltage on a transmitting vacuum tube is 2000 V and the plate current is 350 mA. (The current must be changed to amperes before substitution in the formula, and so is 0.350 A.) Then:

$$P = I \times E = 2000\text{ V} \times 0.350\text{ A} = 700\text{ W}$$

By substituting the Ohm's Law equivalent for E and I, the following formulas are obtained for power:

$$P = \frac{E^2}{R} \qquad (19)$$

and

$$P = I^2 \times R \qquad (20)$$

These formulas are useful in power calculations when the resistance and either the current or voltage (but not both) are known.

Example: How much power will be converted to heat in a 4000-Ω resistor if the potential applied to it is 200 V? From equation 19,

$$P = \frac{E^2}{R} = \frac{(200\text{ V})^2}{4000\,\Omega}$$

$$= \frac{40000\text{ V}^2}{4000\,\Omega} = 10.0\text{ W}$$

As another example, suppose a current of 20 mA flows through a 300-Ω resistor. Then:

$$P = I^2 \times R = 0.020^2\text{ A}^2 \times 300\,\Omega$$

$$P = 0.00040\text{ A}^2 \times 300\,\Omega$$

$$P = 0.12\text{ W}$$

Note that the current was changed from milliamperes to amperes before substitution in the formula.

Electrical power in a resistance is turned into heat. The greater the power, the more rapidly the heat is generated. Resistors for radio work are made in many sizes, the smallest being rated to dissipate (or carry safely) about $^1/_{16}$ W. The largest resistors commonly used in amateur equipment will dissipate about 100 W. Large resistors, such as those used in dummy-load antennas, are often cooled with oil to increase their power-handling capability.

If you want to express power in horsepower instead of watts, the following relationship holds:

$$1 \text{ horsepower} = 746 \text{ W} \quad (21)$$

This formula assumes lossless transformation; practical efficiency is taken up shortly. This formula is especially useful if you are working with a system that converts electrical energy into mechanical energy, and vice versa, since mechanical power is often expressed in horsepower, in the US.

GENERALIZED DEFINITION OF RESISTANCE

Electrical energy is not always turned into heat. The energy used in running a motor, for example, is converted to mechanical motion. The energy supplied to a radio transmitter is largely converted into radio waves. Energy applied to a loudspeaker is changed into sound waves. In each case, the energy is converted to other forms and can be completely accounted for. None of the energy *just disappears*! This is a statement of the Law of Conservation of Energy. When a device converts energy from one form to another, we often say it *dissipates* the energy, or power. (Power is energy divided by time.) Of course the device doesn't really "use up" the energy, or make it disappear, it just converts it to another form. Proper operation of electrical devices often requires that the power must be supplied at a specific ratio of voltage to current. These features are characteristics of resistance, so it can be said that any device that "dissipates power" has a definite value of resistance.

This concept of resistance as something that absorbs power at a definite voltage-to-current ratio is very useful; it permits substituting a simple resistance for the load or power-consuming part of the device receiving power, often with considerable simplification of calculations. Of course, every electrical device has some resistance of its own in the more narrow sense, so a part of the energy supplied to it is converted to heat in that resistance even though the major part of the energy may be converted to another form.

EFFICIENCY

In devices such as motors and vacuum tubes, the objective is to convert the supplied energy (or power) into some form other than heat. Therefore, power converted to heat is considered to be a loss, because it is not useful power. The efficiency of a device is the useful power output (in its converted form) divided by the power input to the device. In a vacuum-tube transmitter, for example, the objective is to convert power from a dc source into ac power at some radio frequency. The ratio of the RF power output to the dc input is the efficiency of the tube. That is:

$$\text{Eff} = \frac{P_O}{P_I} \quad (22)$$

where:

Eff = efficiency (as a decimal)

P_O = power output (W)

P_I = power input (W).

Example: If the dc input to the tube is 100 W, and the RF power output is 60 W, the efficiency is:

$$\text{Eff} = \frac{P_O}{P_I} = \frac{60 \text{ W}}{100 \text{ W}} = 0.6$$

Efficiency is usually expressed as a percentage — that is, it tells what percent of the input power will be available as useful output. To calculate percent efficiency, just multiply the value from equation 22 by 100%. The efficiency in the example above is 60%.

Suppose a mobile transmitter has an RF power output of 100 W with 52% efficiency at 13.8 V. The vehicle's alternator system charges the battery at a 5.0-A rate at this voltage. Assuming an alternator efficiency of 68%, how much horsepower must the engine produce to operate the transmitter and charge the battery? Solution: To charge the battery, the alternator must produce 13.8 V × 5.0 A = 69 W. The transmitter dc input power is 100 W / 0.52 = 190 W. Therefore, the total electrical power required from the alternator is 190 + 69 = 260 W. The engine load then is:

$$P_I = \frac{P_O}{Eff} = \frac{260\ W}{0.68} = 380\ W$$

We can convert this to horsepower using the formula given earlier to convert between horsepower and watts:

$$380\ W \times \frac{1\ \text{horsepower}}{746\ W} = 0.51\ \text{horsepower}$$

ENERGY

When you buy electricity from a power company, you pay for electrical energy, not power. What you pay for is the *work* that electricity does for you, not the rate at which that work is done. Work is equal to power multiplied by time. The common unit for measuring electrical energy is the watt-hour, which means that a power of 1 W has been used for one hour. That is:

W hr = P T

where:

W hr = energy in watt-hours

P = power in watts

T = time in hours.

Actually, the watt-hour is a fairly small energy unit, so the power company bills you for kilowatt-hours of energy used. Another energy unit that is sometimes useful is the watt-second (joule).

Energy units are seldom used in amateur practice, but it is obvious that a small amount of power used for a long time can eventually result in a power bill that is just as large as if a large amount of power had been used for a very short time.

One practical application of energy units is to estimate how long a radio (such as a hand-held unit) will operate from a certain battery. For example, suppose a fully charged battery stores 900 mA hr of energy, and a radio draws 30 mA on receive. You might guess that the radio will receive 30 hrs with this battery, assuming 100% efficiency. You shouldn't expect to get the full 900 mA hr out of the battery, and you will probably spend some of the time transmitting, which will also reduce the time the battery will last. The **Real-World Component Characteristics** and **Power Supplies** chapters include additional information about batteries and their charge/discharge cycles.

Circuits and Components

SERIES AND PARALLEL CIRCUITS

Passive components (resistors for dc circuits) can be used to make voltage and current dividers and limiters to obtain a desired value. For instance, in **Fig 5.8A**, two resistors are connected in series to provide a voltage divider. As long as the device connected at point A has a much higher resistance than the resistors in the divider, the voltage will be approximately the ratio of the resistances. Thus, if E = 10 V, R1 = 5 Ω and R2 = 5 Ω, the voltage at point A will be 5 V measured on a high-impedance voltmeter. A good rule of thumb is that the load at point A should be at least ten times the value of the highest resistor in the divider to get reasonably close to the voltage you want. As the load resistance gets closer to the value of the divider, the current drawn by the load affects the division and causes changes from the desired value. If you need precise voltage division from fixed resistors and know the value of the load resistance, you can use Kirchhoff's Laws and Thevenin's Theorem (explained earlier) to calculate exact values.

Similarly, resistors can be used, as shown in Fig 5.8B, to make current dividers. Suppose you had two LEDs (light emitting diodes) and wanted one to glow twice as brightly as the other. You could use one resistor with twice the value of the other for the dimmer LED. Thus, approximately two-thirds of the current would flow through one LED and one-third through the other (neglecting any effect of the 0.7-V drop across the diode).

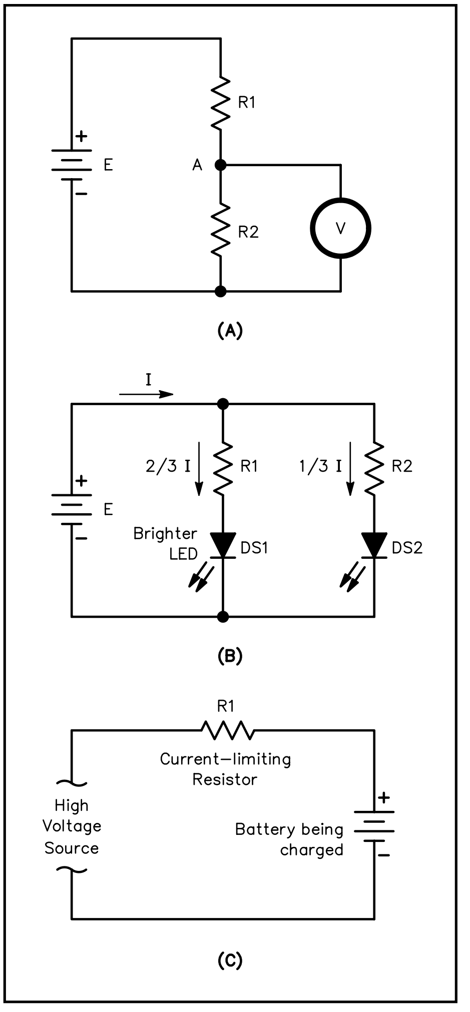

Fig 5.8 — This circuit shows a resistive voltage divider.

Resistors can also be used to limit the current through a device from a fixed voltage source. A typical example is shown in Fig 5.8C. Here a high-voltage source feeds a battery in a battery charger. This is typical of nickel cadmium chargers. The high resistor value limits the current that can possibly flow through the battery to a value that is low enough so it will not damage the battery.

SWITCHES

Switches are used to start or stop a signal (current) flowing in a particular circuit. Most switches are mechanical devices, although the same effect may be achieved with solid-state devices. Relays are switches that are controlled by another electrical signal rather than manual or mechanical means.

Switches come in many different forms and a wide variety of ratings. The most important ratings are the voltage and current handling capabilities. The voltage rating usually includes both the breakdown rating and the interrupt rating. Normally, the interrupt rating is the lower value, and therefore the one given on (for) the switch. The current rating includes both the current carrying capacity and the interrupt capability.

Most power switches are rated for alternating current use. Because ac voltage goes through zero with each cycle, switches can successfully interrupt much more alternating current than direct current without arcing. A switch that has a 10-A ac current rating may arc and damage the contacts if used to turn off more than an ampere or two of dc.

Switches are normally designated by the number of *poles* (circuits controlled) and *positions* (circuit path choices). The simplest switch is the on-off switch, which is a single-pole, single-throw (SPST) switch as shown in **Fig 5.9A**. The off position does not direct the current to another circuit. The next step would be to change the current path to another path, and would be a single-pole, double-throw (SPDT) switch as shown in Fig 5.9B. Adding an off position would give a single-pole, double-throw, center-off switch as shown in Fig 5.9C.

Several such switches can be "ganged" to the same mechanical activator to provide double pole, triple pole or even more, separate control paths all activated at once. Switches can be activated in a variety of ways. The most common methods include lever, push button and rotary switches. Samples of these are shown in **Fig 5.10**. Most switches stay in the position set, but some are spring loaded so they only stay in the desired position while held there. These are called momentary switches.

Switches typically found in the home are usually rated for 125 V ac and 15 to 20 A. Switches in cars are usually rated for 12 V dc and several amperes. The breakdown voltage rating of a switch, which is usually higher than the interrupt rating, primarily depends on the insulating material surrounding the contacts and the separation between the contacts. Plastic or phenolic material normally provides both structural support and insulation. Ceramic material may be used to provide better insulation, particularly in rotary (wafer) switches.

The current carrying capacity of the switch depends on the contact material and size and on the pressure between the contacts. It is primarily determined from the allowable contact temperature rise. On larger ac switches, or most dc switches, the interrupt capability may be lower than the current carrying value.

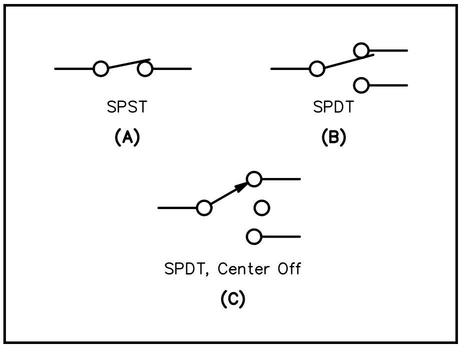

Fig 5.9 — Schematic diagrams of various types of switches. A is an SPST, B is an SPDT, C is an SPDT switch with a center-off position.

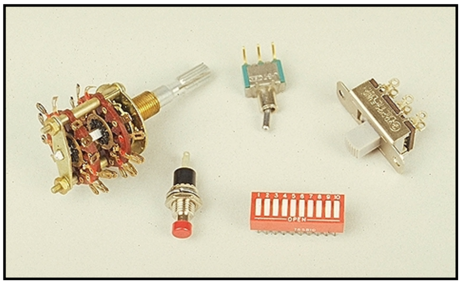

Fig 5.10 — This photo shows examples of various styles of switches.

Rotary/wafer switches can provide very complex switching patterns. Several poles (separate circuits) can be included on each wafer. Many wafers may be stacked on the same shaft. Not only may many different circuits be controlled at once, but by wiring different poles/positions on different wafers together, a high degree of circuit switching logic can be developed. Such switches can select different paths as they are turned, and can also "short" together successive contacts to connect numbers of components or paths. They can also be designed to either break one contact before making another, or to short two contacts together before disconnecting the first one (make before break) to eliminate arcing or perform certain logic functions.

In choosing a switch for a particular task, consideration should be given to function, voltage and current ratings, ease of use, availability and cost. If a switch is to be operated frequently, a slightly higher cost for a better-quality switch is usually less costly over the long run. If signal noise or contact corrosion is a potential problem, (usually in low-current signal applications) it is best to get gold plated contacts. Gold does not oxidize or corrode, thus providing surer contact, which can be particularly important at very low signal levels. Gold plating will not hold up under high-current-interrupt applications, however.

FUSES

Fuses self-destruct to protect circuit wiring or equipment. The fuse element that melts is a carefully shaped piece of soft metal, usually mounted in a cartridge of some kind. The element is designed to safely carry a given amount of current and to melt at a current value that is a certain percentage over the rated value. The melting value depends on the type of material, the shape of the element and the heat dissipation capability of the cartridge and holder, among other factors. Some fuses (Slo-blo) are designed to carry an overload for a short period of time. They typically are used in motor starting and power-supply circuits that have a large inrush current when first started. Other fuses are designed to blow very quickly to protect delicate instruments and solid-state circuits. A replacement fuse should have the same current rating and the same characteristics as the fuse it replaces. **Fig 5.11** shows a variety of fuse types and sizes.

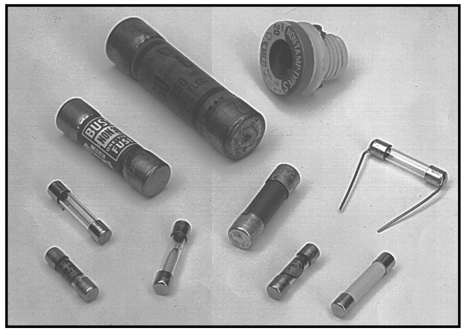

Fig 5.11 — This photo shows examples of various styles of fuses.

The most important fuse rating is the nominal current rating that it will safely carry. Next most important are the timing characteristics, or how quickly it opens under a given current overload. A fuse also has a voltage rating, both a value in volts and whether it is expected to be used in ac or dc circuits. While you should never substitute a fuse with a higher current rating than the one it replaces, you can use a fuse with a higher voltage rating. There is no danger in replacing a 12-V, 2-A fuse with a 250-V, 2-A unit.

Fuses fail for several reasons. The most obvious reason is that a problem develops in the circuit, which causes too much current to flow. In this case, the circuit problem needs to be fixed. A fuse may just fail eventually, particularly when cycled on and off near its current rating. A kind of metal fatigue sets in, and eventually the fuse goes. A fuse can also blow because of a momentary power surge, or even turning something on and off several times quickly when there is a large inrush current. In these cases it is only necessary to replace the fuse with the same type and value. Never substitute a fuse with a larger current rating. You may cause permanent damage (maybe even a fire) to the wiring or circuit elements if/when there is an internal problem in the equipment.

RELAYS

Relays are switches that are driven by an electrical signal, usually through a magnetic coil. An armature that moves when current is applied pushes the switch contacts together, or pulls them apart. Many such contacts can be connected to the same armature, allowing many circuits to be controlled by a single signal. Usually, relays have only two positions (opening some contacts and closing others) although there are special cases.

Like switches, relays have specific voltage and current ratings for the contacts. These may be far different from the voltage and current of the coil that drives the relay. That means a small signal voltage might control very large values of voltage and/or current. Relay contacts (and housings) may be designed for ac, dc or RF signals. The control voltages are usually 12 V dc or 125 V ac for most amateur applications, but the coils may be designed to be "current sensing" and operate when the current through the coil exceeds a specific value. **Fig 5.12** shows some typical relays found in amateur equipment. Relays with 24- and 28-V coils are also common.

Coaxial relays are specially designed to handle RF signals and to maintain a characteristic impedance to match certain values of coaxial-cable impedance. They typically are used to switch an antenna between a receiver and transmitter or between a linear amplifier and a transceiver. **Fig 5.13** shows how several relays may be controlled by a microphone button to switch various functions in an amateur station. This simple system does not include control circuitry to provide proper sequencing of the relays.

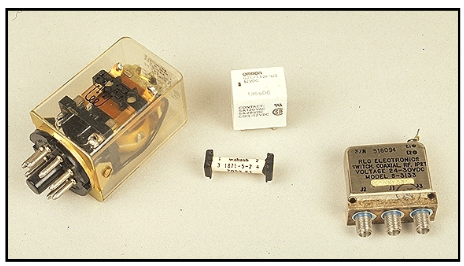

Fig 5.12 — This photo shows examples of various styles of relays.

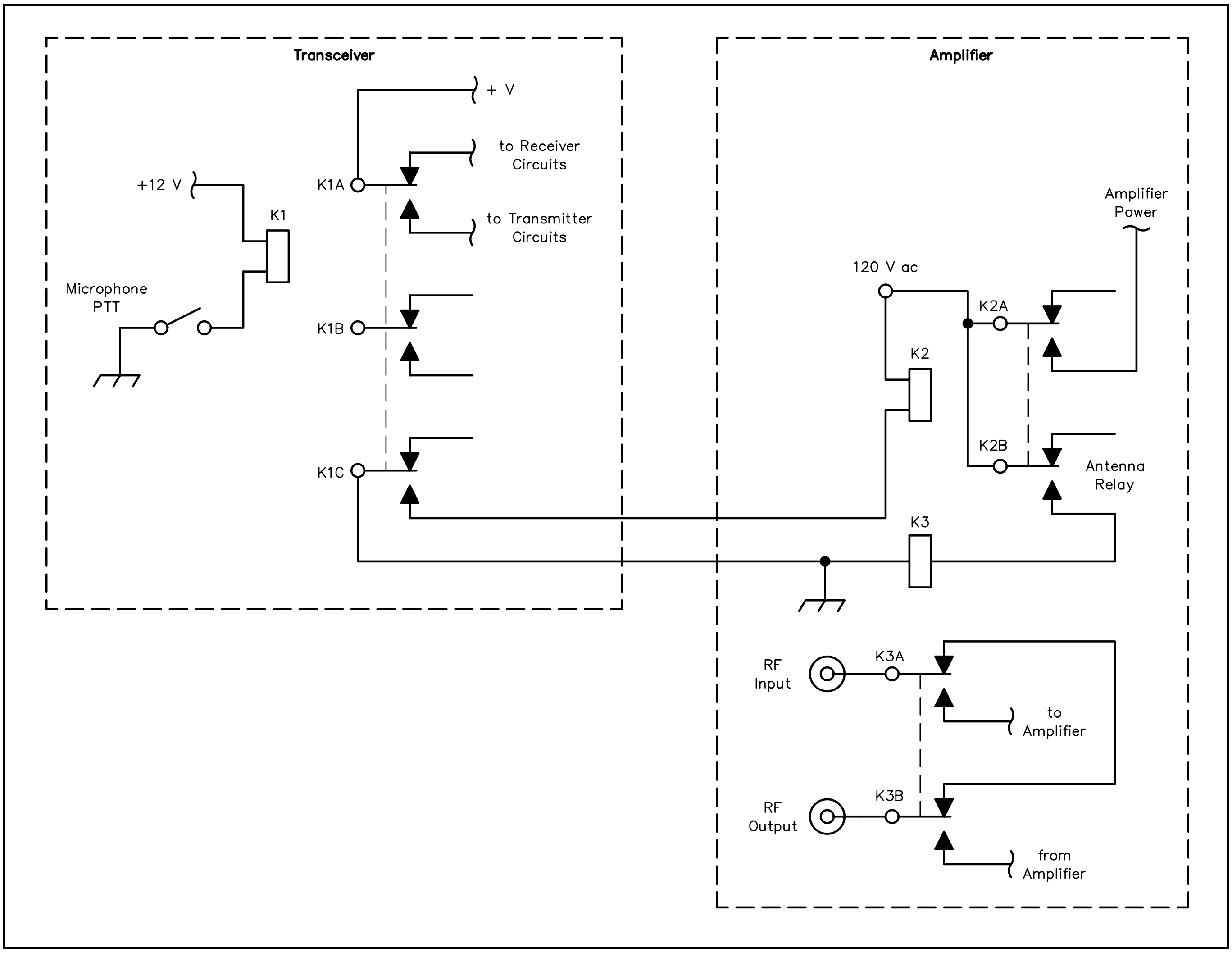

Fig 5.13 — A simple station control circuit. This example does not include control circuitry to provide proper sequencing of the relays.

POTENTIOMETERS

Potentiometer is a big name for a variable resistor. They are commonly used as volume controls on radios, televisions and stereos. A typical potentiometer is a circular pattern of resistive material, usually a carbon compound, that has a wiper on a shaft moving across the material. For higher power applications, the resistive material may be wire, wound around a core. As the wiper moves along the material, more resistance is introduced between the wiper and one of the fixed contacts on the material. A potentiometer may be used primarily to control current, voltage or resistance in a circuit. **Fig 5.14** shows several circuits to demonstrate various uses. **Fig 5.15** shows several different types of potentiometers.

Typical specifications for a potentiometer include maximum resistance, power dissipation, voltage and current ratings, number of turns (or degrees) the shaft can rotate, type and size

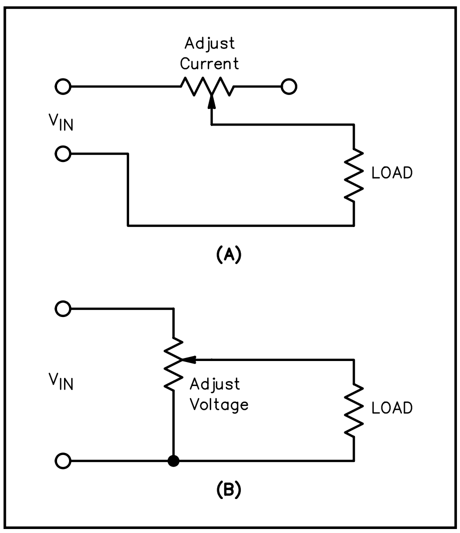

Fig 5.14 — Various uses of potentiometers.

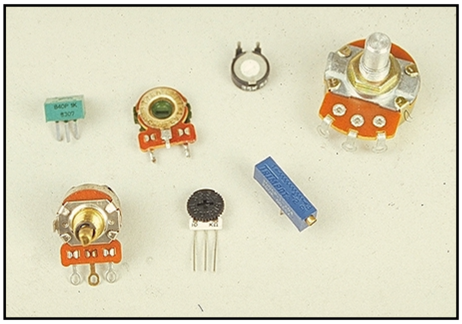

Fig 5.15 — This photo shows examples of different styles of potentiometers.

of shaft, mounting arrangements and resistance "taper."

Not all potentiometers have a *linear* taper. That is, the resistance may not be the same for a given number of degrees of shaft rotation along different portions of the resistive material. A typical use of a potentiometer with a nonlinear taper is as a volume control. Since the human ear has a logarithmic response to sound, a volume control may actually change the volume (resistance) much more near one end of the potentiometer than the other (for a given amount of rotation) so that the "perceived" change in volume is about the same for a similar change in the control. This is commonly called an "audio taper" as the change in resistance per degree of rotation attempts to match the response of the human ear. The taper can be designed to match almost any desired control function for a given application. Linear and audio tapers are the most common.