Lesson 2
CIRCUITS

Task. The skills and knowledge taught in this lesson are common to all missile repairer tasks.

Objectives. When you have completed this lesson, you should be able to explain what an electric circuit is, define the standard electrical units of measure, and explain and use Ohm's and Kirchoff's laws.

Conditions. You will have this subcourse book and work without supervision.

Standard. You must score at least 75 on the end-of-subcourse examination that covers this lesson and lessons 1, 3, and 4 (answer 29 of the 38 questions correctly).

AN ELECTRIC CIRCUIT

Before discussing direct current and the laws which apply to it, you need to understand the elements of a direct or alternating circuit as well as electromotive force and resistance. An electric circuit is formed when a source of electrical potential is connected to an electrical device by means of a conductor. Figure 2-1 shows a simple circuit with circuit components.

Terminology

Electrical Potential. The potential (in this case, a battery) provides the driving force for the circuit. Since the negative terminal of the battery has

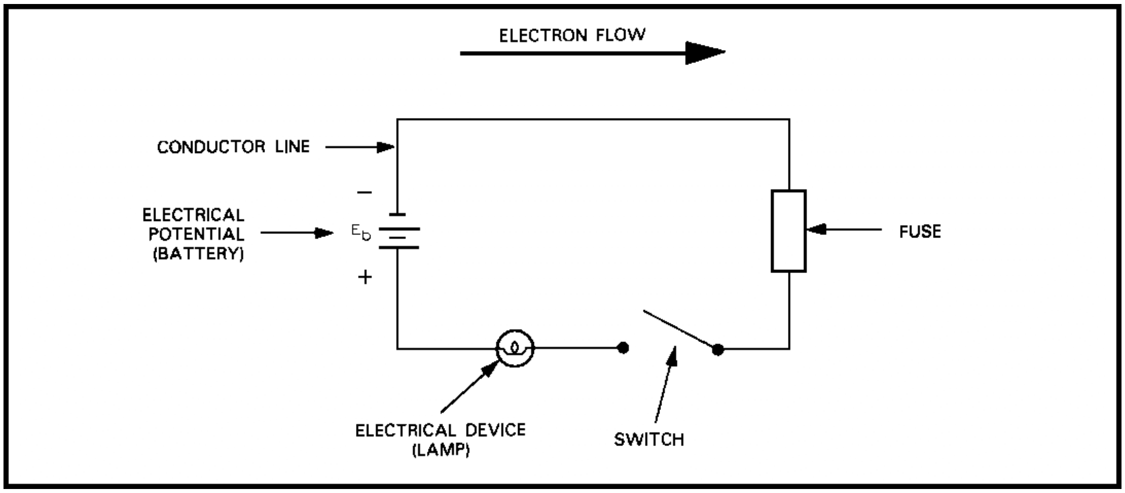

Figure 2-1. Simple Electrical Circuit.

an excess of electrons, as compared to the positive terminal, the electrons move from the negative to the positive terminal when there is a completed path.

Conductor. The item which provides this path for the electrons is the conductor. The phenomenon which allows this conduction is at the atomic level. Electrons are not readily separated from an atom because they are maintained within the atom by the attraction force of the positive nucleus. However, electrons are known to exist in a free state apart from the atom. Such electrons are called free electrons. Some substances such as copper, silver, gold, and aluminum contain great quantities of these electrons and are good conductors. Although all conductors offer some opposition to current flow, you can assume this opposition is negligible here.

Electrical Device. In order to use the electrons flowing in the conductor, an electrical device must be inserted. As the electrons pass through the device, they activate the device. In figure 2-1, the electrical device is a lamp.

Switch. A switch allows you to start and stop the flow of electrons. When you close the switch (start electron flow), a closed circuit is formed, and when you open the switch (stopping current flow), an open circuit is formed.

Fuse. If the electron flow in a circuit is too great, it may damage the electrical device or excessively heat the conductors. To prevent this, a fuse can be inserted. Excessive electron flow produces sufficient heat to melt the fuse and open the circuit, turning it off. A fuse may be considered as an automatic safety switch.

Kinds of Circuits

Series. Series circuit provides only one path for current to flow. So the current flows through the first resistor, then the second, etc. in series.

Parallel. In a parallel circuit, the current has parallel paths through which it can flow. Each resistor has one end connected to the battery, and the other end is connected to the other end of the battery. The line current or total current leaving the battery must equal the sum of the currents entering the parallel branches.

ELECTRICAL MEASUREMENTS

In order to learn any more about electrical phenomena, you need to learn the five basic electrical quantities and to specify the units by which they are measured. Other definitions will be added as the need arises.

Coulomb

The unit of electrical charge (the quantity of excess electrons) is called the coulomb (C). It is the charge that you would get by collecting approximately

6,280,000,000,000,000,000 (6.28×10^{18}) free electrons on a single charged body. Although this large unit is seldom used in calculations, it is important because it is the basis for the definition of other units.

Ampere

The unit of electron flow is called the ampere (amp). If one C of charge passes a given point on a wire in 1 second, then 1 amp is said to flow. In other words, the ampere is a special name given to a C per second. This electron flow is called current and is represented by the symbol I, which is an abbreviation for "intensity of flow."

Ohm

The practical unit of resistance to electric current flow is called the ohm. It is that resistance in which 1 volt will maintain a current of 1 amp. The symbol for ohms is Ω, which is the Greek letter omega.

Volt

The unit of electromotive force (pressure) is the volt. It is the force that will cause 1 amp to flow through a resistance of 1 Ω. Voltage is represented by the symbol V or E.

Watt

The unit of electrical power is the watt (W). There is one watt of power in a 1-Ω resistor in which a current of 1 amp is flowing. The basic formula is $P = IE$.

Practical Values of Electrical Terms

Because it is difficult to visualize the size of these units from the definitions, the following information may be helpful. You can get a better idea of the size of the C by imagining that, if a charge of 6.8 millionths of a C were placed 1 ft from a similar charge, there would be a repelling force of 1 lb. acting between them. A 100-W light takes about 1 amp of current. The resistance of an electric toaster or flat iron is about 25 Ω.

ELECTROMOTIVE FORCE

As already stated, one requirement of a circuit is a difference of potential or electromotive force (EMF). The EMF may be two unequally charged bodies. If a conductor is placed between them, a current will flow (fig 2-2) for only an instant. The difference in potential is then neutralized. To have an effective current, an EMF must be provided that will remain constant for relatively long periods of time. Batteries or generators are often used for this, with the output terminals being the two unequally charged bodies.

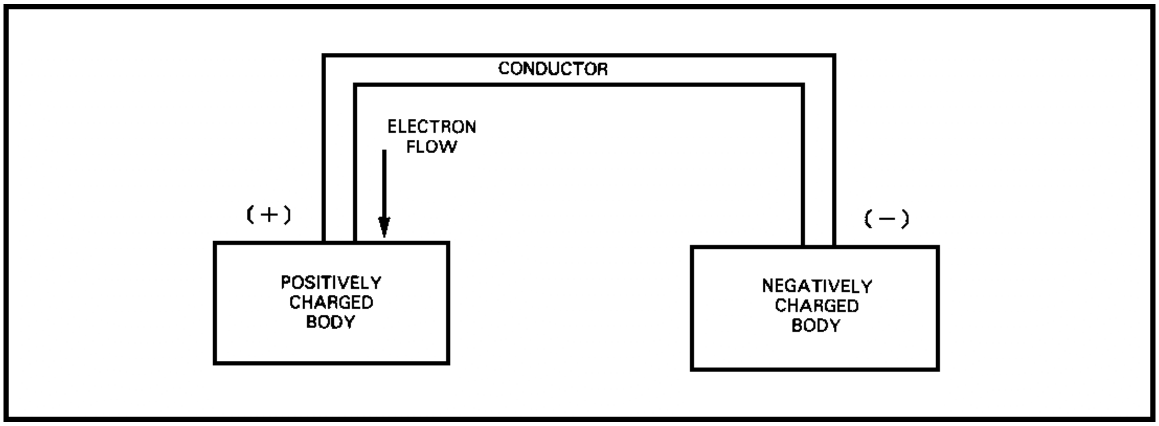

Figure 2-2. Electromagnetic Force.

CURRENT

To understand the electron flow produced by an EMF, consider the behavior of electrons in a copper wire. At any instant, the copper wire has free electrons drifting about within the wire. These electrons are attached to the positively charged body and repelled by the negatively charged body. The movement of these free charges through the copper wire makes an electric current. Current flow, as visualized in the electron theory, is illustrated in figure 2-3. AB is a conductor, composed of atoms (enlarged many, many thousands of times in the illustration), each of which is made up of electrons revolving about its center (including free electrons around the outer orbits). When an EMF is impressed across AB, electrons tend to transfer from atom to atom, from the A end to the B end. This electron movement is current and can be defined as a moving charge.

RESISTANCE

Resistance is produced by any device in a circuit which offers a continuous opposition to current flow. Energy in some form is dissipated when the EMF overcomes this resistance and causes current to flow. In many cases, resistance is added in a circuit, not to dissipate useful energy, but to improve overall operation. These types of resistors are classified as wire-wound or carbon. The wire-wound variety is made of resistance wire such as nichrome, German silver, or manganin. Carbon resistors are made by mixing powdered carbon with some suitable binder. The mixture is molded into the proper shape. Resistors, can be fixed, adjustable, or variable.

Fixed

Fixed resistors are used to introduce a constant value of resistance into a circuit. The resistor's size and construction is determined by the amount of power it dissipates without damage to itself. For low-power requirements, small carbon or metalized resistors are used; where heavier dissipation is required, larger resistors of wire-wound construction are used.

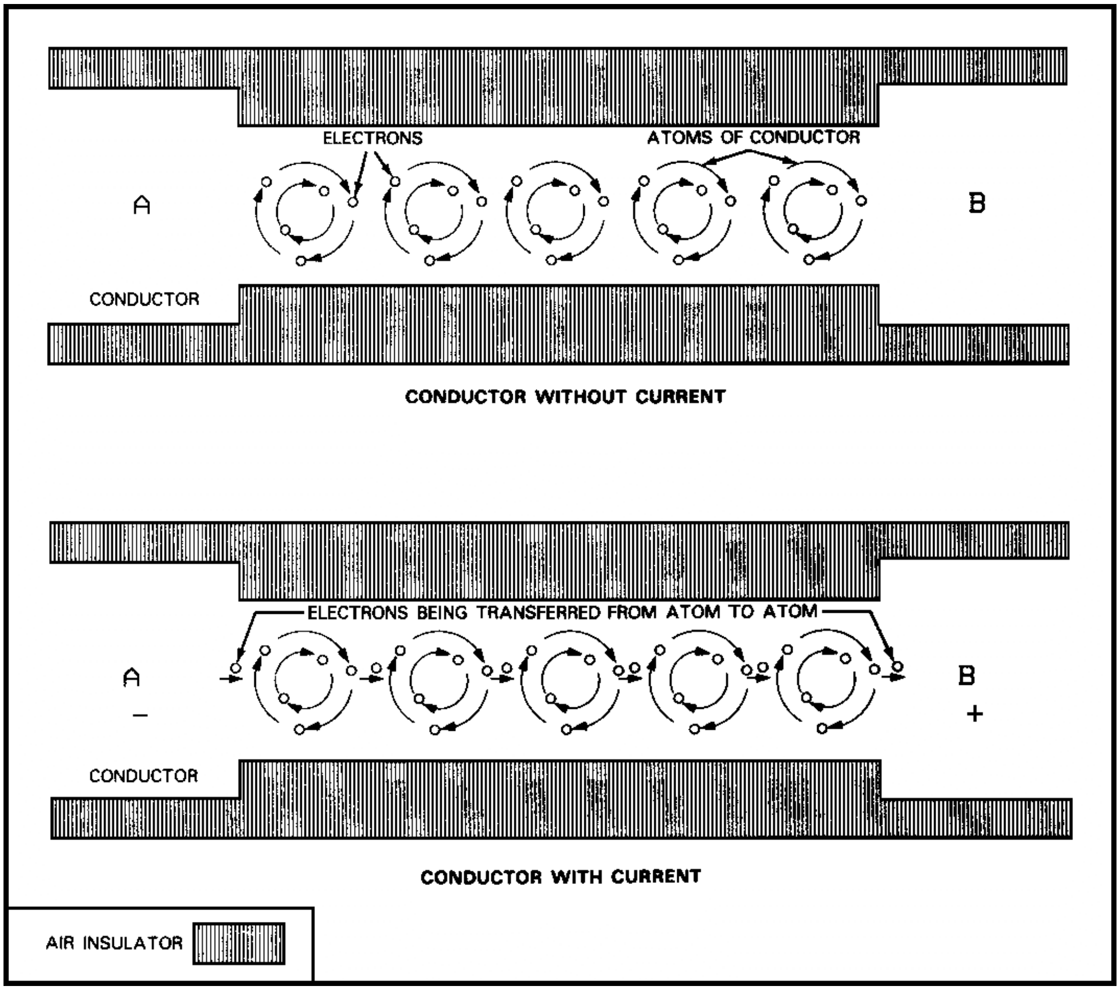

Figure 2-3. Electron Behavior.

Adjustable

Adjustable resistors are used to adjust the value of the resistance in a circuit to compensate for changes in resistor values due to age. The adjustable resistor is usually wire-wound and has one or more sliding collars which may be moved along the resistance element to the desired resistance value. It is then clamped into place and remains fixed until the value changes when it must be readjusted.

Variable

Variable resistors are used when a resistance requires frequent change. The volume control on your radio is an example of this. Depending on the power requirements, variable resistors are either carbon or wire-wound. The resistance element of the variable resistor is usually circular. The sliding tap (arm), which makes contact with it, has a knob and a shaft with which the resistance can be smoothly varied. Variable resistors are called rheostats or potentiometers.

LAWS

Kirchoff's Laws used with Ohm's Law makes the solutions of many problems very simple. Application of Ohm's Law is the same for any circuit. Application of Kirchoff's Laws is shown for all three kinds of circuits; series, parallel, and series-parallel.

Ohm's Law

Ohm's Law states; The current in a circuit is directly proportional to the applied potential (voltage) and inversely proportional to the resistance. It is written mathematically as follows:

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

where I = current in amps,
E = EMF in V,
R = resistance in Ω.

This law is based on the findings of George Simon Ohm in 1827. It shows that the amount of current that flows in a circuit increases if the potential applied is increased and decreases if the resistance is increased. It also shows that current decreases when the potential applied decreases, and increases if the resistance decreases. To further understand Ohm's Law, you have to understand the relationships between current, voltage, resistance, and power. Review the paragraph, Electrical Measurements, if you are unsure. Table 2-1 shows Ohm's Law as applied to direct current (DC) and alternating current (AC) circuits. The next lesson is on AC and DC.

The following are some applications of Ohm's Law.

Look at figure 2-4. The EMF is 24 V and the resistance is 60 Ω. Solve for current.

Step one--copy formula for I:

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

Step two--substitute known values:

$$I = \frac{24V}{60\Omega}$$

Step three--perform indicated division:

$$I = .4 \text{ A.}$$

(Note, in equations, *amp* can be further abbreviated to A.)

Table 2-1. Ohm's Law.

Known Values	Formulas For Determining Unknown Values of:			
	I Current	R Resistance	E Voltage	P Power
I and R	- - - -	- - - - -	$E = IR$	$P = I^2R$
I and E	- - - -	$R = \frac{E}{I}$	- - - -	$P = IE$
I and P	- - - -	$R = \frac{P}{I^2}$	$E = \frac{P}{I}$	- - - -
R and E	$I = \frac{E}{R}$	- - - - -	- - - -	$P = \frac{E^2}{R}$
R and P	$I = \sqrt{\frac{P}{R}}$	- - - - -	$E = \sqrt{PR}$	- - - -
E and P	$I = \frac{P}{E}$	$R = \frac{E^2}{P}$	- - - -	- - - -

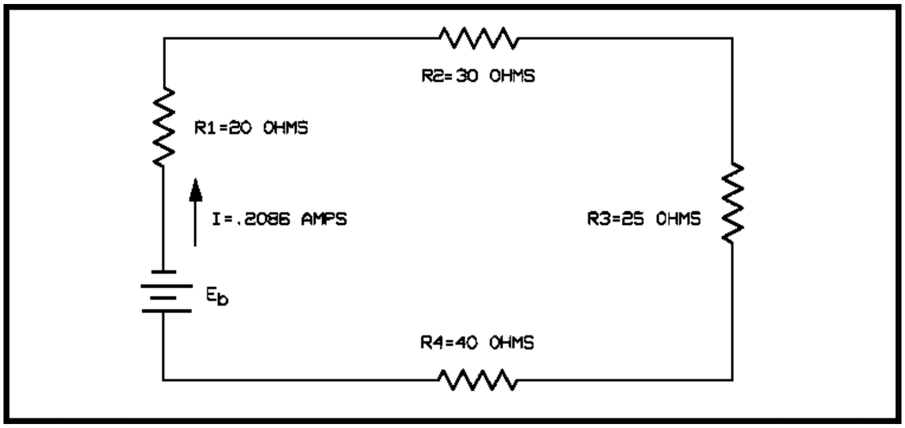

Figure 2-4. A Series Circuit.

Suppose in figure 2-4, the I is .4 A and the EMF is 24 V. Solve for resistance.

$$R = \frac{E}{I} = \frac{24V}{.4A} = 60\Omega$$

Suppose in figure 2-4, the R is 60 Ω, and the I is .4 A. Solve for EMF.

$E = IR = .4 \times 60\Omega = 24V$.

When current flows through a resistor, a voltage is developed across the resistor. The voltage developed on a resistor is often called a voltage drop. Ohm's Law applies to this voltage drop. Here are some examples.

Suppose R1 = 20Ω and I_{R1} = .4 A. Solve for E_{R1}, the voltage drop on R1.

$$E_{R1} = I_{R1} \text{ X } R_1 = .4\text{A X } 20\ \Omega = 8\text{V}.$$

Suppose E_{R2} = 60V, and R2 = 30 Ω. How much is I_2?

$$I_2 = \frac{E_2}{R_2} = \frac{60\text{V}}{30\Omega} = 2\text{A}$$

Suppose E_{R3} = 20 V and I_{R3} = 2A. How much is R3?

$$R_3 = \frac{20\text{V}}{2\text{A}} = 10\Omega$$

Kirchoff's Laws

Kirchoff's Laws are also used to solve for voltages, currents and resistances.

Current. Kirchoff's Law for current is that the sum of the currents entering a point is equal to the sum of the currents leaving a point.

In a series circuit there is only one path for current to flow, so $I_T = I_{R1} = I_{R2} = I_{R3}$ etc.

In figure 2-4, if the total current flowing is .4 A, then I_{R1}, the current flowing in R1, is .4A; I_{R2}, the current flowing in R2, is .4 A; and I_{R3}, the current flowing in R3, is .4A.

In figure 2-5 is a parallel circuit. In it, according to Kirchoff,

$I_T = I_{R1} + I_{R2}$.

Let

I_{R1} = .2A

and

I_{R2} = .6A.

Then

I_T = .2A + .6A = .8A.

In the series-parallel circuit, shown in figure 2-6, R3 is a series resistor. R1 is in parallel R2. R3 is called a series resistor because it is the only path through which line current (total current) can flow into the circuit. R1 and R2 make up a parallel combination. The current leaving R3 enters R1 and R2, two parallel paths for current to flow. That is, $I_3 = I_T$ and $I_1 + I_2 = I_T$.

In figure 2-6,

let

I_T = .5A,

then

I_3 = .5A.

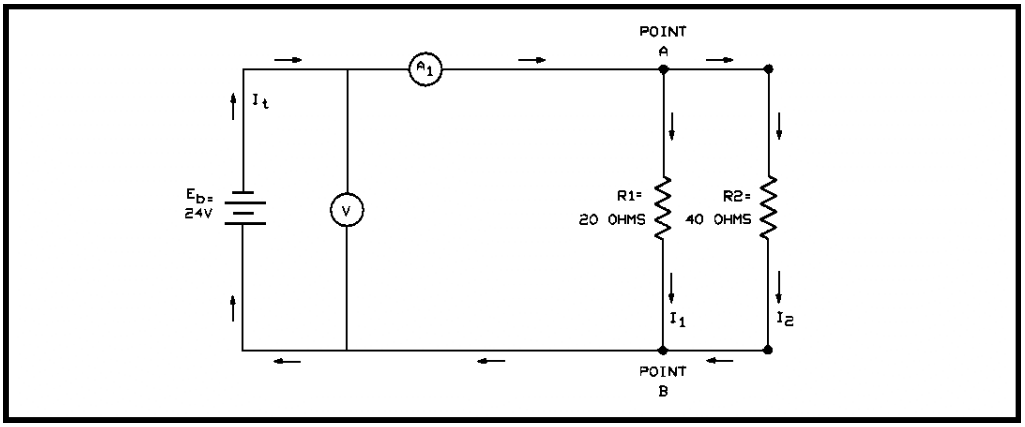

Figure 2-5. A Parallel Circuit.

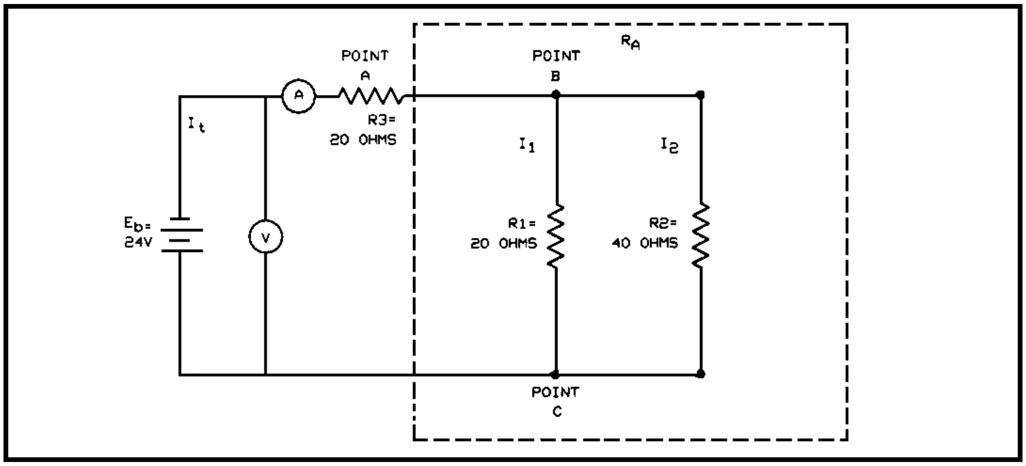

Figure 2-6. A Combination Series-Parallel Circuit.

Then let
$I_1 = .3A$
and
$I_2 = .2A.$
Then
$I_T = I_1 + I_2 = .3A + .2A = .5A$

Voltage. Kirchoff's Law for voltage is that the sum of the voltages in a loop equals the applied voltage (EMF). A loop is one complete path for current flow from the negative side of the battery, through the circuit, and back to the positive side of the battery.

For the series circuit in figure 2-4: $E_{R1} + E_{R2} + E_{R3} = E_b$ (E_A or EMF).

For example,
let
$E_{R1} = 8V$,
$E_{R2} = 12V$,
$E_{R3} = 4V$.
Then
$E_A = E_{R1} + E_{R2} + E_{R3} = 8V + 12V + 4V = 24V$.

For the parallel circuit in figure 2-5: $E_{R1} = E_A$ because R1 is the only resistor in its loop. Likewise $E_{R2} = E_A$ for R2 is the only resistor in its loop. So $E_A = E1 = E2$.

For example,
let
$E_A = 24V$.
Then
$E_{R1} = 24V$,
and
$E_{R2} = 24V$.

For the series-parallel circuit of figure 2-6: $E_{R3} + E_{R1} = E_A$ because R3 and R1 are the only resistors in their loop. Likewise $E_{R3} + E_{R2} = E_A$.

For example,
let
$E_{R3} = 15V$
and
$E_{R2} = 30V$.
Then
$E_A = E_{R3} + E_{R2} = 15V + 30V = 45V$.

Resistance. Kirchoff's Laws for resistance follow from the laws for current and voltage. Actually Kirchoff stated only two laws, one for voltage and one for current. The principles for resistance are mathematical derivations from Kirchoff's Laws for voltage and current.

In a series circuit, total resistance equals the sum of the individual resistances. That is, in figure 2-4, $R_T = R1 + R2 + R3$.

For example in figure 2-4,

let
$R_1 = 20\Omega$,
$R_2 = 30\Omega$,
and
$R_3 = 10\Omega$.
Then
$RT = R_1 + R_2 + R_3 = 20\Omega + 30\Omega + 10\Omega = 60\Omega$.

In a parallel circuit, the total resistance equals the reciprocal of the sum of the reciprocals of the resistors. (Recall that the reciprocal of a number is one divided by that number.)

So, in figure 2-5,

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

This is called the reciprocal formula for total resistance of resistors in parallel.

For example in figure 2-5,

let

R_1 = 120Ω

and

R_2 = 40Ω

Then

$$RT = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{1}{\frac{1}{120} = \frac{1}{40}} = \frac{1}{\frac{1}{120} = \frac{3}{120}}$$

$$RT = \frac{1}{\frac{4}{120}} = 1 \;\; X\frac{120}{4} = \frac{120}{4} = 30$$

If there are only two resistors in parallel, then the reciprocal becomes

$\frac{R_1 \times R_2}{R_1 + R_2}$ as shown here:

$$RT = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{1}{\frac{R_2}{R_1 \times R_2} + \frac{R_1}{R_1 \times R_2}} = \frac{1}{\frac{R_2 + R_1}{R_1 \times R_2}}$$

$$RT = 1 \times \frac{R_1 \times R_2}{R_2 + R_1} = \frac{R_1 \times R_2}{R_2 + R_1}$$

This is known as the product-over-the-sum formula for two resistances in parallel.

If all the resistors in parallel are equal, the reciprocal formula becomes RT = R1 R_n, where R1 is value of one resistor, and R_n is number of resistors.

Proof: In figure 2-5 if R1 = R2, then the reciprocal formula

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

Now

$$\frac{1}{\frac{1}{R_1} + \frac{1}{R_1}} = \frac{1}{\frac{2}{R_1}} = 1 \times \frac{R_1}{2} = \frac{R_1}{2}$$

This is known as the equal value formula for resistance of equal resistors in parallel.

Series-parallel circuit resistance is found by adding resistance of series resistors to the equivalent resistance of combinations. Combinations may be resistors in parallel or in series with each other but not with the battery.

The symbol for the equivalent resistance of the combination of R1 and R2 in parallel with each other may be Req1, 2 or R_{C1}, 2 or R_{par} 1, 2. The tags of schematic numbers may be omitted if there is only one combination in the circuit.

In figure 2-6,

let
$R_1 = 100\Omega$,
$R_2 = 150\Omega$,
and
$R_3 = 30\Omega$.
Then
$R_T = R1 + Req_{2,3}$ (Kirchoff's Law).
Now,

$$Req_{2,3} = \frac{R_1 \times R_2}{R_1 + R_2} (\text{product} - \text{over} - \text{the} - \text{sum})$$

Substituting

$$Req_{2,3} = \frac{100 \times 150}{100 + 150} = \frac{15{,}000}{250} = 60\Omega$$

So,
$R_T + R_C + 60\Omega = 90\Omega$.

POWER

Power is work done. Power is a product of voltage and current. The formulas for power are

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

The most commonly used are EI and I^2R. I^2R losses is a term commonly used by electric power companies transferring power through miles of wire from the generator on a dam to a city.

The basic unit of measurement of power is the watt. Standard units are kilowatt (kW), megawatt (MW), milliwatt (mW), and microwatt (µW).

Power dissipated is power used (consumed) by resistance. It may be in the form of heat, as in a toaster, oven, or iron. The power ratings of components in electrical circuits are often 2-1/2 times as much as would be dissipated in the circuit.

To find total power dissipated by a circuit, whether it is series, parallel, or series-parallel; simply add the powers dissipated by each resistor.

SPECIAL-CASE PROBLEM SOLVING

Ohm's law, as previously stated, is

Where: I is the current in amperes,
E is the EMF in volts,
R is the resistance in ohms,
P is the power in watts,

$$I = \frac{E}{R}, \quad R = \frac{E}{I}, \quad E = IR, \quad \text{then} \quad P = EI$$

Problem 1. Find the total resistance of the circuit in figure 2-7.

Solution:

$$R_T = R1 + R2 + R3 = 20 + 30 + 10 = 60\Omega$$

Problem 2. Find the total current flowing in the circuit in figure 2-7.

Given:

$E_b = 24V \quad R_T = 60\Omega$

Solution:

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

$$IT = \frac{24}{60} = .4\text{amp}$$

Problem 3. Find the voltage drops across each resistor in the circuit in figure 2-7.

Solution:

$E = IR$

Solving for E_{R1}, $E = .4 \times 20 = 8$ V.

Solving for E_{R2}, $E = .4 \times 30 = 12$ V.

Solving for E_{R3}, $E = .4 \text{ X } 10 = 4$ V.

Assuming $E_b = 24$ V, $E_b = E_{R1} + E_{R2} + E_{R3} = 8 + 12 + 4 = 12$ V.

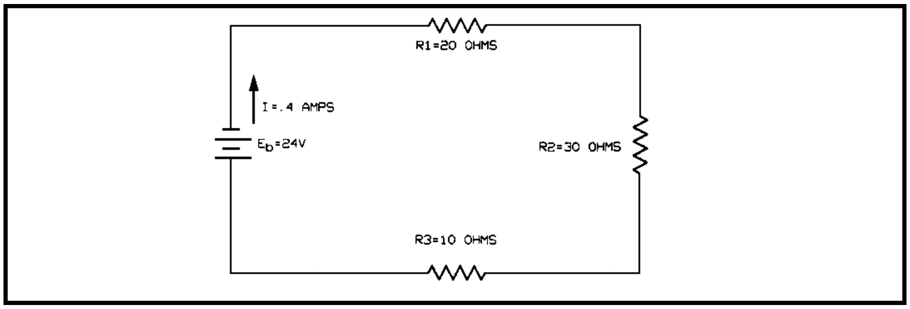

Figure 2-7. Series Circuit for Problems 1, 2, and 3.

Problem 4. Find the value of R3 in the circuit of figure 2-8.

Given:
E = 24V
I = .5 amp

With E and I known, you can solve for RT.

Solution:

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

$$RT = \frac{24}{.5} = 48\Omega$$

Then,
R3 = R_T - R1 - R2 = 48 - 10 = 8Ω.

Problem 5. Prove that E_b in the circuit in figure 2-8 equals 24 V.

Given:
I = .5 amp
R = 48Ω

Solution:
E = IR
E_b = .5 X 48 = 24V

Problem 6. Find the total resistance in the circuit of figure 2-9.

Given:
E = 24V
I = 6 amps

Solution:

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

$$RT = \frac{24}{6} = 4\Omega$$

Problem 7. Solve for the resistance of R3 in the circuit of figure 2-9. Several methods could be used in this problem. First determine what information is known. Total resistance (solved in problem 6), total current, and the

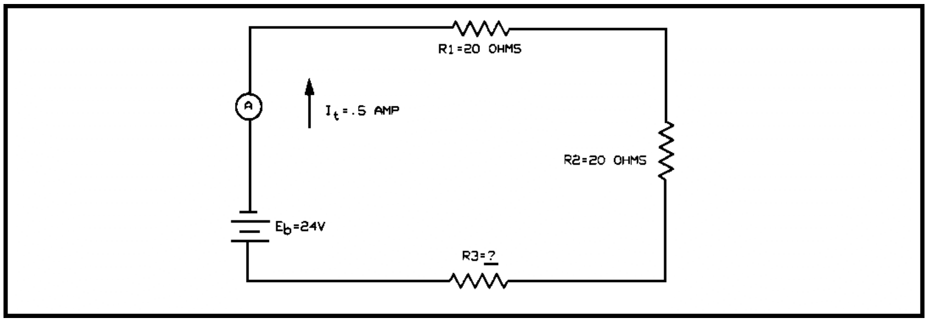

Figure 2-8. Series Circuit for Problems 4 and 5.

applied voltage are all known values. Referring to Kirchoff's law (current coming out of a branch is equal to the current entering the branch), at point A there are 6 amps of current and at point B there must be this same 6 amps of current. Notice at point A there are three paths for current flow. The same voltage (potential) is felt across each path.

Given:

where

$I_T = I_{R1} + I_{R2} + I_{R3}$,

Solution:

$$I_{R1} = \frac{24}{10} = 2.4\text{amp}$$

$$I_{R2} = \frac{24}{40} = 1.2\text{amp}$$

Then,

$I_{R3} = I_T - I_{R1} - I_{R2} = 6 - 2.4 - 1.2 = 2.4$ amp.

$$R3 = \frac{24}{2.4} = 10\Omega$$

or

$$RT = \frac{1}{\frac{1}{R1}+\frac{1}{R2}+\frac{1}{R3}} = \frac{1}{\frac{1}{10}+\frac{1}{20}+\frac{1}{10}} = \frac{1}{\frac{2}{20}+\frac{1}{20}+\frac{2}{20}} = \frac{1}{\frac{5}{20}}$$

$$1 \times \frac{20}{5} = 4\Omega$$

Problem 8. Find the total power consumed in the circuit of figure 2-9;

Solution.

$P = 1E$

$P_T = I_T = 6 \text{ X } 24 = 144W$,

or

$P_T = I^2R = 36 \text{ X } 4 = 144W$,

or

$$PT = \frac{E^2}{R} = \frac{576}{4} = 144W,$$

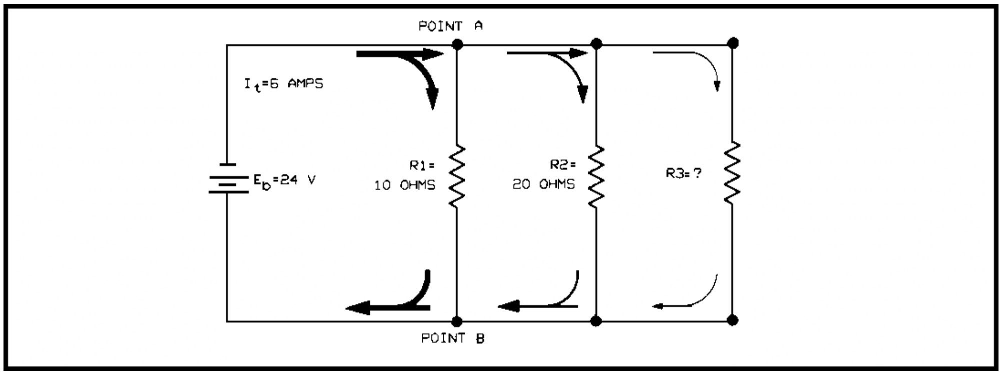

Figure 2-9. Parallel Circuit for Problems 6, 7, and 8.

Problem 9. Find the total resistance of the series-parallel circuit in figure 2-10. The first problem is to find the equivalent resistance of R2 and R3, which are in parallel. Once you find this value, the resistance of the branch is referred to as RA then,

Solution:

$$R_A = \frac{R2 \times R3}{R2 + R3} = \frac{20 \times 20}{20 + 20} = \frac{400}{40} = 10\Omega$$

With the value of RA known, the circuit can be handled as a series circuit in calculating the total resistance:

$R_T = R1 + R_A + R4 = 10 + 10 + 20 = 40\Omega$.

Problem 10. Find the current flowing in the circuit of figure 2-10;

Solution:

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

$$I_T = \frac{E_b}{R_T} = \frac{24}{40} = .6\text{amp}$$

Problem 11. Find the voltage drop across each resistor or branch in the circuit of figure 2-10;

Solution:

$E = IR.$

$E_{R1} = .6 \times 10 = 6V$

$ERA = .6 \times 10 = 6V$

$ER4 = .6 \times 20 = 12V$

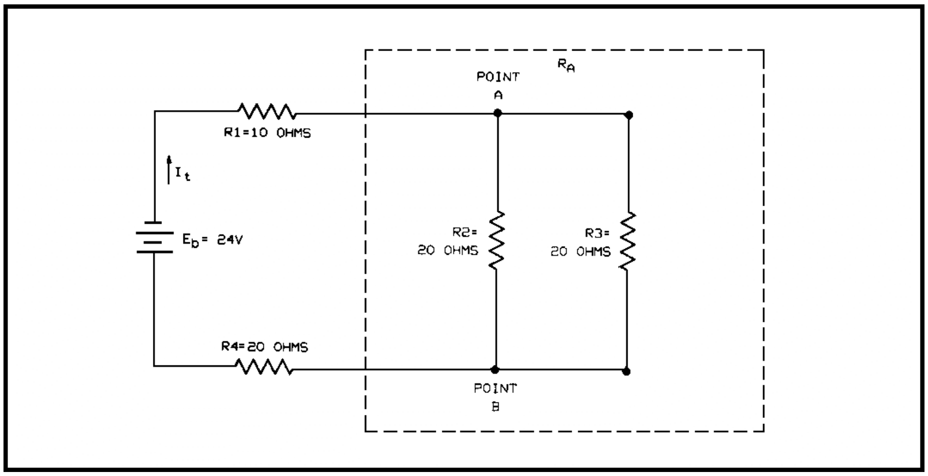

Figure 2-10. Series-Parallel Circuit for Problems 9, 10, 11, and 12.

Problem 12. Find the current flow through R2 and R3 (figure 2-10).

Given:

I_T = .6 amp

E_{RA} = 6V

Solution:

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

$$I_{R2} = \frac{6}{20} = .3\text{amp}$$

$$I_{R3} = \frac{6}{20} = .3\text{amp}$$

$I_T = I_{R2} + I_{R3} = .3 + .3 = .6$ amp