6) What is a material called that does not conduct electricity well?
   a) Insulator
   b) Conductor
   c) Resistor
   d) Capacitor

7) What is the term used to describe current that flows in a constant direction?
   a) Alternating current
   b) Straight current
   c) Direct current
   d) Discontinuous current

3. Components and operation of a simple electrical circuit

Overview

Purpose

The gas technician/fitter requires a basic knowledge of the components and operation of simple electrical circuits in order to connect and troubleshoot the type of electrical equipment he/she encounters in the gas industry.

Objectives

At the end of this Chapter, you will be able to:

- describe the components of a simple electrical circuit; and
- describe the operation of a simple electrical circuit.

Terminology

Term	Abbreviation (symbol)	Definition
Electromotive force	emf	Potential difference of an energy source (for example, battery or generator)
Ohm's law		States that the current flowing in an electrical circuit is directly proportional to the applied voltage
Potential		Positive or negative, measured at one point with respect to another

Term	Abbreviation (symbol)	Definition
Potential difference		Difference in potential between any two points in a circuit
Resistance		Opposition that a material offers to the flow of current
Voltage		Alternative term for potential difference
Voltage drop		Potential difference across individual loads in a circuit

Components of a simple electrical circuit

Electrical circuits

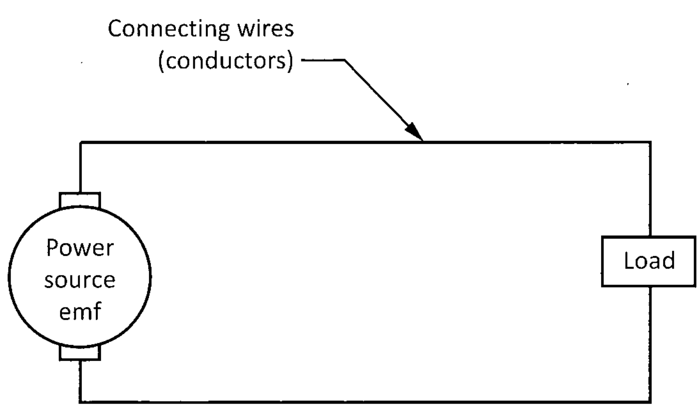
An electric circuit performs work using electrical energy. The part of the circuit that does the work is the *load*. The circuit provides a path for the flow of electric current. In a closed circuit, the path is complete and current can flow. In an open circuit, the path is incomplete and current cannot flow. Opening a circuit is possible through breakage, by disconnection from an energy source, or by a switch.

A simple electrical circuit consists of the following components:

- an energy source (such as a battery or a wall plug);
- conductors (connecting wires); and
- a load (a device that uses electrical energy to do work).

A circuit often has a switch and an overcurrent protective device such as a fuse or circuit breaker. Figure 3-1 shows a simple circuit.

Figure 3-1
An electric circuit



Three elements required to form an electrical circuit

Energy sources, potential, and electromotive force

An electrical energy source may supply electrical energy in several ways. For example, a wet-cell battery produces electrochemical energy, which is in the form of a *potential difference* between the charges on the output terminals. This is the measure of the ability (potential) of a Unit of electric charge to do a certain amount of work. You may compare the negative charge at one terminal and the positive charge at the other with the low and high-pressure points in a fluid piping system.

The difference in the potential between the two terminals provides the force to drive the current. This force is the *electromotive force* (emf). The Unit that indicates the strength of the emf is the *volt* (V). For example, a power source might be a 12-volt battery. You often call sources of emf *voltage sources*.

The sizes of voltages may vary a great deal, so the size of the Units used can also vary:

Voltage	Equivalent
1 volt (1 V)	1000 millivolts (= 10^3 mV) 1 000 000 microvolts (= 10^6 μV)
1 kilovolt (1 kV)	1000 volts (= 10^3 V)
1 megavolt (1 MV)	1 000 000 volts (= 10^6 V)

Current flow

Electric current flows whenever there is a difference of potential across a circuit. Electrons tend to flow toward the positive terminal. The amount of voltage across the circuit determines how much current can flow through the load. The polarity of the source determines the direction of current flow.

Ampere (A) is a measure of current, which may be quite small or very large:

Current	Equivalent
1 ampere (1 A)	1000 milliamperes (= 10^3 mA) 1 000 000 microamperes (= 10^6 μA)
1000 amperes	1 kiloampere (= 1 kA)

Conductors

The ease with which a current flows through a conductor varies. In dc circuits, the opposition that a material offers to the flow of current is what you call *resistance*.

A conductor in a circuit should have low resistance, allowing maximum current flow. Copper wire is the most commonly used conductor. You may use more expensive (even silver) wires in some specialized equipment.

Materials with high resistance oppose the flow of current. The Unit of measurement of resistance is the *ohm* (Ω). Some resistances are very large, so you may use a larger Unit:

Ohm (Ω)	Equivalent
1 kilohm (1 k Ω)	1000 ohms (= 10^3 Ω)
1 megohm (1 M Ω)	1 000 000 ohms (= 10^6 Ω)

Some are small, for example:

Ohm (Ω)	Equivalent
milliohm (1 m Ω)	0.001 ohms (= 10^{-3} Ω)
1 microhm (1 µ Ω)	0.000 001 ohms (= 10^{-6} Ω)

Load

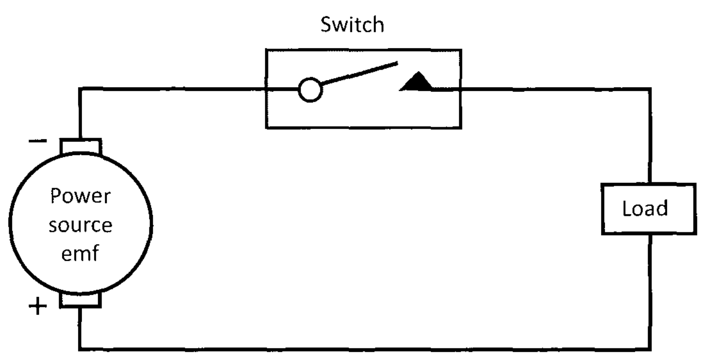
The load uses electrical energy to do useful work such as producing motion, light, or sound or providing heating.

The load usually has resistance in the electrical circuit. The energy source performs work by driving the current through the resistive load. The term *load* also refers to the amount of energy demanded from the source. For example, when you increase or decrease the load, it means that the energy source is supplying more or less energy.

Switches

A switch opens or closes an electric circuit as required. The simplest type has two pieces of conducting metal connected to the conductor of the circuit. You arrange switches so that they can easily make or break contact with the conductor. See Figure 3-2.

Figure 3-2
Switch opens and closes circuit



Switch opens and closes circuit

Contacts in an electrical relay function as switches in control circuits. These contacts are either *normally closed* (NC) or *normally open* (NO). When you energize a relay, the contacts switch position to energize or de-energize circuits. Control circuits frequently employ relays containing both NO and NC contacts depending on the circuit requirements.

Circuit protective devices

Circuit protective devices include:

- fuses;
- circuit breakers; and
- thermal and magnetic overloads.

Operation of a simple electrical circuit

Electron flow in a circuit

An electric current is the movement of electrons along a conductor. Electrons are extremely small atomic particles that have a negative electric charge. The flow of these electrons through a conductor can cause any combination of the following three effects:

- heating of the conductor;
- chemical changes; and
- production of a magnetic field around the conductor.

You can use these effects to power machinery and other devices.

An electric circuit is like the flow of water through a piping system. In a piping system, you can measure the pressure of the water and the volume of water flowing through the system at any point. For water to flow through the pipe, there must be a difference in pressure. The water flows from the area of higher pressure to the area of lower pressure. If you measure the pressure at several points in the piping system, it will be lower at each point as measured in the direction of flow. You usually measure pressure of a liquid in pounds per square inch (psi) in the imperial system or in kilopascals (kPa) in the metric system of measurement.

The amount of water flowing through a piping system depends on two things:

- the pressure applied across the piping; and
- the restrictions in the piping.

The greater the pressure applied to the system, the greater the water flow that will occur at a given resistance.

The restrictions in the piping system include length and diameter of pipe, as well as the number of fittings. For example, consider two piping systems: one using small-diameter pipe, the other using large-diameter pipe. If you apply the same pressure difference across both piping systems, more water will flow through the system with the larger-diameter pipe. Maintaining this pressure difference will require a larger pump. You often measure water flow in gallons per minute (gal/min) in the imperial system or in litres per second (L/s) in the metric system of measurement.

Voltage, resistance, and current in a circuit

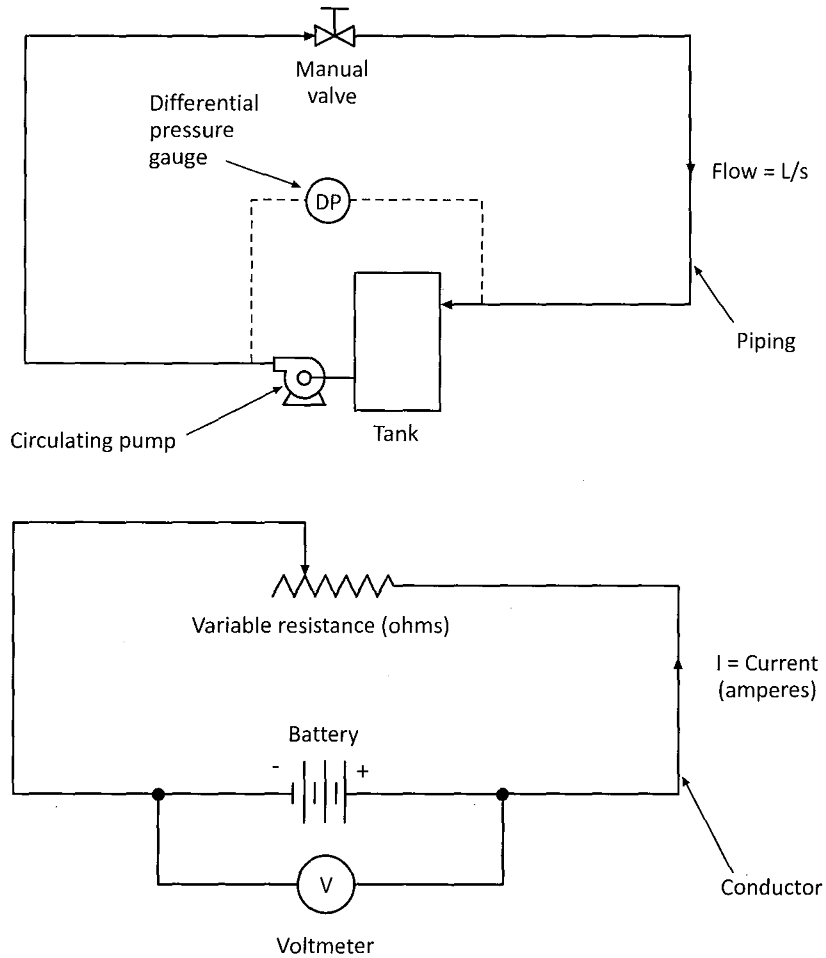
The same variables as water flow affect the flow of electricity. The amount of electricity flowing through an electric circuit depends on the electrical pressure (*termed potential difference or voltage*) applied and the restriction (*termed resistance*) in the wiring circuit.

In an electric circuit, the Units of measurement of voltage and electric current are volts (V) and amperes (A), respectively. Meanwhile, the ohm is a measure of the restriction in electric circuits, which is a function of the cross-sectional area of the conductor and the type of material the conductor is made of.

In Figure 3-3, the top circuit shows a piping system. You use a pump to pump water through the piping and back to the tank. The piping system has a valve that you can open and close to control the amount of water flowing through the system. The pump develops the pressure that causes the water to flow. This pressure is greater at the discharge of the pump and drops throughout the system. It is lowest where the water returns to the tank. A differential pressure gauge connected between these two points can measure the difference in pressure.

If the pump is running and the valve is fully open, there is very little restriction to the flow of water through the piping system. Circulation of a large volume of water occurs under these conditions. However, if you partially close the valve to increase the restriction, expect a reduced amount of water flowing (gallons per minute). Assuming that the pump discharge pressure is constant, the flow of water will be directly proportional to the restriction at the valve or to how far the valve is open. Assuming no restriction in the piping, the pressure drop across the valve will be equal to the pressure increase across the pump.

Figure 3-3
Electric circuits vs. liquid circuits



The bottom part of the diagram represents a simple electric circuit: a battery is connected to a variable electrical resistance. In a direct current (dc) circuit, a battery acts like the pump in a water circuit. If, for example, a 12 V battery is used, the voltmeter will show voltage across the battery of 12 V. You use this voltage to force the electrons around the electric circuit and thus cause a flow of electric current.

In this case, the variable resistor acts like a valve. You can adjust this resistor to increase the resistance (ohms) to current flow. As the resistance increases, less electricity flows through the circuit. When you apply a voltage of one volt, one ampere of current passes through a circuit having a resistance of one ohm.

In this circuit, a voltmeter measures the voltage. Note that a voltmeter measures a difference in electrical pressure between two points. In this case, the instrument measures the voltage across the battery. Assuming that the wires have no resistance, the voltage drop across the resistance would equal the voltage across the battery.

In fact, a pressure gauge also measures a difference in pressure. You usually measure the pressure in a piping system in comparison to atmospheric pressure.

Electrical pressure

Several terms are used for electrical pressure:

Term	Definition
Potential	Positive or negative, measured at one point with respect to another
Potential difference	Difference in potential between any two points in a circuit
Voltage	Alternative term for potential difference
Electromotive force (emf)	Potential difference of an energy source (for example, battery or generator)
Voltage drop	Potential difference across individual loads in a circuit

Often, you use voltage interchangeably with potential difference and emf and never in place of the term potential.

Ohm's law

The three quantities, voltage (V or E for emf), current (I), and resistance (R), are present in any complete electrical circuit.

Ohm's law defines the relationship between current flow (amperes), electrical pressure (volts), and resistance in a circuit (ohms) is very specific: *The current flowing in an electrical circuit is directly proportional to the applied voltage*. That is, as voltage increases, current increases. As resistance increases, current decreases, and vice versa. Expressed more simply: It takes an emf of 1 volt to push a current of 1 ampere through 1 ohm of resistance.

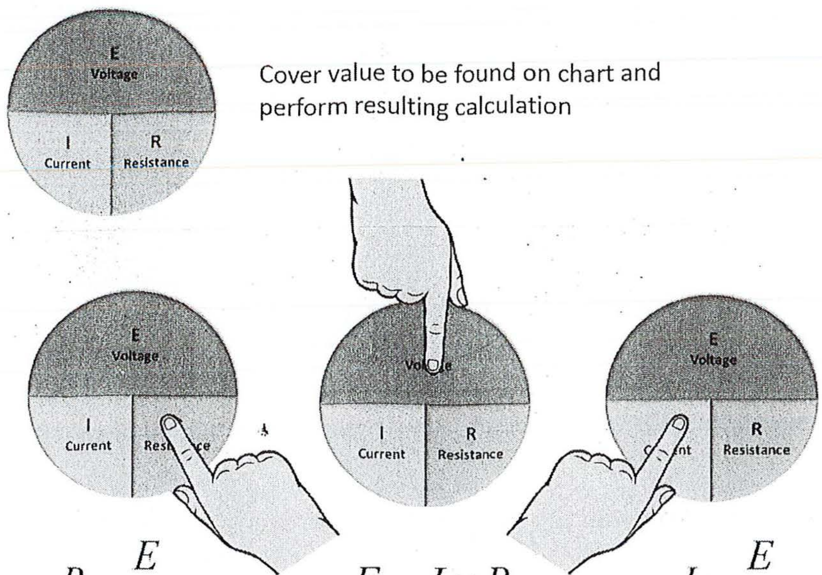
Expressed as equations, Ohm's law is:

$$I = \frac{E}{R} \text{ or } R = \frac{E}{I} \text{ or } E = IxR$$

When any two of these quantities are known, it is simple to calculate the third. These equations use amperes, volts, and ohms. If you use larger or smaller Units other than these, you must convert them first to these basic Units.

A handy visual aide to these calculations is the Ohm's law pie chart. See Figure 3-4.

Figure 3-4
Ohm's law pie chart



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

Using Ohm's law to calculate circuit values

Current

Figure 3-5 shows a circuit with a 20-volt source of emf and a resistor with resistance of 10 ohms. How much current flows in this circuit?

Substitute the values E = 20 V and R = 10 Ω into the Ohm's law equation for calculating current:

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

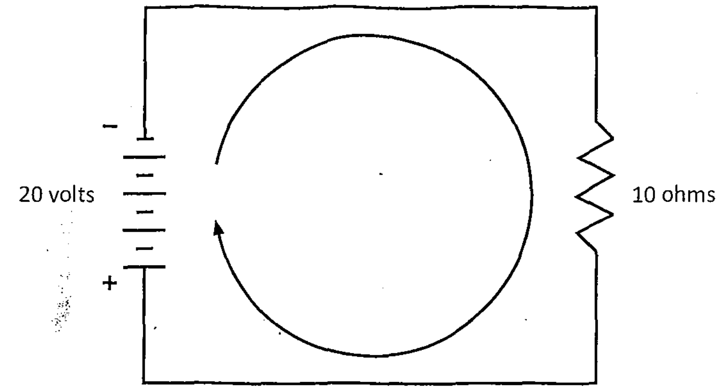
$= \frac{20V}{10ohm}$

$= 2A$

A current of 2 amperes flows in this circuit.

You might need to use a calculation like this to see if the current in a circuit will exceed the safe current rating of a resistor.

Figure 3-5
A circuit with a 20-volt source of emf and a 10-ohm resistance



Resistance

Figure 3-6 shows a circuit with a variable resistance. When you use variable resistors to control current, you call it *rheostats*. Rheostats help regulate current in a circuit by adding or subtracting resistance.

With this rheostat setting and a 60-volt source of emf, a current of 5 amperes flows in the circuit.

1) What is the resistance of the rheostat?
2) Also, what must you do to double the current to 10 amperes?

Substitute the values in this circuit into the Ohm's law equation for calculating resistance:

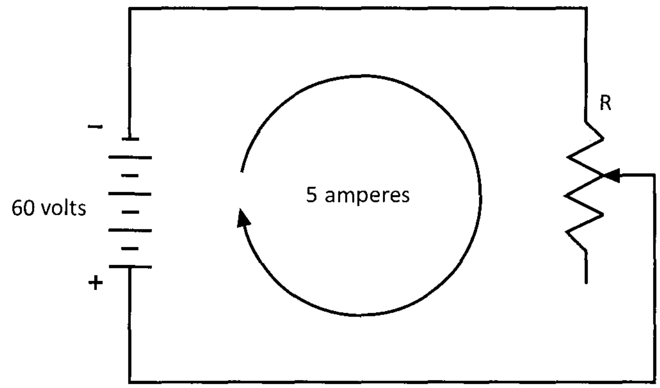
$$R = \frac{E}{I}$$

$$= \frac{60V}{5A}$$

$$= 12 \text{ ohm}$$

The resistance in this circuit is 12 ohms. Resistance and current are inversely proportional. Therefore, to double the current, halve the resistance by adjusting the rheostat to reduce resistance in the circuit to 6 ohms. You can check this using the equation again:

Figure 3-6
A circuit containing a rheostat to vary current



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

$= \frac{60\,V}{10\,A}$

$= 6\,ohm$

Similarly, you may use the other Ohm's law equation (E = I x R) to calculate the emf in a circuit.

Work and power

Work is the process of changing one form of energy into another. For example, a motor changes electrical energy into kinetic energy, so it is doing work. Power is the rate at which work is done. The faster work is done, the greater the power.

The Unit of electrical work is the joule (J). A more common Unit of work is the kilowatt hour (kWh).

The Unit of power (P) is watts (W) or horsepower (hp). A watt is the consumed power when 1 ampere of current flows through a potential difference of 1 volt in 1 second. Power values are often very large, and larger Units of measurement are used.

Power	**Equivalent**
1 watt (1 W)	1 joule/second (1 J/s) 0.00134 horsepower (0.00134 hp)
1 kilowatt (1 kW)	3413 Btu/h
1 hp	746 W
1 kilowatt (1 kW)	1000 W (= 10^3 W)
1 megawatt (1 MW)	1 000 000 W (= 10^6 W)

Calculating power

The pump in Figure 3-3 circulates water. It delivers a pressure of 207 kPa above tank pressure. If the piping and valve are small, you only need a small pump to maintain the pressure and pump water around the system. If the piping and valve are large, you will require a more powerful pump. Even though the pressure in both cases is the same, pumping a greater amount of water will require more power.

The power of the pump is a function of the pressure that the pump has developed and the flow of water. If all other conditions remain the same, you will need a more powerful pump engine to develop a higher pressure or to pump more water through the system.

The same is true for electric circuits. If you use small wires and high resistances, the current flow may be small. If conductors are large and the resistance low, much more current flows. Maintaining this flow requires a more powerful battery.

In electric circuits, power is a function of current flow and applied voltage. Although this is more complex in alternating current circuits, the power increases if you increase the current or voltage.

Power is the rate at which you supply energy to a circuit. In direct current circuits, it can be calculated using the following formula:

Power in watts = (current in amperes) x (voltage in volts)

Power and Ohm's law

Combining the definitions of work and power with Ohm's law, power is equal to the product of current and voltage. Increasing current increases the power in a circuit. (That is, it increases the rate at which the circuit can do work.) Increasing voltage also increases the power. See equations below:

$P = IxE \text{ or } E = \frac{P}{I} \text{ or } I = \frac{P}{E}$

You can use these equations to calculate the power in a circuit. For example, in Figure 3-3 the voltage is 60 volts and the current is 5 amperes:

$P = IxE$

$= 5Ax60V$

$= 300W$

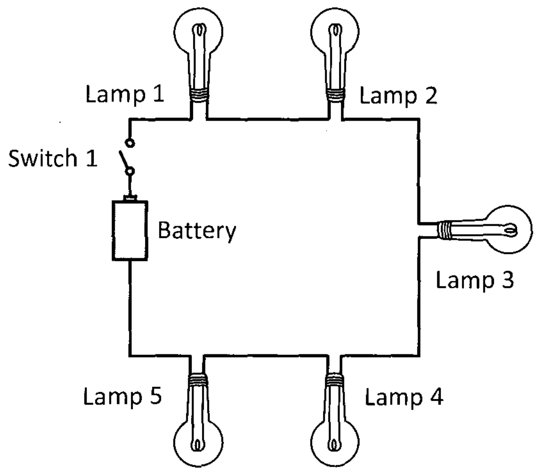
Therefore, the power of this circuit is 300 watts.

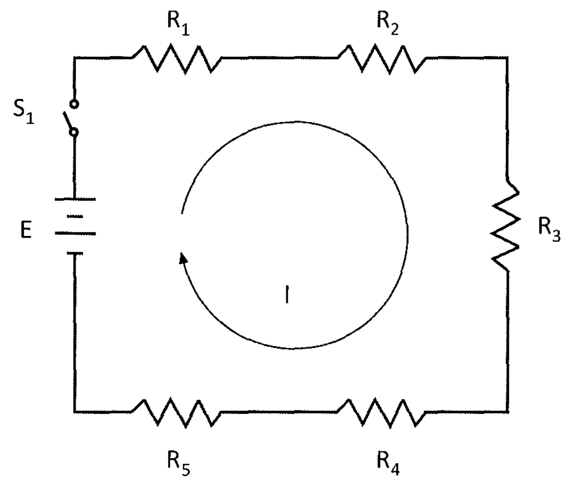
Series circuits

The circuits that this module described so far have only one possible path for the current flow. The same amount of current flows through every part of each circuit. The parts of the circuit follow one after the other in series in a single loop. This is called a series circuit.

Although the circuits shown have only one load, such as a resistor, series circuits may have several or many loads connected end to end (connected *in series*), as Figure 3-7 shows. Older forms of Christmas tree lights are connected in series. Each lamp is a resistive load. Current through each of them is the same. If one lamp burns out or if the switch becomes open, the entire string goes out because the series circuit has been broken and current cannot flow. Note that an open switch has infinite resistance (∞), while a closed switch or closed contacts have zero resistance (0 Ω).

Figure 3-7
Series loads such as Christmas lights connected in series





Calculating values in a series circuit

In a series circuit, the total resistance (R_T) is the sum of all the individual resistances in the circuit.

In Figure 3-8:

$$R_T = R_1 + R_2 + R_3 + R_4 + R_5$$
$$= 8\ \Omega + 4\ \Omega + 6\ \Omega + 7\ \Omega + 10\ \Omega$$
$$= 35\ \Omega$$

That is, the total resistance in this series circuit is 35 ohms. Use this value in the Ohm's law equation to find the current in the circuit:

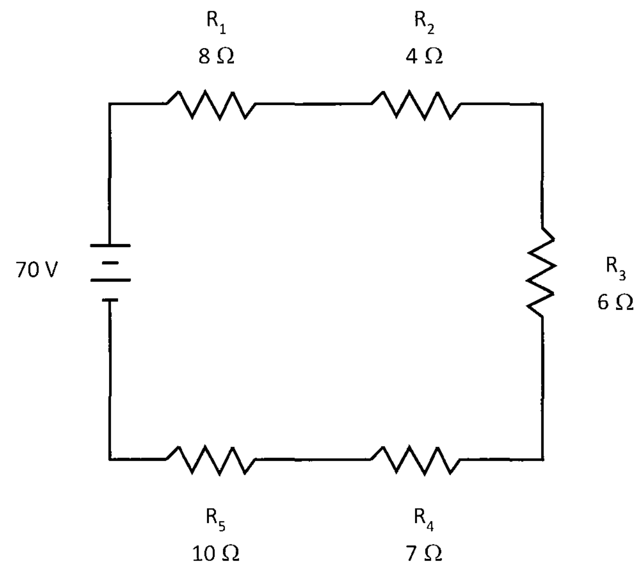
$$I = \frac{E}{R_T}$$

$$= \frac{70V}{35\,ohm}$$

$$= 2A$$

Thus, the current all around this series circuit is 2 amperes.

Figure 3-8
Determining resistance and current in a series circuit



Series voltage drops

As electrons move from the negative to the positive terminal, they lose energy to the circuit resistance. This occurrence is *voltage drop*. As the current flows through each resistor, energy is lost, mostly to heat. Some voltage is lost at each resistor around the circuit.

Total voltage drop in a circuit equals the applied voltage of the energy source. This is true for circuits with one load or 20 loads. In circuits with only one load, the total voltage drop occurs across that load as current passes through it. If there are several loads, some voltage drop occurs across each load. The same current passes through them all, so Ohm's law means that the voltage drop across each load is proportional to the resistance of that load.

For example, suppose a series circuit has a total voltage of 48 volts and contains a 2-ohm resistor and a 4-ohm resistor (see Figure 3-9).

Total resistance is 2 Ω + 4 Ω = 6 Ω.

Current throughout the circuit is:

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

$$= \frac{48\,V}{6\,ohm}$$

$$= 8\,A$$

The voltage drop across the 2-ohm resistor is:

$$E_2 = I \times R$$

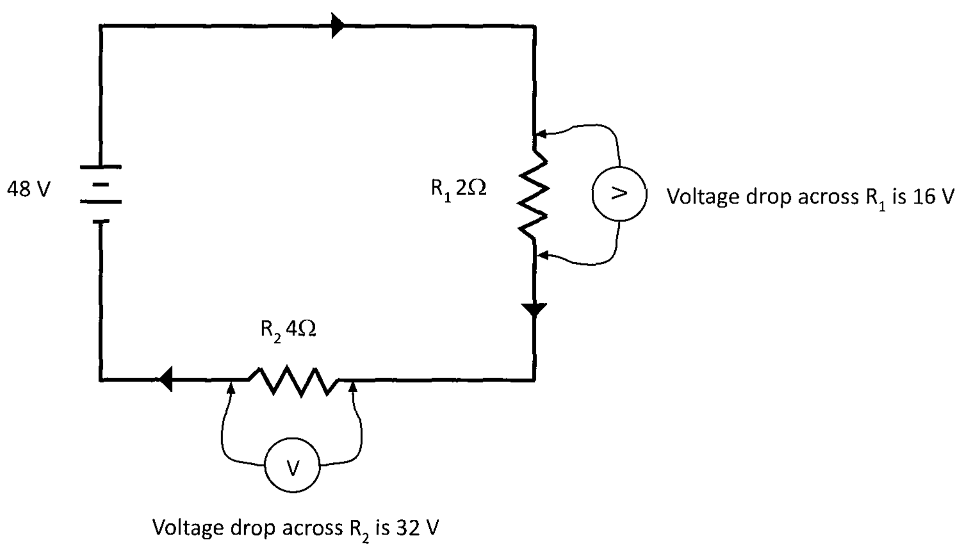
$$= 8\text{ A} \times 2\,\Omega = 16\text{ V}$$

The voltage drop across the 4-ohm resistor is:

$$E_4 = I \times R$$
$$= 8\ A \times 4\ \Omega = 32\ V$$

Note: The total voltage drop in the series circuit (48 V) is the sum of the voltage drops across the two resistors (16 V + 32 V).

Figure 3-9
Voltage drop in a series circuit



Parallel circuits

If some parts of a circuit are *connected in parallel*, the current is not the same in all parts of the circuit. Figure 3-10 and Figure 3-11 show two parallel circuits, one more simple than the other.

Current flows through more than one complete path. These paths are what you call *branches*. The supply voltage is common to each branch.

If one branch of a parallel circuit becomes open, current still flows through the other branches. For example, ordinary house lamps are connected in parallel; if one burns out, the rest stay lit.

In Figure 3-10, notice that energy sources as well as loads may be connected in parallel. Sources connected in parallel maintain the same terminal-voltage, but supply greater amounts of current.

Figure 3-10
Parallel circuit

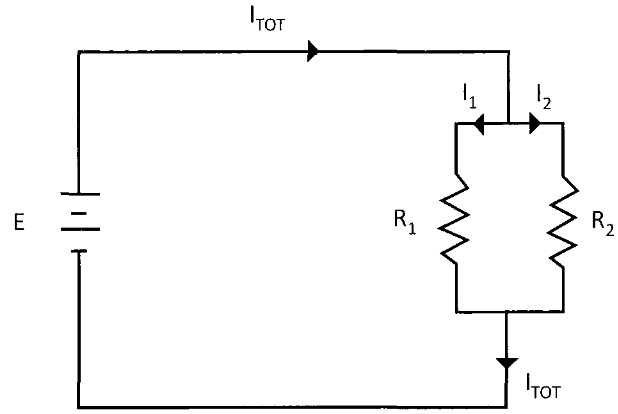
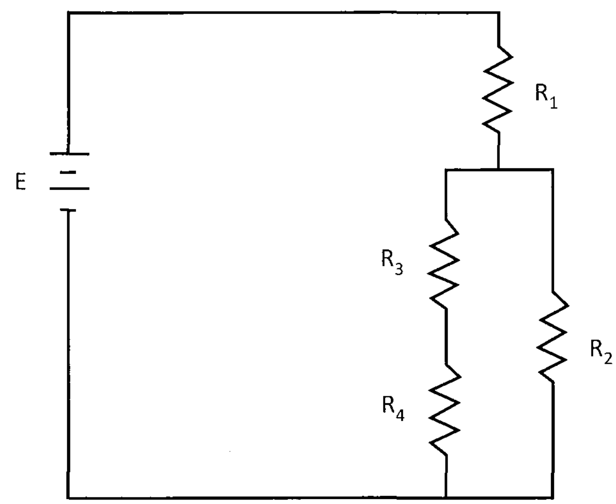


Figure 3-11
Series-parallel circuit

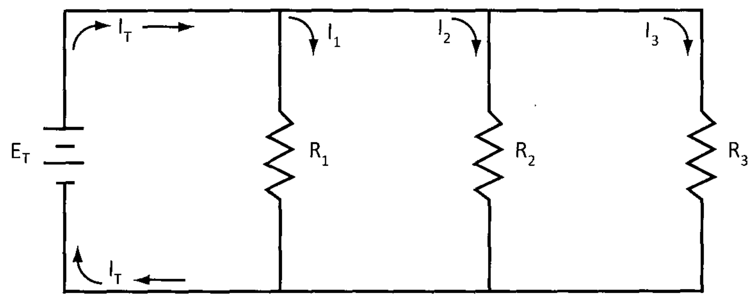


Calculating values in a parallel circuit

In Figure 3-12, there are three possible complete paths for the current to flow through between the terminals. The sum of the currents in each branch equals the supply current. If the load R_1 burns out, current can still flow through R_2 and R_3. However, if the energy source is disconnected, no current flows in any of the branches.

In a parallel circuit (see Figure 3-12), you can calculate the total resistance (R_T) using the following formula:

Figure 3-12
Parallel circuit



If the total current and voltage of a parallel circuit are known, you can calculate the total resistance from Ohm's law.

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

Parallel voltage drops

Parallel loads are connected directly across the same energy source. This means that, when loads are connected in parallel, the entire source voltage is applied across each branch. This is the most important and useful feature of a parallel circuit, because all loads are supplied with a common voltage.

Parallel resistances and current flow

The current in each branch is inversely proportional to the resistance of the load in the branch (Ohm's law). Branches with less resistance carry more current and vice versa.

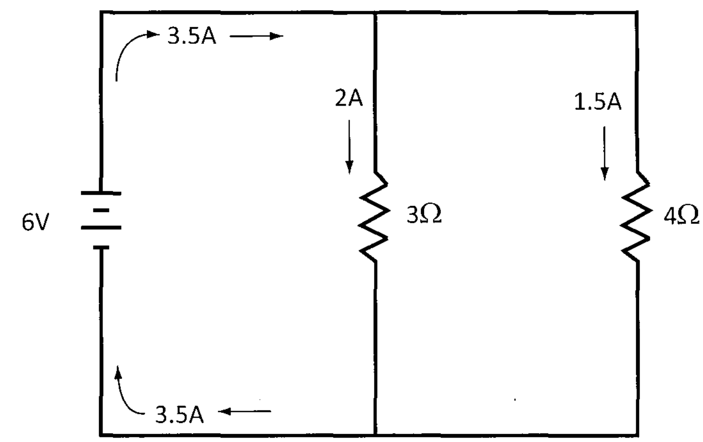
When resistances are connected in parallel, they reduce overall opposition to current flow. For example:

In a simple circuit with a 6-volt power source and a resistance of 3 ohms, a current of 2 amps flows. (This is calculated as before, using Ohm's law.)

Suppose another load, with a resistance of 4 ohms, is connected in parallel with the first one. (The circuit would look like Figure 3-13.) A current of 2 amperes still flows through the 3-ohm resistor, but a current of 1.5 amperes now also flows through the 4-ohm resistor.

Total current flow (IT) in the circuit has increased to 3.5 amperes.

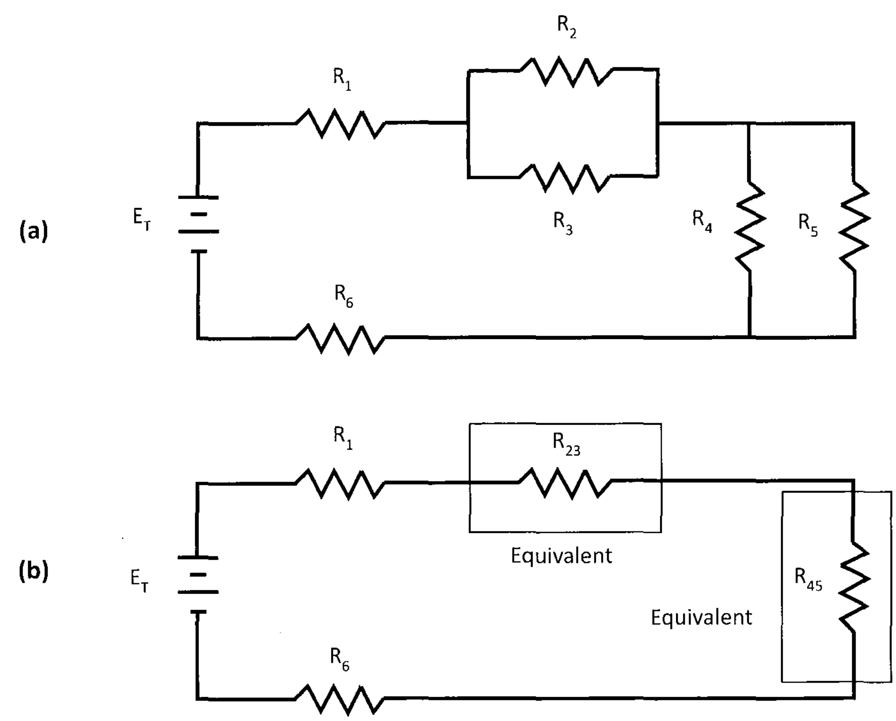
Figure 3-13
Parallel circuit showing current flow through branches



Series-parallel circuits

Figure 3-14 shows a circuit that combines series and parallel connections. Such circuits are what you call a series-parallel circuit.

Figure 3-14
Series-parallel circuits



You can systematically break down series-parallel or combination circuits into series and parallel components. The same laws that apply to individual series and parallel circuits are applicable to the analysis of series-parallel circuits.

In the series parallel circuit in Figure 3-14a, resistors R_2 and R_3 (the first parallel component) are in parallel, but only with each other. Resistors R_4 and R_5 (the second parallel component) are also in parallel, but only with each other. These two parallel components of the circuit are in series with one another and with resistors R_1 and R_6.

Calculating values in a series-parallel circuit

In order to calculate values in a series-parallel circuit, it is necessary to break the circuit down into its equivalent series components by means of the product-over-sum method of calculating the equivalent resistance of pairs of parallel resistances in the circuit.

You can calculate parallel resistors R_2 and R_3 (Figure 3-14a) as an equivalent single resistance (R_{23} in Figure 3-14b). The other parallel component of the circuit in Figure 3-14a, consisting of R_4 and R_5, is the single equivalent resistance R_{45} in Figure 3-14b.

After substituting the two pairs of parallel resistances with their equivalent resistances, the simple series circuit shown in Figure 3-14b represents the original circuit in Figure 3-14a.

You can apply the laws applicable to series circuits to this circuit to determine:
- total circuit resistance;
- total line current;
- voltage drops across the series components; and
- branch current flow.

Calculating circuit resistance

For example, in Figure 3-15a, the first step is to calculate the equivalent resistances as follows:

Resistors R_2, R_3, and R_4 form a series circuit that is in parallel with resistor R_5.

Calculate resistors R_2, R_3, and R_4 as a single equivalent resistance R_{234}.

Figure 3-15b shows R_{234}, connected in parallel with resistor R_5.

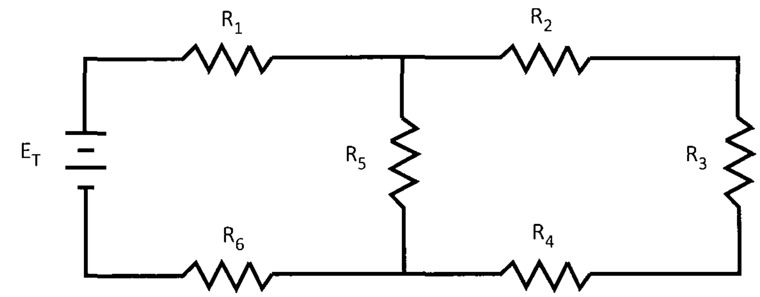
The parallel combination of R_{234} and R_5 becomes the single equivalent resistance, R_{2345}.

Connect R_{2345} in series with R_1 and R_6 (see Figure 3-15c) to produce a simple series circuit.

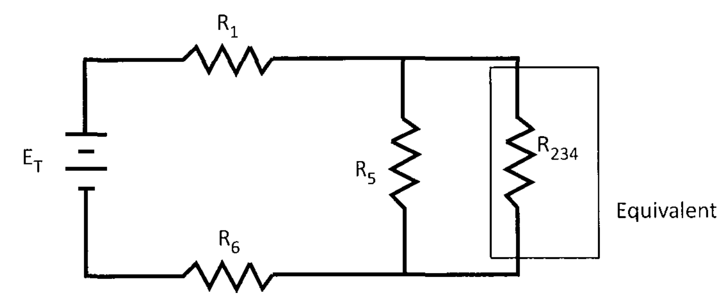
Calculate the total resistance using the series circuit law ($R_T = R_1 + R_{2345} + R_6$).

Figure 3-15
Calculating values in series-parallel circuits

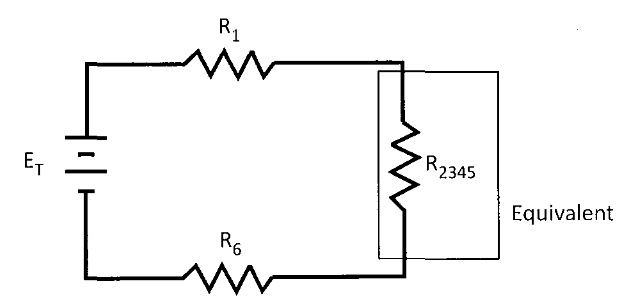
(a)



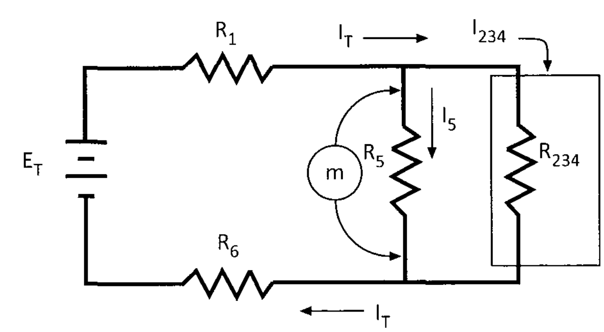
(b)



(c)



(d)



Calculating line current

Once you determine the total circuit resistance, you can calculate the total line current by using Ohm's law ($I = E \div R$). See Figure 3-16.

Calculating voltage drops

You can calculate the individual voltage drops across the resistances using the following equations:

$E_1 = I_T \times R_1$

$E_5 = I_T \times R_{2345}$

$E_6 = I_T \times R_6$

The sum of $E_1 + E_5 + E_6 = E_T$.

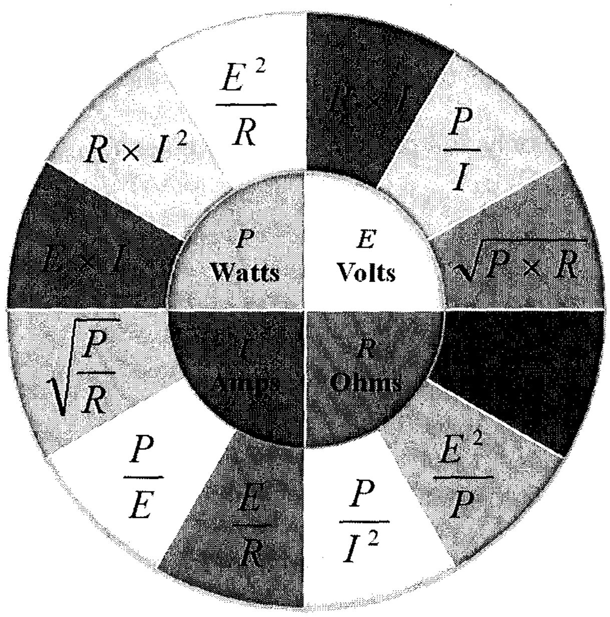
Calculating branch current flows

You can use the voltage drop E_5 to calculate the branch currents (Figure 3-15d).

For this parallel component of this series-parallel circuit, the voltage drops across the two branches are the same.

$I_T = I_5 + I_{234}$ for the parallel portion.

Figure 3-16
Ohm's law pie chart with power formulas



Assignment Questions – Chapter 3

1) What is the unit to indicate the strength of electromotive force?
   a) Amps
   b) Ohms
   c) Volts

2) What is the unit to measure electric current?
   a) Amperes
   b) Ohms
   c) Volts

3) What is the unit to measure the restriction of electric circuits?
   a) Amperes
   b) Ohms
   c) Volts

4) What is the unit to measure electrical power?
   a) Amperage
   b) Ohms
   c) Watts or horsepower

5) What is the purpose of an electrical switch?
   a) To change alternating current to direct current
   b) To change direct current to alternating current
   c) To open or close an electrical circuit as required

6) What is Ohm's law?
   a) The current flowing in an electrical circuit is directly proportional to the applied voltage
   b) The resistance in a circuit is directly proportional to the amperage of the circuit

7) What type of circuit allows only one possible path for current flow?
   a) Open circuit
   b) Parallel circuit
   c) Series circuit
   d) Short circuit

8) What must the voltage drop in a circuit equal?
   a) Amperage in the circuit
   b) Resistance in the circuit
   c) Voltage of the energy source

9) What type of circuit allows current to flow through more than one complete path?
   a) Open circuit
   b) Parallel circuit
   c) Series circuit
   d) Short circuit

10) In a parallel circuit, what voltage is applied across each branch?
   a) Only what is required for the load
   b) 75% of what is required
   c) The entire source voltage