5) What simple rule is used to determine the direction of the magnetic lines of force around a wire?
   a) The right hand rule
   b) The left hand rule
   c) Ohm's Law

6) What is always produced when current flows through a conductor?
   a) A magnetic field is produced around the conductor
   b) Light is produced around the conductor
   c) Heat is produced around the conductor

7) What is generated whenever a magnetic field moves across a conductor?
   a) Amperage
   b) Voltage
   c) Current

5. Theory of direct and alternating current

Overview

Purpose

The gas technician/fitter requires knowledge of direct and alternating current theory in order to properly size, connect, and troubleshoot the type of electrical equipment encountered in the gas industry.

Objectives

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

- describe direct and alternating current;
- describe leading and lagging in ac circuits; and
- describe capacitance in ac circuits.

Terminology

Term	Abbreviation (symbol)	Definition
ac energy		Energy consumed in an ac circuit
Alternating current	ac or AC	Electric current that reverses its direction many times a second at regular intervals, typically used in power supplies
Direct current	dc or DC	Electric current flowing in one direction only
Waveform		Describes complete cycle of alternating current goes from zero to a maximum positive value, back through zero to a maximum negative value, and back again to zero

Direct and alternating current

Direct current

In the first example, at the top of Figure 5-1, a battery supplies the circuit. Batteries have a positive and a negative terminal. The battery shown has a voltage of 12 V. In this case, when the circuit is connected, the current flows from one terminal to the other. The flow is always in the same direction and this is what you call direct current (dc).

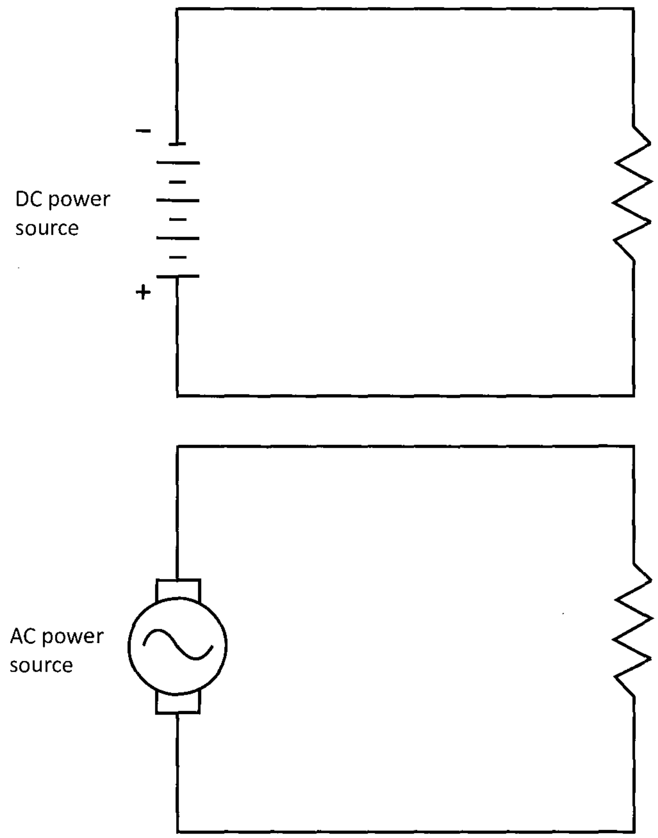
Electronic devices, small appliances, and automobile electrical systems extensively use direct current. Some type of battery often supplies DC. Batteries have a very limited supply of electrical power. You must replace or recharge them regularly. This makes them impractical for some applications. To supply the large quantities of electrical power required for consumer and industrial needs, mechanical generation is necessary. In most cases, mechanical generators produce alternating current (ac). While in dc circuits, current flow is always in the same direction, in ac circuits, the current flow switches from one direction to the other (it “alternates”).

In North America, generators produce and transmit electrical energy as alternating current with a frequency of 60 hertz (cycles per second). This means that the current flows in one direction for 1/120th of a second and then in the other direction for 1/120th of a second. This is where current differs from water piping systems. Although alternating current changes direction continuously, transmission of the energy still occurs throughout the system.

The circuits described so far use *direct current* (dc). That is, the current that the energy source generates flows in one direction only. Its direction is reversed only if the terminal connections are reversed. Energy sources that produce direct current are called dc energy sources. Batteries are *dc energy sources*.

In a dc energy source, one terminal is always negative and the other positive. The circuit diagrams that this section used so far have used the symbol for a battery (see Figure 5-1, top).

Figure 5-1
Diagrams of simple dc and ac circuits



Alternating current

Another type of current flows alternately in both directions. The flow changes or *alternates* direction rapidly and constantly. This is what you call *alternating current* (ac). The energy consumed in an ac circuit is *ac energy.*

Most motors and other devices in the home and industry operate using alternating current. Nearly all the energy consumed in the world is alternating current for the following reasons:
- It is more versatile than dc and is usable in a wide variety of ways.
- It is cheaper to produce than dc.
- It allows transmission of electricity over long distances more economically.
- It easily transforms into lower or higher voltages for use in various equipment.
- Transmission of ac energy at high voltage and low current keeps energy losses to a minimum.
- Many combinations of voltage and current can produce the same energy level.

In ac circuits (see Figure 5-1, bottom), current, voltage, and resistance have the same relationships that they have in dc circuits. You use Ohm's law to calculate values in ac circuits in much the same way as for dc circuits.

AC generators

The most common source of ac is the ac *generator* or *alternator*. Most ac generators produce an electromotive force (emf) by the rotary movement of a magnetic field within a coil. The movement of a conductor in a magnetic field induces a current in the conductor as follows:

1) A conductor moved in a magnetic field, or vice versa, crosses the flux lines.
2) The field applies a force to the free electrons in the conductor, moving them.
3) The moving electrons result in a potential difference across the ends of the conductor.

EMF of a generator

The amount of voltage generated depends on:

- the strength of the magnetic field;
- how fast the conductor moves, cutting through the flux lines; and
- the angle at which the conductor cuts the flux lines.

How an AC generator works

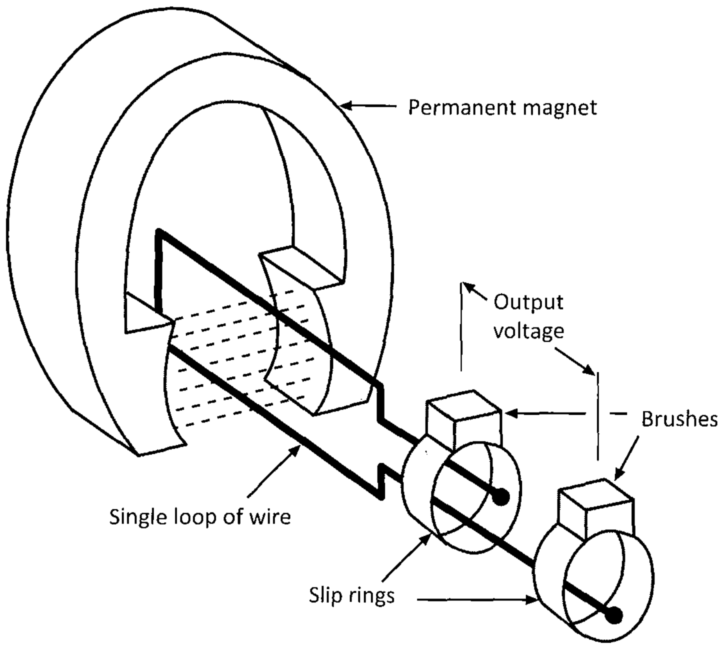
To see how a generator works, imagine a single loop or coil of conducting wire placed between the poles of a permanent magnet, as shown in Figure 5-2. In practice, there is a series of windings in the machine called the rotor or armature.

A simple generator works as follows:

1) An outside power source such as flowing water, an internal combustion engine, or steam turns the coil.
2) As the loop rotates, the wire cuts the magnetic flux lines, generating a voltage at the ends of the loop.
3) The generator transfers the voltage to an external circuit via slip rings and brushes. These maintain proper electrical contact while allowing free rotation of the loop.

In reality, however, the coil is fixed and the field is made to rotate around it.

Figure 5-2
The basic principle of an ac generator



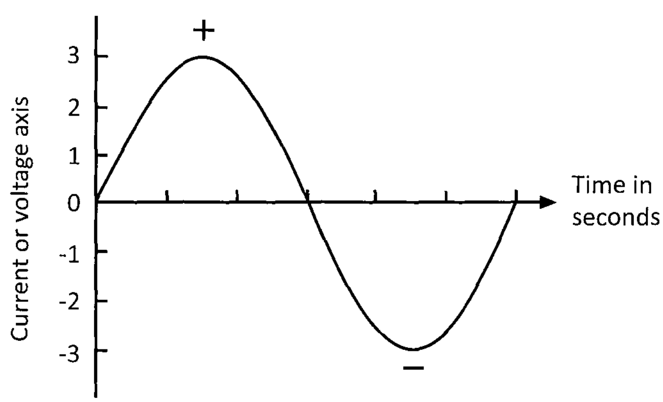
As the generator rotates, as in Figure 5-2, a voltage appears across the ends of the coil. The generator transfers this voltage to an external circuit via slip rings and brushes.

The ac waveform

A complete cycle of alternating current goes from zero to a maximum positive value, back through zero to a maximum negative value, and back again to zero. The voltage makes a similar pattern, rather like a wave.

Figure 5-3 is a graph of these changes with time, which you call the *waveform*. The correct name for the shape of this waveform is *sinusoidal* or a *sine wave*.

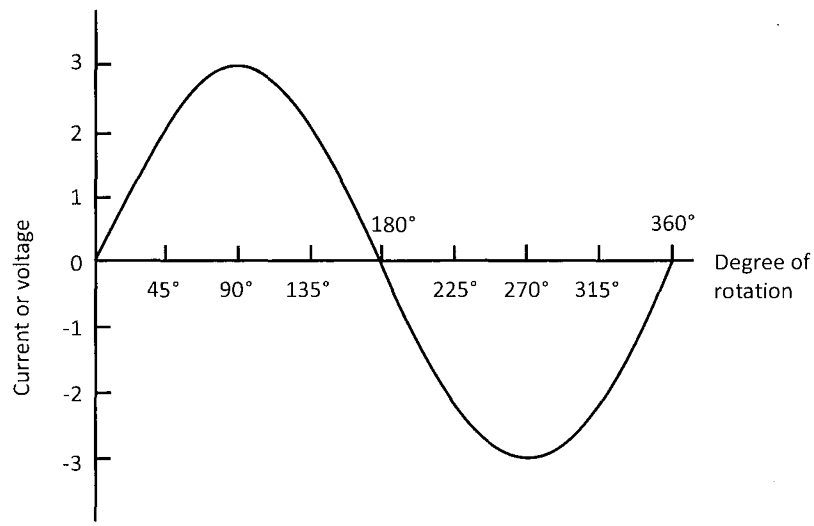
Figure 5-3
The sinusoidal waveform of ac voltage (or current)



At any point on this sine wave, the magnitude of the voltage (or current) is the distance to the time axis. When the waveform is below the zero line, the current has reversed direction. Note that the waveform is the same shape above and below the horizontal axis (*symmetrical*) — the positive and negative parts vary in the same way.

You may divide the horizontal axis into degrees of rotation rather than Units of time. Figure 5-4 shows the 360° in one complete rotation or cycle. This graph shows how the output voltage (or current) of the generator varies with the position of the rotor.

Figure 5-4
The waveform of ac voltage (or current) showing degrees of rotation of the rotor



Frequency

In Canada, standard ac electrical power goes through 60 complete cycles each second. That is, its *frequency* is 60 cycles per second or 60 *hertz* (60 Hz). A simple generator would turn 60 times each second to produce power at 60 hertz.

Phase

You can describe phase as the difference in electrical degrees between two waveforms.

Single-phase generator

A single-phase generator produces one alternating (sinusoidal) voltage waveform.

Three-phase generator

You connect three-phase generators to provide three separate circuits. Each of these circuits carries a sinusoidal voltage waveform. The three waveforms are displaced by 120° from each other. See Figure 5-5.

Calculating alternating current

Alternating current is somewhat difficult to understand (see Figure 5-4). Mathematically, the currents might appear to cancel out over time because the negative current during one-half of the cycle equals the positive current during the other half. In fact, however, the movement of electrons provides electrical energy. This is true whether they move back and forth or in one direction only.

You therefore calculate current by determining the effective work that the electric current performs or heat it generates. This is what you refer to as *root-mean-square* or *rms current* and is the peak current (V_{max} or V_m) divided by square root of 2 (0.707).

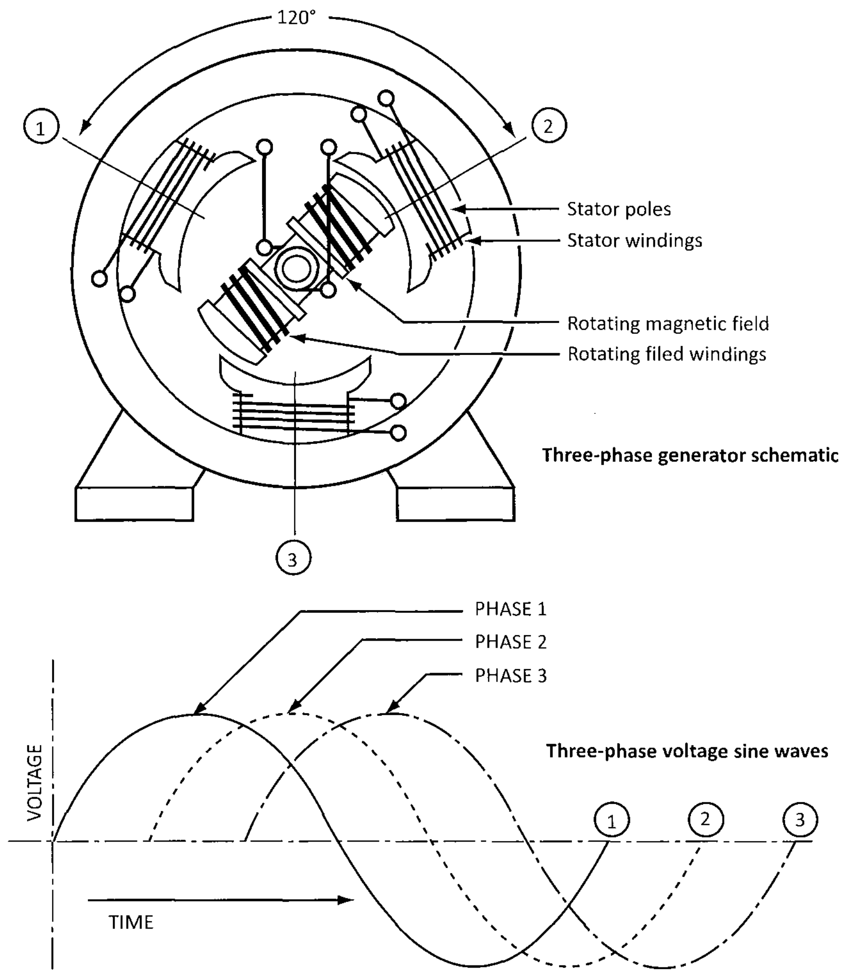
$I_{rms} = 0.707\ I_{max}$

Similarly,

$V_{rms} = 0.707\ V_{max}$

You always use this value when referring to the voltage of a circuit. Residential voltages in this country are 120 V, which is the rms voltage. The actual supplied voltage is alternating according to a sine curve with a peak of approximately 170 V.

Figure 5-5
The windings and voltages of a three-phase, ac generator



Leading and lagging in alternating currents

AC circuits

Every real electrical circuit exhibits a combination of resistance, inductance, and capacitance. The nature of the circuit determines which of these quantities predominates. For example, in a heating circuit, the resistance predominates; in motor circuits, the inductance predominates; in long supply lines, capacitance predominates. Whichever quantity predominates, the other two are always present to some extent or other—although, from a practical point of view, at least one of the others is so insignificant that you may ignore it.

Quality	Symbols	Definition	Measured in
Resistance	R	Ratio of applied emf to the resulting current in a circuit and the real component of impedance in an ac circuit	Ohm (Ω)
Reactance	X	Depends upon a circuit's inductance or capacitance and the frequency of the supply voltage (In purely inductive or capacitive circuits, the opposition to current is called inductive reactance or capacitive reactance.)	Ohm (Ω)
Impedance	Z	Total opposition to the flow of current in a circuit and consists of a circuit's resistance and reactance	Ohm (Ω)
Inductance	L	Property of an electric circuit by virtue of which a varying current induces an emf in that circuit or an adjacent circuit	Henry (H)
Capacitance	C	Ratio of a quantity of electricity to a potential difference and ability of conductors separated by dielectric (non-conducting) material to store energy in the form of electrically separated charges	Farad (F)

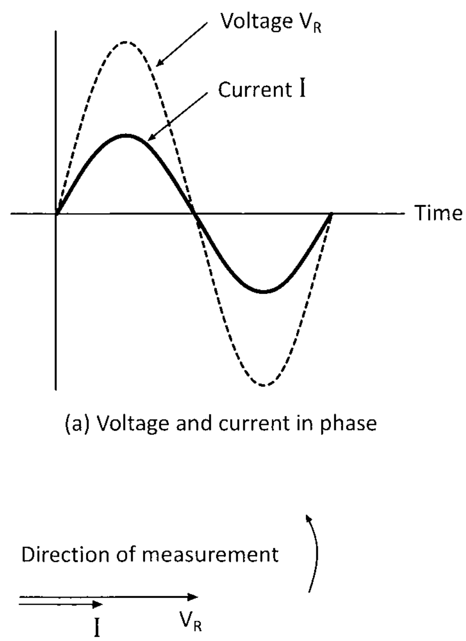
In order to understand the behaviour of ac circuits, it is usual to start off by considering the behaviour of circuits in which only one of the three quantities exist, then extend what you have learned to circuits that contain combinations of these quantities.

Purely resistive circuit

When an ac current flows through pure resistance, a voltage-drop (V_R) occurs across that resistance. You use Ohm's law to calculate the value of that voltage-drop: $V_R = I_R$.

As you would expect, when the current is maximum, the corresponding voltage-drop is also maximum; as the current falls to zero and reverses direction, the resulting voltage-drop also falls to zero and changes direction. We say that the current and voltage are in phase with each other (see Figure 5-6a).

Figure 5-6
Voltage and current in phase



(b) Phasor diagram showing voltage and current in phase

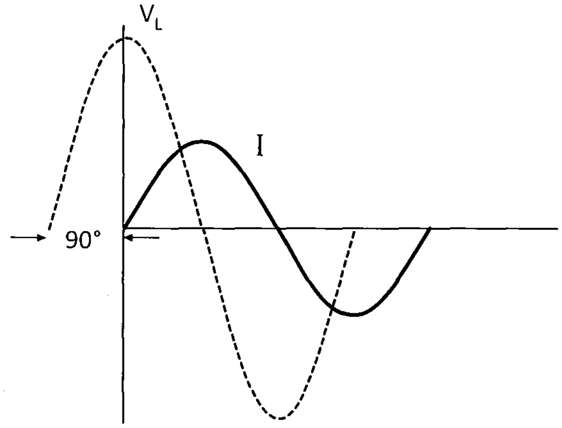
In order to avoid the difficulty of drawing sine waves, you often draw the current and voltage drop in the form of a phasor-diagram. A phasor-diagram is the electrical equivalent of a vector diagram, in which the length of each phasor represents the rms-value of the quantity and the angle between them the phase-angle. In Figure 5-6b, the current and voltage phasors lie along the same direction because they are in phase.

Purely inductive circuit

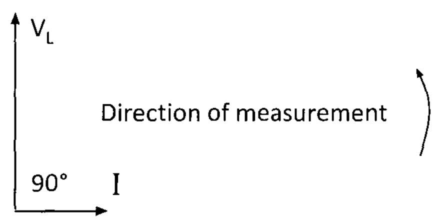
When an ac current flows through pure inductance, a voltage (V_L) appears across that inductance. Again, you use Ohm's law to calculate the value of that voltage. This time, however, the opposition to current is inductive-reactance (X_L) and not resistance, so (V_R) = I X_L.

The changing current induces the voltage (V_L) into the inductance. The greater the rate of change of current, the greater this voltage. The greatest rate of change occurs as the current passes through zero, so this is where the maximum voltage occurs. If you examine the waveforms in Figure 5-7a, you will see that in a purely inductive circuit, the current peaks behind the voltage by 90°. It is said to lag the voltage by 90°.

Figure 5-7
Current lags voltage by 90°



(a) Current lags voltage by 90°



(b) Phasor diagram showing current lagging voltage

Figure 5-7b shows the phasor-diagram for the circuit. Note that, this time, there is a 90° angle between the current and voltage phasors.

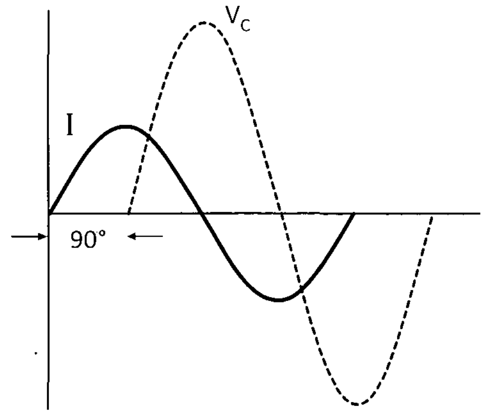
By convention, all measurements are counterclockwise, so the voltage phasor is drawn 90° counterclockwise from the current phasor, indicating that current lags voltage.

Purely capacitive circuit

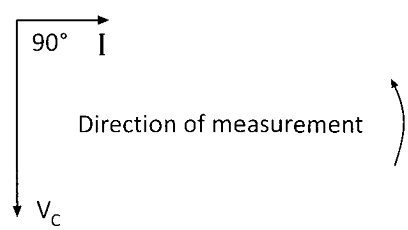
When an ac current flows through pure capacitance, a voltage (V_C) appears across that capacitance. You use Ohm's law again to calculate the value of that voltage. This time, however, the opposition to current is capacitive-reactance (X_C) and not resistance, so (V_L) = I X_C.

The voltage (V_C) builds up across the plates of the capacitor as the current flows onto those plates. This voltage increases as the current decreases and reaches its maximum value as the current falls to zero. If you examine the waveforms in Figure 5-8a, you will see that, in a purely capacitive circuit, the current peaks ahead of the voltage by 90°. It is said to lead the voltage by 90°.

Figure 5-8
Current leads voltage by 90°



(a) Current leads voltage by 90°



(b) Phasor diagram showing current leading voltage

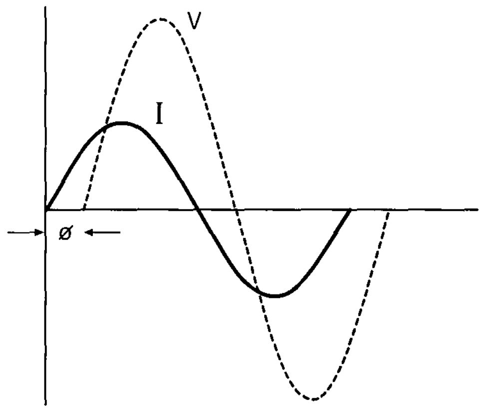
Figure 5-8b shows the phasor-diagram for the circuit. Note that, this time, there is a 90° angle between the current and voltage phasors.

By convention, all measurements are counterclockwise, so the voltage phasor is drawn 90° clockwise from the current phasor, indicating that current leads voltage.

Resistive-inductive (R-L) circuit

Many real circuits are resistive-inductive (R-L) circuits. An R-L circuit is one that has both resistance and inductance. If the current in a purely resistive circuit is in phase with the voltage-drop, and the current in a purely inductive circuit lags the voltage-drop by 90°, then it follows that, in an R-L circuit, the current will lag the voltage by some angle between 0° and 90° (see Figure 5-9). This is what you call the *phase angle* (ø, Greek letter *phi*). Exactly what this angle will be will depend on the values of the circuit's resistance and inductive-reactance.

Figure 5-9
Phase angle (ø) in resistive-inductive circuit



Resistive-capacitive (R-C) circuit

Less common than R-L circuits, R-C circuits are those that have both resistance and capacitance. Current in an R-C circuit leads the voltage by some angle (the phase-angle, ø) between 0° and 90°.

Resistance, reactance, and impedance

Resistance

In purely resistive circuits, the opposition to current is resistance. Resistance (R) depends upon the length, cross-sectional area, and material of a conductor. You measure resistance in ohms.

Reactance

In purely inductive or capacitive circuits, you call the opposition to current:

- inductive reactance (X_L); or
- capacitive reactance (X_C).

Reactance depends upon a circuit's inductance (L) or capacitance (C) and the frequency (f) of the supply voltage. You calculate it as follows:

(Inductive reactance) $X_L = 2\pi fL$

(Capacitive reactance) $X_C = \frac{1}{2\pi fC}$

You measure reactance in ohms.

Impedance

Impedance (Z) is the total opposition to the flow of current and consists of a circuit's resistance and reactance when:

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

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

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

You measure impedance in ohms.

Power factor

The angle between the voltage and current sine curves is measurable. You call this angle the phase angle (ø, Greek letter *phi*). The cosine of this angle is the *power factor* of the circuit. A circuit's power factor varies between 0 (corresponding to a phase angle of 90°) and 1 (corresponding to 0°).

Power in ac circuits

In ac circuits, the rate of supplying energy to a load is *true power* (or *useful power*, or *active power*). However, establishing alternating magnetic and electric fields requires some energy. The circuit supplies the energy to the fields as they expand, and the energy alternately returns to the circuit as the fields collapse. The rate of this alternate energy movement in the circuit is what you call *reactive power* and is necessary in addition to the circuit's true power. An ac circuit then must supply both true power and reactive power. The "total" of both these forms of power is what you call the *apparent power* of the circuit. The following Units of measurement are traditionally used ones for distinguishing between each of these powers:

- True power is measured in watts (W)
- Reactive power is measured in reactive volt amperes (var)
- Apparent power is measured in volt amperes (V•A)

The use of the word *total* in the preceding paragraph is a simplification; in fact, the relationship between the three forms of power is based on the Pythagorean Theorem:

$$(Apparent power)^2 = (True power)^2 + (Reactive power)^2$$

$$\text{or } Apparent power = \sqrt{(\text{True power})^2 + (\text{Reactive power})^2}$$

Unlike dc circuits, the product of voltage and current in ac circuits gives the apparent power of the circuit in volt amperes:

$$Apparent power = Voltage \times Current$$

To calculate the true power of the circuit, multiply the apparent power by the circuit's power factor:

$$True power = Apparent power \times Power factor$$

$$True power = Voltage \times Current \times Power factor$$

For a given value of true power, the apparent power increases as the power factor falls. For low values of power factor, then, a generator must produce a large amount of apparent power in order to supply a relatively small amount of true power. As the apparent power determines the amount of current that a generator supplies, it is desirable to make the value of the apparent power as close as possible to the true power. You can achieve this by ensuring that the circuit's power factor is as high (as close to 1) as possible.

Capacitance in AC circuits

Capacitors

The two common types of capacitor that the gas technician/fitter will encounter in the field are the starting capacitor and the running capacitor. You use these capacitors to boost the starting torque and running efficiency of single-phase electric motors.

The capacitor consists of two aluminum electrodes (plates) with dielectric material between them. The non-conducting dielectric prevents electron flow between the plates but allows storage of an electrical charge. The dc resistance of a capacitor is infinite (∞).

Starting capacitors

The starting capacitor consists of two aluminum plates separated by a dielectric of chemically treated paper, impregnated with non-conducting electrolyte. Starting capacitors are available with capacitance ratings from 75 to 600 microfarads (μF) and with voltage ratings of 110 V to 330 V.

Starting capacitors have relatively small cases. You only use them for a short period on each cycle of the motor they serve. Therefore, they have no need to dissipate heat, although their capacity is larger than that of running capacitors.

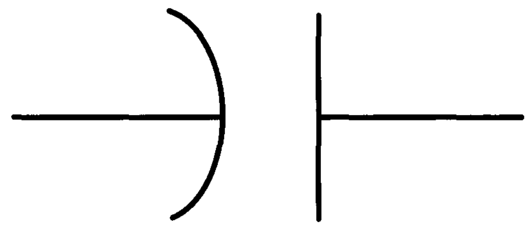
Running capacitors

Running capacitors stay in the motor circuit for the entire cycle of operation. For this reason, they must have some means of dissipating the resulting heat. They do this by means of an oil-filled case. The oil-filled running capacitor is larger than the starting capacitor, but its capacity is smaller.

Capacitance in series and parallel

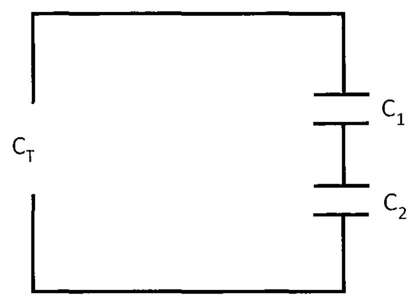
The capacitance (e.g., μF) of two or more capacitors connected in parallel is the sum of the individual capacitances (see Figure 5-10).

Figure 5-10
Parallel capacitance



See Figure 5-11 to know how you can calculate the capacitance (e.g., μF) of two or more capacitors in series.

Figure 5-11
Series capacitance



$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} \ldots}$$ or for 2 capacitors in series $$C_T = \frac{C_1 \times C_2}{C_1 + C_2}$$

Assignment Questions – Chapter 5

1) Which type of electrical current flows in both directions?
   a) Bi-directional
   b) Alternating
   c) Direct

2) Indicate True or False:
   Alternating current is more versatile than direct current.
   a) True
   b) False