

## Transformers and AC Circuits



LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

LOUISIANA TRANSPORTATION RESEARCH CENTER

TECHNOLOGY TRANSFER AND TRAINING

2019



# TABLE OF CONTENTS

page

Chapter 1: Principles of Alternating Current.....	5
Chapter 2: Mathematics in AC Circuits.....	23
Chapter 3: Inductance and Inductive Reactance.....	43
Chapter 4: Capacitance and Capacitive Resistance.....	63
Chapter 5: Impedance.....	83
Chapter 6: Power and Energy in AC Circuits.....	101
Chapter 7: Three-Phase Circuits.....	121
Chapter 8: Principles of Transformers.....	139
Chapter 9: Transformer Applications.....	157
Chapter 10: Maintaining Transformers.....	175
Appendix: Answers to chapter exercises.....	203



# Chapter 1: Introduction to Electricity

## In This Chapter:

AC and DC Electricity

Average Values

Waveforms

Effective Values

AC Waveform

Energy Storage

Frequency

Faraday's Law

Peak-to-Peak Values

Basic Circuit Concepts

## Objectives

After completing this manual, you should be able to:

- State the definition of a waveform.
- Demonstrate how to calculate the frequency of an alternator's output.
- Explain how to calculate an effective value
- Name the kinds of values that must be used when applying the dc rules and laws to ac circuits.

## Terminology

**Waveform:** A graph showing changes in electrical values over a period of time

**Sine wave:** The most common ac waveform, based on the sine function in trigonometry

**Amplitude:** The maximum height of a waveform above the horizontal axis

**Frequency:** The number of cycles an electrical system goes through in a unit of time

**Hertz:** The standard unit of frequency, equal to one cycle per second

**Peak-to-peak value:** The distance of a waveform from the maximum point to the minimum point, equal to twice the amplitude if the waveform is symmetrical about zero

AC circuits are more complex than DC circuits because alternating current is always changing while direct current remains steady. In order to maintain the equipment in your plant, you must first understand the fundamentals of alternating current.

This lesson explains the principles and characteristics of ac circuits. This information will help you understand why and how certain electrical equipment works. It will also make the job of troubleshooting electrical faults easier.

This lesson explains waveforms, sine waves, amplitude, and peak-to-peak values. It also explains how to calculate frequency and average and effective values. The last section of this lesson explains the basic laws and rules governing electric circuits.

## AC and DC Electricity

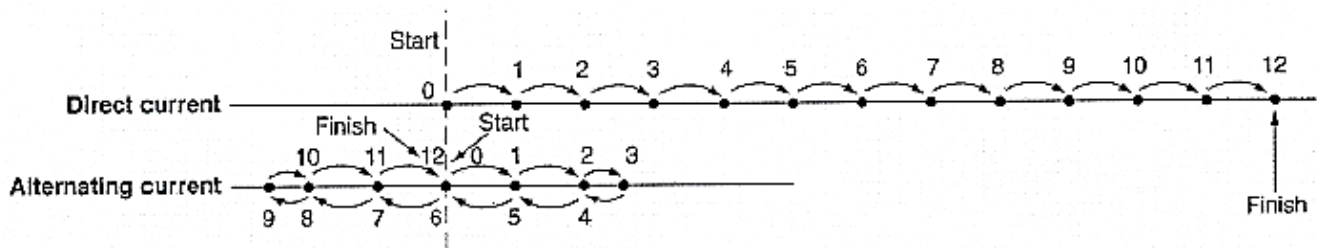
1-1 The electricity from an electrochemical cell, from a battery, or from a DC power supply is the simplest kind of electricity.

- The potential difference between the terminals is constant and steady. The positive terminal is always positive, and the negative terminal is always negative.
- The current from such a source is steady and in one direction. The electrons move in only one direction and at a constant rate.
- The calculations of power, energy, current, and other values do not depend on which instant of time you are referring to, because all the values are the same at one instant as at any other instant.

1-2 The electricity commonly used in industrial plants, homes, hospitals, and almost every other place is more complex. This electricity almost always comes from the generating plants of public utilities.

- The potential difference between the terminals is always changing. The terminal that is positive at one moment is negative a moment later.
- The current also keeps changing. It alternates back and forth from one direction to the other. Electrons move in both directions.
- The calculations of power, energy, current, and other values depend on which instant of time you are referring to. All the values in the equations keep changing from instant to instant, changing the result.

1-3 Figure 1.1 is a diagram showing the difference between direct current (DC) and alternating current (AC). Each line represents a conductor. The dots on the lines represent the positions of a single electron after equal intervals of time. The positions are numbered.



**Figure 1.1: Movement of One Electron in a Conductor**

1-4 On the line labeled Direct current, the electron starts from the position labeled 0.

- At the end of the first interval of time, it has moved to the position labeled 1.
- At the end of the second interval of time, it has moved an equal distance to the position labeled 2.

1-5 This process continues. The electron moves equal distances in equal time intervals. At the end of the twelfth interval, it has moved twelve equal distances along the wire and is in the position labeled 12.

## AC and DC Electricity (continued)

- 1-6 On the line labeled AC in Figure 1.1, the electron also starts from the position labeled 0. The time intervals are the same as those for the AC line. But the electron does not move equal distances, because its speed changes. It reaches a certain point, labeled 3, and then reverses its motion. At the end of the sixth interval, it has returned to its starting point.
- 1-7 Then the electron moves to the left of its starting position. At the end of the ninth interval, it again reverses its direction and heads back toward the starting position. At the end of the twelfth interval, the electron has returned to the starting position.
- 1-8 In an AC circuit, each electron moves in a special way. Its motion is exactly like the motion of a mass moving up and down on the end of a spring. It moves at its highest speed past the central position, and slows down as it reaches each extreme. It reverses its direction at regular intervals. The overall motion of the electron over a long period of time—many oscillations—is zero, just as for the mass on the spring.

## Waveforms

- 1-9 A *waveform* is a graph showing how electrical values change over a period of time.
- The value being measured is always represented by the height of the graph, measured on the *vertical axis*.
  - Time is always represented along the *horizontal axis*.
- 1-10 A typical waveform for DC potential difference is shown in Figure 1.2. The graph is a straight, horizontal line, indicating that the potential difference does not change as time goes on.

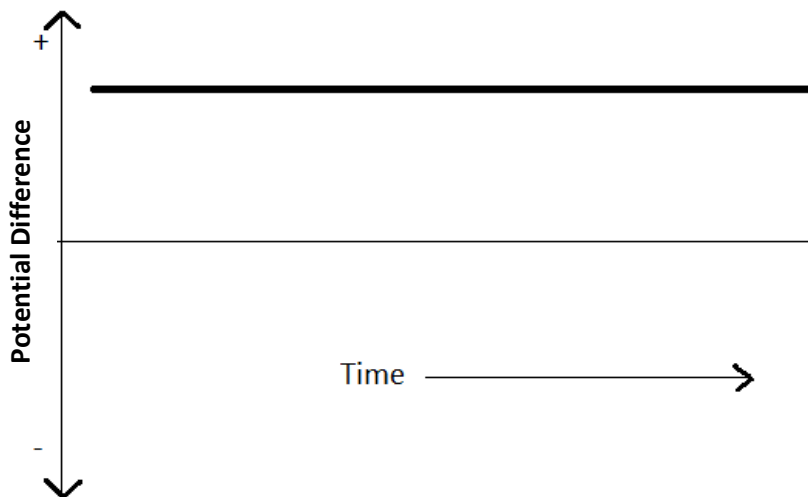


Figure 1.2: Movement of One Electron in a Conductor

## Waveforms

1-11 Figure 1.3 shows the circuit for a bell operated by a battery.

- When current flows in the coil of the electromagnet, the magnet attracts the armature and the hammer strikes the bell.
- When the armature moves, it opens the contact that controls the flow of electricity through the coil, and the current is interrupted.
- The electromagnet then releases the armature, and the spring pulls the armature back.
- As it returns, the armature closes the contacts again, and the cycle repeats itself.

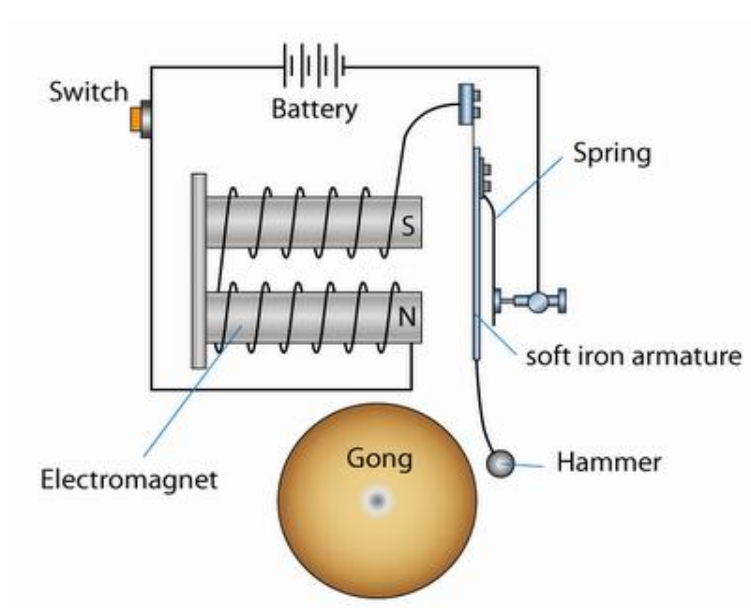


Figure 1.3: Bell Circuit

1-12 A graph of the current in the electromagnet coil looks like the waveform in Figure 1.4.

- The current increases quickly to a constant value when the bell is first turned on.
- The current remains constant until the armature moves far enough to open the contacts.
- Then the current drops to zero until the contacts close again.

This cycle repeats itself as long as the main switch stays closed.

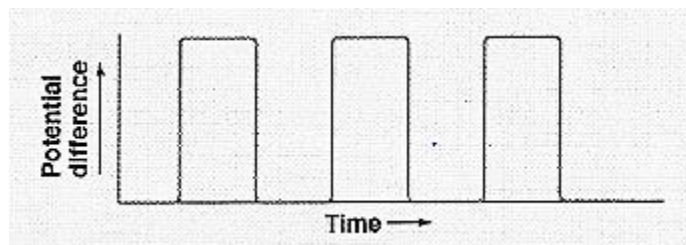


Figure 1.4: Waveform for Pulsating DC



## AC Waveform

- 1-13 The waveform for alternating current has a special shape. This shape is determined by the construction of the generator that produces alternating current. The shape is the same as the shape of a graph showing the height of a mass oscillating up and down on the end of a spring.
- 1-14 The AC waveform is called a *sine wave*. The name "sine" comes from the branch of mathematics called *trigonometry*. The waveform matches a graph of the sine of an angle as the angle increases. The output of an ac generator is proportional to the sine of the angle of the spinning rotor in the generator. The waveform for one complete revolution of the generator is shown in Figure 1.5.

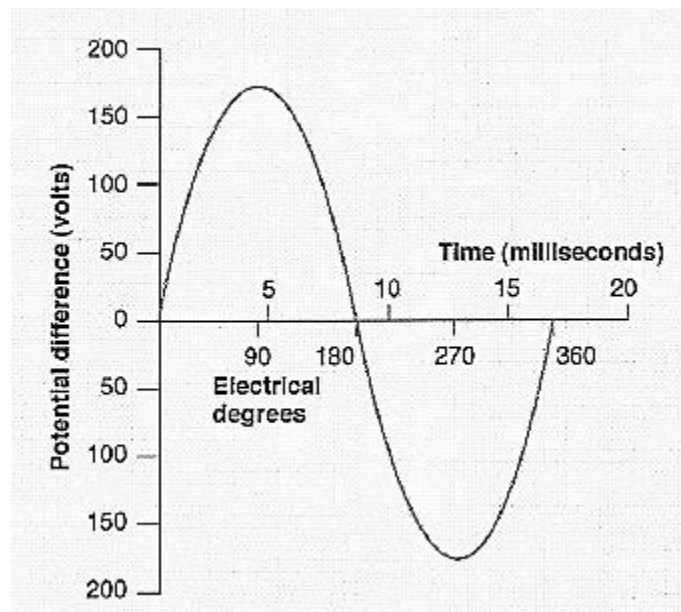


Figure 1.5: AC Cycle for 120V, 60 Hz

- 1-15 In AC electricity, the potential difference changes in a very regular way.
- It increases from zero to a maximum value.
  - Then it decreases to zero again.
  - It continues decreasing until it reaches a maximum negative value.
  - Then it increases and returns to zero.
- 1-16 This complete set of values is called a *cycle*. It repeats continuously as long as the circuit remains unchanged.
- 1-17 The maximum height of the waveform is called its *amplitude*. It is the value at the peak of the waveform. In a sine wave, the amplitude is the height of the peak above the horizontal axis. The minimum points, the "negative peaks", are equal distance below the horizontal axis as shown in Figure 1.5.

## AC Waveform (continued)

1-18 Almost all the AC waveforms you will work with will be sine waves. They may differ in their height above and below the horizontal axis, and they may differ in the amount of time between peaks. Variations in both these values are shown in Figure 1.6, on the following page. But all the sine waves will have the same basic shape.

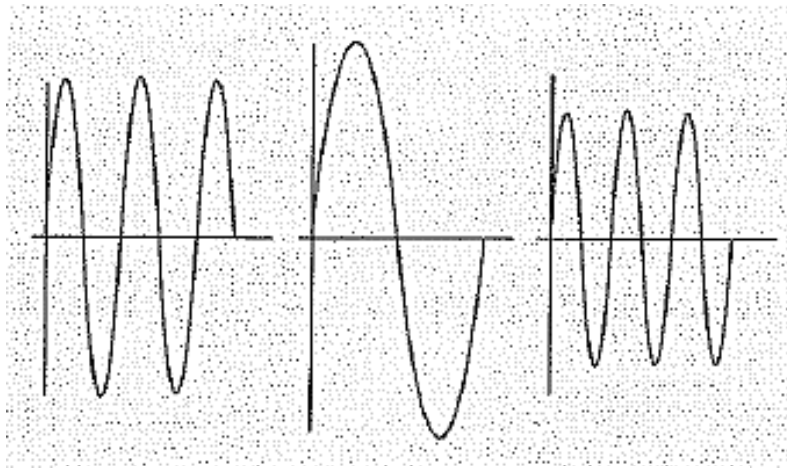


Figure 1.6: AC Waveforms

## Frequency

1-19 How many cycles an electrical system goes through in a unit of time is called the *frequency* of the system. Most AC equipment is designed to operate on an input that has a specific frequency. If the input frequency differs from the frequency the equipment is designed for, the equipment will not work properly.

1-20 Frequency is measured in *hertz*, abbreviated Hz. One hertz is defined as one cycle per second. The unit is named in honor of Heinrich Hertz, a German physicist who, in 1887 and 1888, performed important experiments dealing with the formation of electromagnetic waves.

1-21 In the United States and Canada, the standard ac frequency is 60 Hz. Many other countries have also adopted a standard AC frequency of 60 Hz, and nearly all the rest have adopted 50 Hz as the standard.

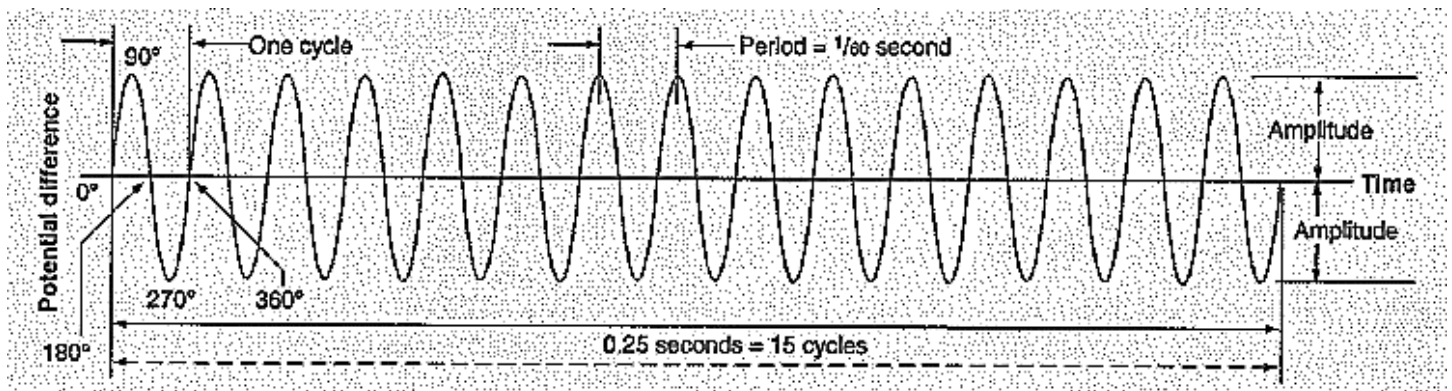


Figure 1.7: 60Hz AC Waveform

## Frequency

- 1-23 The amount of time required for one complete cycle is related to the frequency. This amount of time is called the *period* of the waveform. On the graph, it is the amount of time represented by the horizontal distance from one peak to the next. Mathematically, the period is the reciprocal of the frequency.

$$P = \frac{1}{f}$$

Where  $P$  = period, measured in seconds

$f$  = frequency, measured in Hz

- 1-24 High frequencies are measured in *kilohertz* (thousands of hertz, abbreviated kHz) and in *megahertz* (millions of hertz, abbreviated MHz). Frequencies measured in these units are common in radio, television, and other electronic equipment. Electrical equipment in the plant normally runs on frequencies measured simply in hertz, as for example, 50Hz or 60Hz.

- 1-25 To generate AC electricity, a conductor must pass through a magnetic field. The magnetic field exists between two magnetic poles, one north and one south. Some alternators have complex magnetic fields produced by more than one pair of poles. For example, a four-pole alternator has two north poles and two south poles located 90° apart around the machine.

- 1-26 An alternator cannot have an odd number of magnetic poles. The poles are always in pairs, a north pole plus a south pole, and they always alternate around the machine. As the rotor spins, each conductor goes past a north pole, then a south pole, and then comes to another north pole. As it does so, the output of the conductor goes through one complete cycle of 360 electrical degrees.

- 1-27 The number of cycles in one complete revolution of the rotor equals half the number of poles. The following equation expresses this relationship mathematically:

$$C = \frac{N}{2}$$

Where  $C$  = number of electrical cycles/revolutions

$N$  = number of poles in the alternator

- 1-28 You can use this information to figure out the frequency of an alternator's output. If  $S$  is the rotor speed in revolutions per unit of time, then the frequency of the output in Hz is calculated as shown below.

$$f = \frac{\text{Cycles}}{\text{time}} = \frac{\text{Cycles}}{\text{Revolutions}} = \frac{\text{Revolution}}{\text{time}} = C \times S = \frac{N}{2} \times S$$

## Frequency (continued)

1-29 For example, suppose a two-pole alternator rotates at 3600 revolutions per minute (rpm). You calculate the frequency in I-IZ (cycles per second), you must divide the result by 60.

$$f = \frac{N}{2} \times S = \frac{2 \text{ poles/rev.}}{2 \text{ poles/cycle}} \times 3600 \frac{\text{revolutions}}{\text{minute}} = 3600 \frac{\text{cycles}}{\text{minute}} = 3600 \frac{\text{cycles}}{60 \text{ seconds}}$$
$$= \frac{3600 \text{ cycles}}{60 \text{ seconds}} = 60 \frac{60 \text{ cycles}}{60 \text{ seconds}} = 60 \text{ Hertz}$$

1-30 Notice that if the speed of the alternator is in revolutions per minute, the frequency is in cycles per minute. If you want to calculate the frequency in Hz (cycles per second), you must divide the result by 60.

1-31 You can modify the equation so that the result will be in Hz instead of cycles per minute. You simply divide the right side of the equation by 60. The resulting equation is as follows:

$$f = \frac{N}{120} \times S$$

Where  $f$  = Frequency in Hertz

$N$  = number of poles in the alternator

$S$  = speed in revolution per minute (RPM)

1-32 This equation can also be used for calculating the synchronous speed of an ac motor. You simply solve the equation for  $S$ , resulting in the following equation:

$$S = \frac{120 \times f}{N}$$

1-33 For example, suppose a four-pole motor is running on ac power at a frequency of 60 Hz. The synchronous speed is calculated in the following way:

$$S = \frac{120 \times f}{N} = \frac{120 \times 60}{4} = 1800 \text{ RPM}$$

1-34 The same motor running on a frequency of 50 Hz would have a synchronous speed of only 1500 rpm, as shown by the following calculation. In this calculation, the value for  $f$  is changed from 60 Hz to 50 Hz.

$$S = \frac{120 \times f}{N} = \frac{120 \times 50}{4} = 1500 \text{ RPM}$$

## Frequency (continued)

1-35 Table 1-1 lists several combinations of speed, frequency, and number of poles for motors and generators. Notice that a motor runs slower on 50 Hz than on 60 Hz.

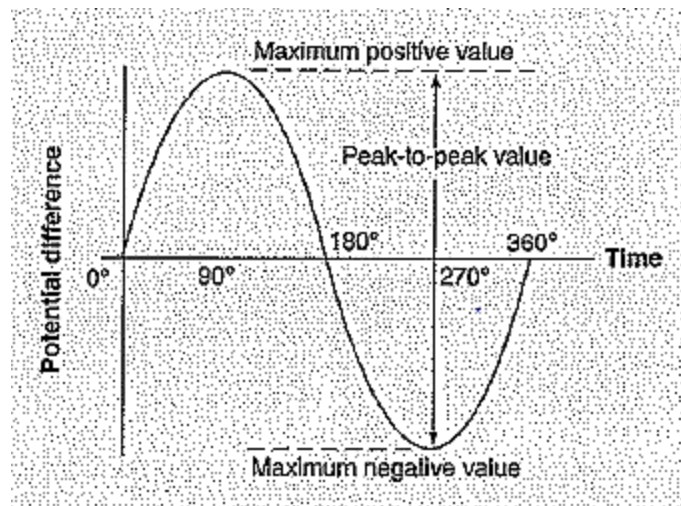
**Table 1-1: Motor and Generator Speeds**

Number of Poles	Speed (RPM)	
	$f = 50 \text{ Hz}$	$f = 60 \text{ Hz}$
2	3000	3600
4	1500	1800
6	1000	1200
8	750	900
40	150	180

1-36 An AC waveform is a continuous sine wave. Every section of the sine wave has the same amplitude, the same period, and the same frequency.

## Peak-to-Peak Values

1-37 The maximum value on a sine curve is the highest point that appears on the graph. If the curve is a graph of potential difference compared to time, the highest point represents the maximum positive potential difference that occurs, as shown in Figure 1.8.



**Figure 1.8: Peak-to-Peak Value**

1-38 Likewise, there is a minimum value. It is represented by the lowest point of the graph. This point represents the maximum negative value that occurs.

## Peak-to-Peak Values (continued)

- 1-39 In all but rare cases, the maximum point on the graph is as far above the horizontal axis as the minimum point is below it. That is, the waveform is symmetrical about zero. The distance from zero to maximum point equals the amplitude of the waveform.
- 1-40 The distance from the maximum point to the minimum point is called the *peak-to-peak* value. It is normally twice the amplitude of the waveform.

### Average Values

- 1-41 The potential difference and the current are always changing in an AC circuit. How can you measure these values without specifying a specific instant in time? One way is to calculate an average of the changing value.
- 1-42 A simple average would be zero, because every point above the horizontal axis is matched by a corresponding point below the axis. Such an average would be useless.
- 1-43 Therefore, the average is calculated in a different way. The average is based on the area between the horizontal axis and the curve. For each half cycle, the average value is defined as the height of a rectangle that has an area equal to the area bounded by the curve and the horizontal axis.
- 1-44 Figure 1.9 shows such an area. When the curve is a sine curve, the height of the rectangle is 0.637 times the height at the peak of the curve.

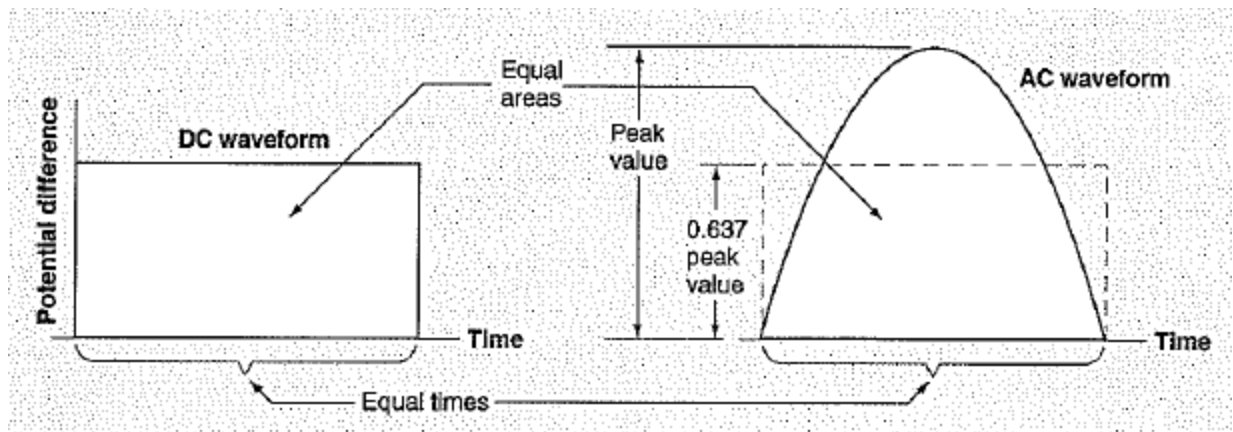


Figure 1.9: Average AC Potential Difference

## Effective Values

- 1-45 If you connect an ac source across a simple resistor, the source will drive current through the resistor. The resistor will increase in temperature, and release heat to the surroundings. The AC source is said to be equivalent to a DC source if the DC source has the right potential difference. The right potential difference is defined as being sufficient to produce heat in a resistor at the same rate as the AC source.
- 1-46 This physical definition has a matching mathematical definition. To calculate an effective value mathematically, you perform the following steps:
1. Calculate the square of each value on the sine curve.
  2. Add all these squares and divide by the total number of squares to find the *mean* (the proper mathematical name for this kind of average) of the squares.
  3. Calculate the square root of the mean.
- 1-47 The result of this calculation, called the *effective value*, is also called the *root mean square* of all the values on the curve. It is abbreviated RMS. The name root mean square comes from the fact that you are calculating the square root of the *mean* of the *squares* of all the individual values.
- 1-48 The RMS value of potential difference or current for a sine wave is always the same fraction of the peak value. It is always 0.707 times the amplitude. The fraction 0.707 is not an arbitrary number. It equals half the square root of two.
- 1-49 When an AC current or potential difference is specified, it is always the RMS value, unless stated otherwise. For example, the potential difference between electrical ground and a standard 120V AC line is a sine wave having an amplitude of about 165 to 170V. The potential difference between two such lines in a 240V circuit is a sine wave having an amplitude of about 330 to 340V.

## Energy Storage

1-50 In 1820, the Danish physicist Hans Christian Oersted showed that a conductor carrying an electric current produces a magnetic field. Any variation in the current in a conductor produces a corresponding change in its magnetic field.

- When the current increases, energy is stored in the magnetic field.
- When the current decreases, the stored energy returns to the electric conductor.

These changes are especially important in inductors.

1-51 Energy is also stored electrically in the space between conductors that differ in electric potential.

- As the potential difference increases between the conductors, more energy is stored in the space.
- As the potential difference decreases, the stored energy is returned to the conductors.

These changes are especially important in capacitors.

## Faraday's Law

1-52 Any change in the magnetic field surrounding a conductor induces a potential difference across the conductor. If the conductor forms a closed path, current is produced. If not, current is not produced.

1-53 The importance of the induced potential difference is greatest when the conductor is in the shape of a coil. The potential difference induced across a coil depends on the number of turns of wire in the coil and the rate at which the magnetic field changes.

1-54 The scientific law that governs the relationship between the induced potential difference and the magnetic field is known as *Faraday's law*. It is named in honor of the English scientist Michael Faraday, who developed the first understanding of electromagnetic induction during the 1830s. According to Faraday's law, any conductor located in a changing magnetic field has a potential difference induced across it that is proportional to the rate at which the field is changing.



## Basic Circuit Concepts

1-55 The basic laws governing electric circuits are fundamental laws of nature. They describe the flow of electricity in any circuit.

1-56 Two laws, Ohm's law and Joule's law, describe the effects of electrical resistance.

- *Ohm's law* expresses the relationship among current, resistance, and potential difference. This law states that the current in a conductor is proportional to the potential difference across it. The constant of proportionality is called the resistance of the conductor. Mathematically, the law is written as follows:

$$E = I \times R$$

where  $E$  = potential difference across the conductor

$I$  = current in the conductor

$R$  = resistance of the conductor, the constant of proportionality between the potential difference and the current.

- *Joule's law* expresses the relationship between the current in a resistor and the rate at which it produces heat. This law states that the amount of heat produced depends on the length of time the current flows, the resistance of the resistor, and the amount of current it carries.

$$H = I^2 \times R \times t$$

where  $H$  = Amount of heat produced

$I$  = Current in the resistor

$R$  = Resistance of the resistor

$t$  = Time the current flows

1-57 *Lenz's law* expresses the relationship between the direction of the electric current induced in a conductor and the direction of the change in the magnetic field that induces the current. According to Lenz's law, the direction of the induced current is such that its magnetic field opposes the direction of the change in the magnetic field that induces the current.

1-58 This law is named in honor of the Russian physicist Heinrich Lenz. Lenz performed experiments in electromagnetic induction and developed his law in the 1830s, at about the same time Faraday was doing similar work in England and Joseph Henry was doing similar work in the United States.

## Basic Circuit Concepts (continued)

1-59 *Kirchhoff's rules*, which are stated below, are important in solving complex electric circuits. There are two rules. They both apply to specific sections of a circuit.

- Kirchhoff's *point rule* says that the sum of the currents flowing toward any point in an electric circuit must equal the sum of the currents flowing away from that point. This rule is shown in Figure 1.10.

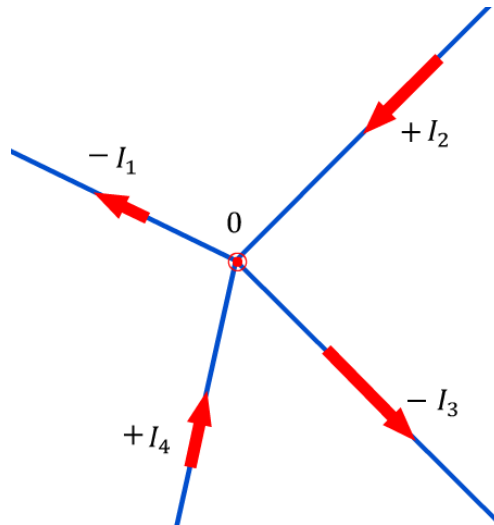


Figure 1.10: Kirchhoff's Point Rule

- Kirchhoff's loop rule says that the sum of the potential differences of all the sources around a loop (within a circuit) equals the sum of all the voltage drops across all the resistors in the loop. This rule is shown in Figure 1.11.

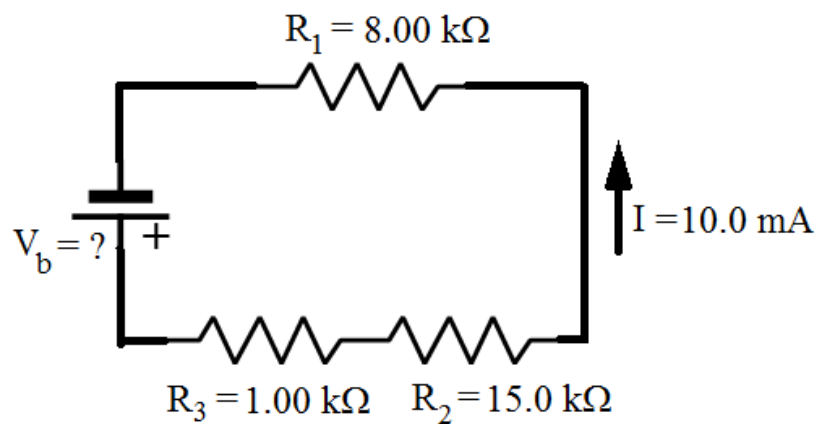


Figure 1.11: Kirchhoff's Loop Rule

## **Basic Circuit Concepts (continued)**

- 1-60 With these two rules, you can write a set of mathematical equations for a circuit and solve for several currents and voltage drops. Solving the equations may not be easy, but it is possible to arrive at a solution.
- 1-61 Many AC circuits consist of pure resistance. They lack both capacitance and inductance. For example, resistors, lamps, and heating elements have very little inductance or capacitance and are considered to be pure resistance. You can apply all the DC rules and laws to AC circuits if the circuits contain only resistance.
- 1-62 When you apply the DC rules and laws to AC circuits, you must use the RMS values of AC current and potential difference. All the AC values specified in technical documents are RMS values.

## Chapter 1 Exercise

Circle the appropriate letter next to the correct answer.

1. On a waveform, what is represented along the horizontal axis?
  - a. AC potential difference
  - b. Current
  - c. DC potential difference
  - d. Time
  
2. Amplitude is the distance from \_\_\_\_\_.
  - a. Maximum to maximum
  - b. Maximum to minimum
  - c. Zero to maximum
  - d. Zero to midpoint
  
3. In a four-pole alternator, the magnetic poles are spaced \_\_\_\_\_ apart.
  - a. 90°
  - b. 180°
  - c. 270°
  - d. 360°
  
4. The number of cycles produced in one complete revolution of the rotor in an alternator equals \_\_\_\_\_ the number of poles.
  - a. 0.707 times
  - b. Exactly
  - c. Half
  - d. Twice
  
5. What is the frequency of the output of a two-pole alternator running at 6000 rpm?
  - a. 50 Hz
  - b. 60 Hz
  - c. 100 Hz
  - d. 120 Hz

## Chapter 1 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. To find the root mean square, you calculate the square root of the mean of all the squares of \_\_\_\_\_.
- a. All individual values
  - b. The amplitude
  - c. The maximum negative values
  - d. The peak-to-peak values
7. The root mean square of potential difference or current for a sine wave is 0.707 times the \_\_\_\_\_.
- a. Amplitude
  - b. Average value
  - c. Maximum negative values
  - d. Peak-to-peak values
8. The importance of an induced potential difference is greatest when the conductor is in the shape of a(n) \_\_\_\_\_.
- a. Closed loop
  - b. Coil
  - c. Open loop
  - d. Straight line
9. Joule's law says the amount of heat produced in a resistor depends in part on the amount of \_\_\_\_\_.
- a. Current in the resistor
  - b. Frequency in the AC source
  - c. Magnetic field produced in the resistor
  - d. Potential difference across the source
10. You can apply all the dc rules and laws to AC circuits if the circuits contain only \_\_\_\_\_.
- a. Capacitance
  - b. Conductance
  - c. Inductance
  - d. Resistance

## Summary

AC circuits are more complex than DC circuits. In AC circuits, the current and the potential difference are always changing. These changes are often shown on a graph called a waveform. The current, potential difference, or other electrical value is always represented by the height of the graph, measured on the vertical axis. The time at which the changes occur is represented along the horizontal axis. The ac waveform is called a sine wave.

Most AC equipment is designed to operate on an input that has a specific frequency. The frequency is the number of cycles an electrical system goes through in a unit of time. Frequency is measured in units of hertz, abbreviated Hz.

You can use Ohm's law, Joule's law, Lenz's law, and Kirchhoff's rules when working with AC circuits. However, you must use RMS values for potential difference and current. RMS stands for root mean square. To arrive at an RMS value, you must calculate the square of each value on the sine curve. In principle, each value on the sine curve is squared; the squares are added together; the sum is divided by the number of squares to get the mean (average); and the square root of the mean is calculated. The result value equals the peak value on the sine curve multiplied by 0.707 which is half the square root of 2.

# Chapter 2: Mathematics in AC Circuits

## In This Chapter:

AC Potential Difference

Angles and Degrees

Right Triangles

Vectors Applied to AC Circuits

Graphic Solutions

Mathematical Solutions

Calculating Instantaneous Values

## Objectives

After completing this chapter, you should be able to:

- Describe a triangle.
- State the definition of a vector.
- Identify the vector representing resistance in a vector diagram.
- Demonstrate how to calculate the total impedance in an ac circuit.

## Terminology

**Vector:** An arrow that represents a physical quantity, including both magnitude and direction

**Impedance:** The combined effect of resistance, inductive reactance, and capacitive reactance in a circuit.

**Parallelogram:** A four-sided figure with opposite sides equal and parallel

**Tangent of an angle:** In a right triangle, the ratio of the side opposite the angle to the side adjacent to the angle

**Electric maintenance requires several skills. To work with AC circuits, you must be good with tools and also have a good understanding of mathematics. One skill without the other causes delays and errors.**

**Angles and degrees are important in determining electrical cycles. Certain angles formed during rotation are especially important, and you must be able to determine them when they occur.**

**This lesson explains angles and degrees, triangles, vectors, and tangents. It also explains how to calculate various electrical values both graphically and mathematically. Use the method that works best for you.**

## AC Potential Difference

2-1 The current and potential difference in AC electricity alternate in a special way. A graph of either one has a shape called a *sine curve*. The curve has this shape because of the way the electricity is generated. Figure 2.1 includes a diagram of a very simple AC generator and a graph of the potential difference produced between the terminals.

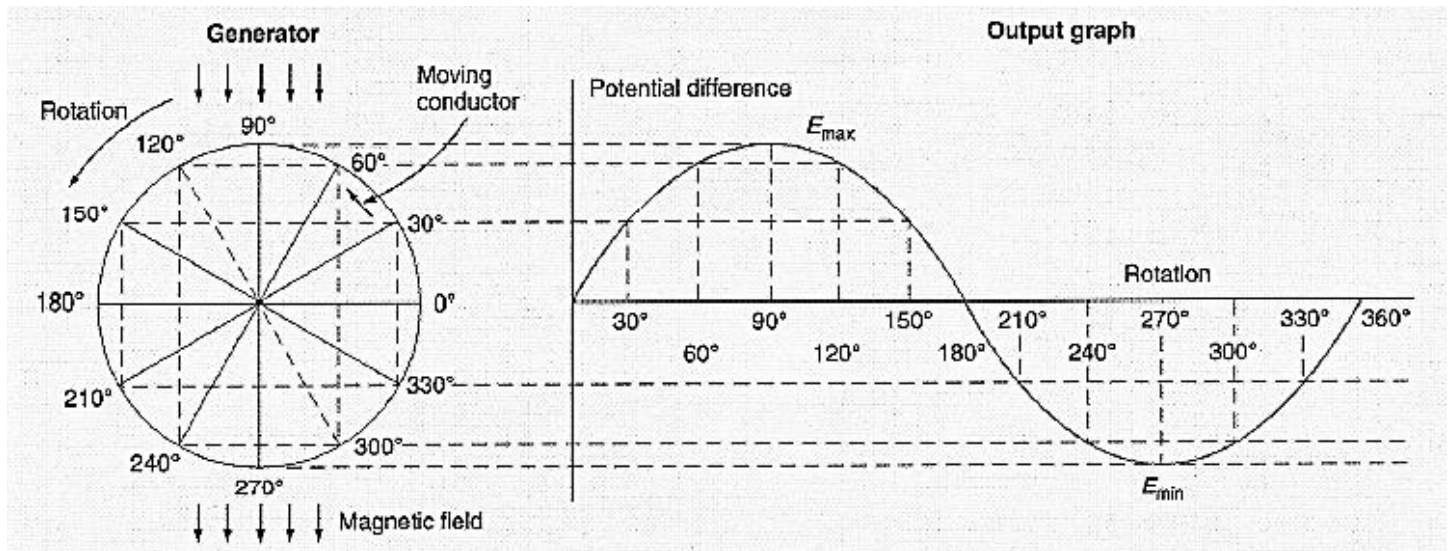


Figure 2.1: Output of an AC Generator

- 2-2 The potential difference between the terminals at any instant depends on two factors. It depends on the *speed* of the conductor as it moves through the magnetic field, and also on the *angle* at which the conductor moves through the magnetic field.
- 2-3 Turning the rotor of a generator causes the wires in the rotor to move through the magnetic field at different angles. In Figure 2.1, the 12 positions of the moving wire are matched to the 12 points on the sine curve at the right. Every time the generator makes another rotation, the potential difference goes through another cycle of 360°.



## Angles and Degrees

2-4 When two lines meet, they form an angle between them. The size of an angle is usually measured in *degrees*. A complete circle forms an angle of 360 degrees. Thus, each degree is  $1/360$  of a full circle.

2-5 Refer again to the rotation shown in Figure 2.1. During one rotation, many angles are formed. Each angle can be measured in degrees. However, certain angles are especially important, as explained below.

- The angles  $0^\circ$  and  $360^\circ$  are important, because they mark the beginning and end of a cycle.
- The angle  $180^\circ$  is important because the graph crosses from positive to negative there.
- The angles  $90^\circ$  and  $270^\circ$  are important because they mark the highest and lowest points on the graph. In addition, they mark the points where the slope of the graph changes from positive to negative and back again.

Understanding angles will help you in calculating power factors, impedance, and other characteristics of ac circuits.

2-6 In Figure 2.2, the right triangles have been formed by using the radius of a circle as the hypotenuse. The radius rotates around the center, forming increasing angles with horizontal line. The two legs of each right triangle consist of one horizontal line and one vertical line.

2-7 The vertical leg of each right triangle represents the sine of the angle. As the radius rotates to larger and larger angles, the vertical line gets longer, then shorter, then turns negative (downward), and finally returns to zero at  $360^\circ$ .

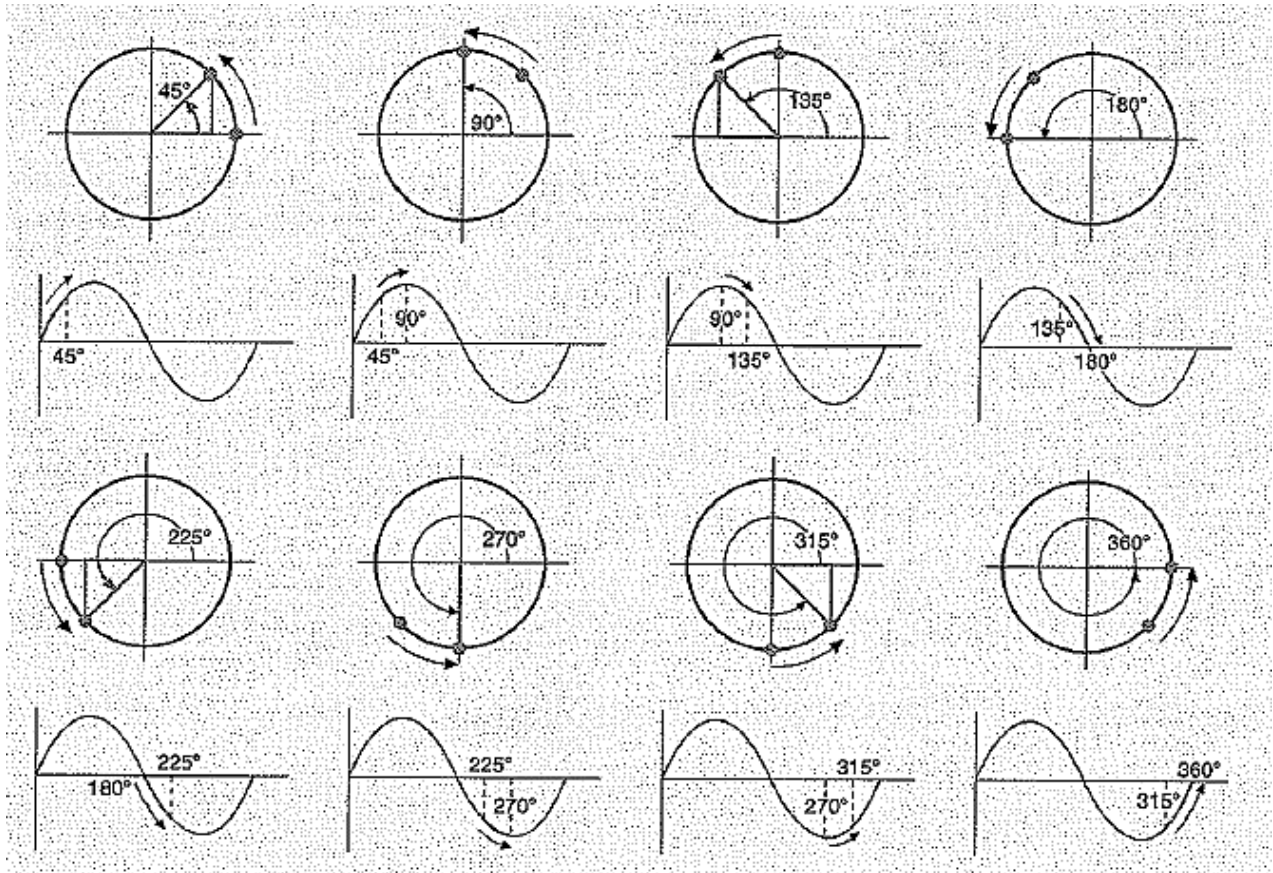
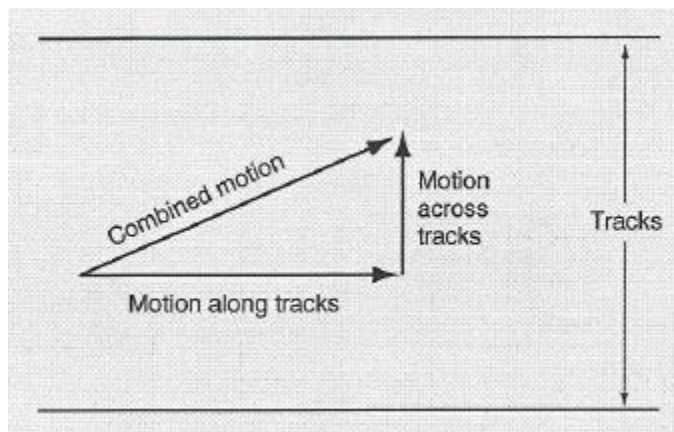


Figure 2.2: Generation of a Sine Curve

## Right Triangles

- 2-8 Three line segments joined at their ends form a figure called a *triangle*. Every triangle has three sides and three angles. In fact, the name triangle means "three angles."
- 2-9 One of the special properties of the triangle is that the sum of its three interior angles is always  $180^\circ$ . Thus, if you know any two of the angles, you can easily calculate the third.
- 2-10 Any triangle that has one angle of  $90^\circ$  is called a *right triangle*. The right triangle is especially useful. One reason is that using a right triangle makes it easier to understand physical quantities that have direction. You can divide any directional quantity into components that lie at right angles to one another.
- 2-11 For example, suppose you need to analyze the motion of the hook on an overhead crane. The crane can move in either direction along tracks. In addition, it can move in either direction along a line perpendicular to the tracks. How does the hook move if the crane performs both motions at the same time?
- 2-12 You can figure out the motion as shown in Figure 2.3. One arrow shows the motion of the hook along the tracks. The other shows the motion across the tracks. The combined motion—called the *resultant motion*—is shown by the hypotenuse of the triangle.

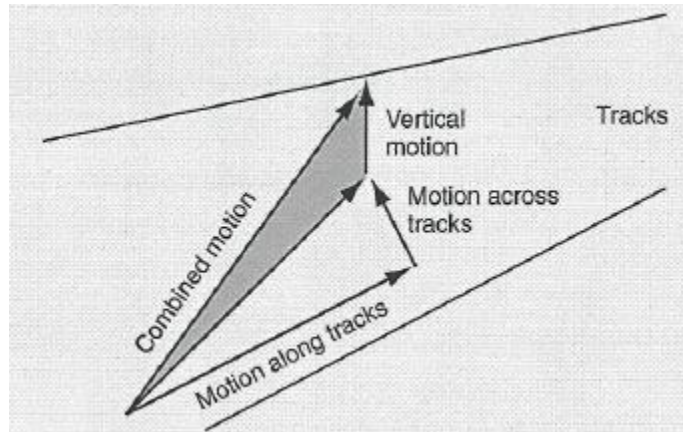


**Figure 2.3: Two-Dimensional Vector Addition**

- 2-13 If you know the combined motion of the hook, you can break the motion down into two components. To do so, you represent the resultant motion by an arrow that forms the hypotenuse of a right triangle. Then you draw one component along the tracks, and a second across the tracks. You draw the two components so that they form the legs of a right triangle. In this way, you can figure out how much of the combined motion comes from each part of the crane's movement.

## Right Triangles (continued)

2-14 The same method works in three dimensions. For example, suppose the crane operator raises the hook in addition to moving the crane along the tracks and across the tracks. The hypotenuse of the triangle in Figure 2.3 then becomes one leg of a vertical triangle. The other leg is the vertical motion, as shown in Figure 2.4. The resultant of all three motions is represented by the hypotenuse, (labeled combined motion), in Fig. 2-4.



**Figure 2.4: Three-Dimensional Vector Additions**

- 2-15 The lines in such diagrams are usually drawn as arrows. The direction of the arrow indicates the direction of the quantity along the line. An arrow that represents a physical quantity is called a *vector*. Each component of a vector is called a *component vector*.
- 2-16 This method also works in reverse. You can represent a physical quantity with a vector, and then break the vector down into two or three component vectors. The component vectors must form right angles where they meet.
- 2-17 If you need to combine two or more resultant motions, you can do so by first breaking each one down into its perpendicular components. Then you can add the components in each direction separately, reducing the problem to a single set of perpendicular components. Finally, you combine the components in this set to find a single resultant motion.
- 2-18 Any physical quantity that has magnitude and direction can be represented by a vector. You can break any such vector down into two or three components. Examples of physical quantities that are often represented by vectors include displacement, velocity, acceleration, force, torque, magnetic field strength, potential difference, and current.

## Vectors Applied to AC Circuits

2-19 Vector diagrams are used in calculating the total *impedance* in ac circuits. Impedance is the combined effect of resistance, inductive reactance, and capacitive reactance in the circuit. In a vector diagram, each value is represented by a vector pointing in a specific direction.

- The *resistance* in the circuit is represented by a horizontal arrow pointing to the right.
- The *inductive reactance* is represented by a vertical arrow pointing upward.
- The *capacitive reactance* is represented by a vertical arrow pointing downward.

2-20 When you combine these three vectors, the length of the resultant vector represents impedance in the circuit. The angle of the resultant from the horizontal represents the phase angle between the applied potential difference and the current in the circuit.

- If the resultant lies *above* the horizontal, the current *lags* the potential difference. That is, it reaches its peak *after* the potential difference reaches its peak, possibly by as much as one fourth of a cycle or 90 electrical degrees.
- If the resultant lies *below* the horizontal, the current *leads* the potential difference, possibly by as much as one fourth of a cycle.

2-21 Many people follow the opposite convention for the two vertical vectors; inductive reactance pointing *downward*, capacitive reactance pointing *upward*. Which convention you use is not important. You will get the right answers either way, but you must be consistent, and you must know the meaning of your results. In this program, vectors for inductive reactance always point upward, and vectors for capacitive reactance always point downward.

2-22 There are two ways of finding the length of the impedance vector and the phase angle.

- You can draw the vector diagram very accurately to scale, and then measure the length of the resultant vector with a scale and the angle with a protractor.
- You can calculate the length of the vector by means of the Pythagorean theorem and the phase angle by trigonometry.

The mathematical method is usually easier.

2-23 For example, suppose a 120-volt AC circuit includes a resistor, a capacitor, and an inductor. Figure 2.5 is a diagram of the circuit. How much current will this circuit carry?

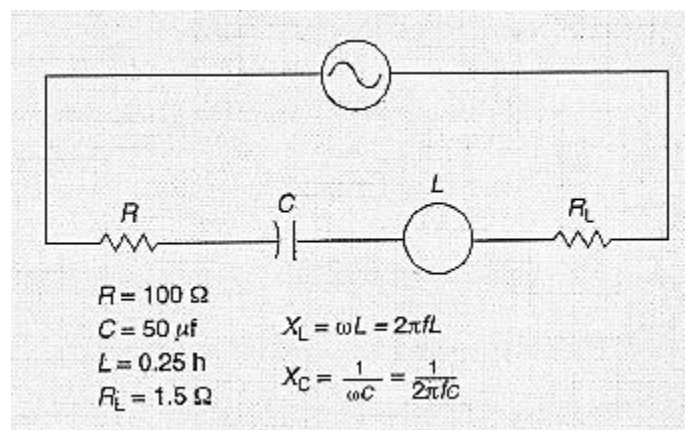


Figure 2.5: Simple AC Circuit

## Vectors Applied to AC Circuits (continued)

2-24 Notice that the circuit includes resistance in two places—an ordinary resistor and the resistance of the coil. The total resistance is  $101.5\Omega$ . To calculate the inductive and capacitive reactances, you must use the following equations:

$$X_L = \omega L \text{ and } X_C = \frac{1}{\omega C}$$

Where  $X_L$  = Inductive reactance in ohms

$\omega$  = Angular speed of the alternating power supply in radians per second

L = Inductance of the coil in henries

$X_C$  = Capacitive reactance in ohms

C = Capacitance of the capacitor in farads

2-25 The angular speed of the alternating power supply,  $\omega$ , is measured in radians per second. Each complete cycle of the ac power,  $360^\circ$  equals  $2\pi$  radians. Therefore, if the frequency of the power supply is 60 Hz, the angular speed is 377 radians per second ( $2 \times \pi \times 60 = 377$ ).

2-26 Using this value for  $\omega$ , you can easily calculate the values  $X_L$  and  $X_C$ . Try each calculation on your own and make sure your results match the values given below.

$$X_L = \omega L = 2\pi fL$$

$$= 2\pi \times 60 \times 0.25$$

$$= 6.2832 \times 60 \times 0.25$$

$$= 94.25\Omega$$

$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi fC}$$

$$= \frac{1}{2\pi \times 60 \times (50 \times 10^{-6})}$$

$$= \frac{1}{6.2832 \times 60 \times 50 \times (10^{-6})}$$

$$= \frac{1}{18849.6 \times 10^{-6}}$$

$$= 53.05\Omega$$

## Vectors Applied to AC Circuits (continued)

2-27 You are now ready to combine these values and find the impedance in the circuit. At this point, you can choose whether to combine them graphically or mathematically. Both solutions are shown in Figure 2.6. The mathematical solution includes a sketch, but the vectors are not drawn to scale.

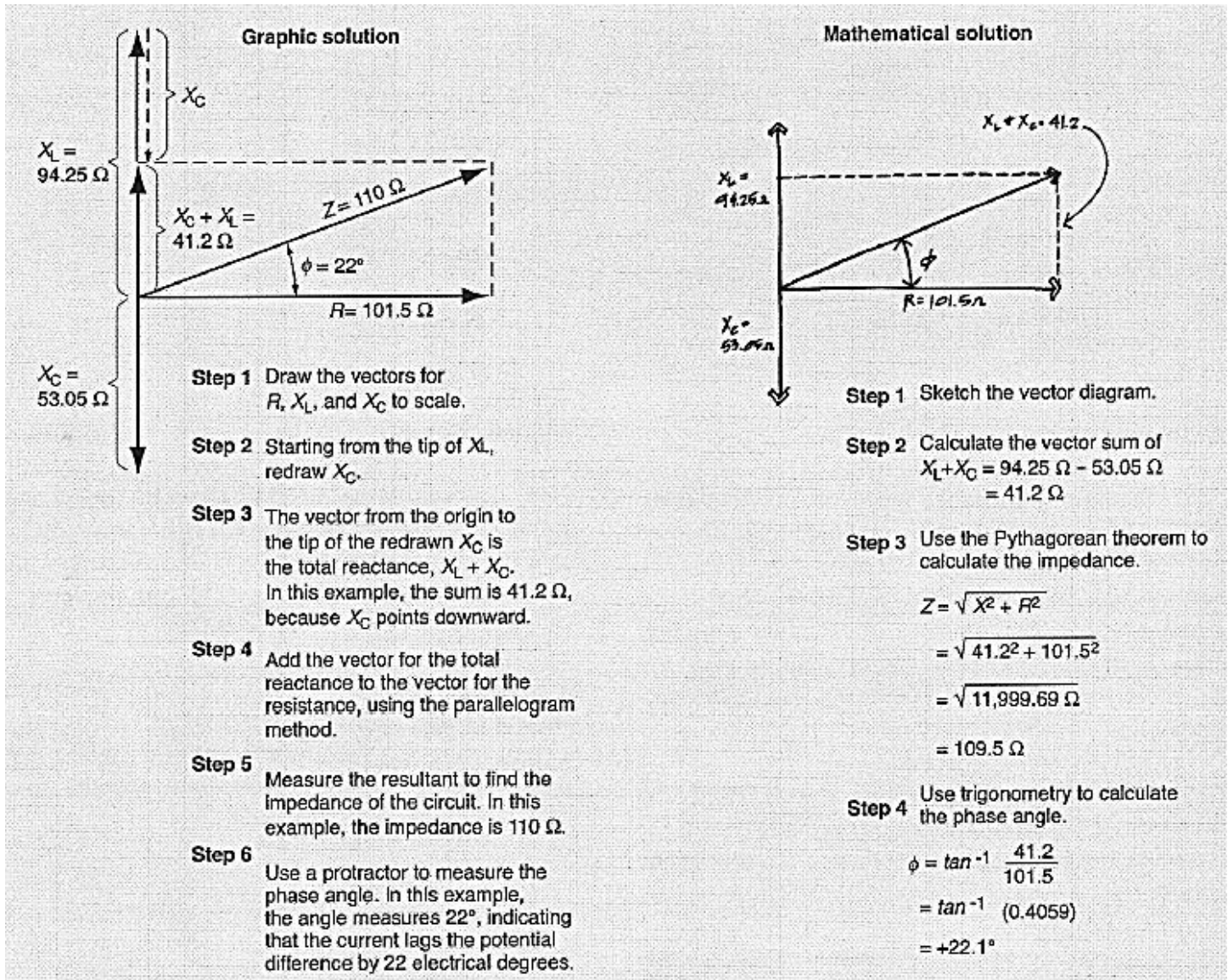


Figure 2.6: Solutions to an Impedance Problem

## Vectors Applied to AC Circuits (continued)

2-28 You can see that the results are almost identical. Use the method you think is easier.

- The graphic method is somewhat easier to understand, and you are not likely to make any mistakes in arithmetic.
- The mathematical method is faster and more accurate. The arithmetic and the trigonometry are easy if you use a calculator.

2-29 The final step in solving the problem is to calculate the current in the circuit. This calculation is an application of Ohm's law. When you divide the potential difference by the impedance, you find that the current is 1.091 amperes RMS.

2-30 The following sections of this lesson explain the graphic method and the mathematical method in more detail. You may already know some or all of the information in these sections. If so, read them quickly as a review. If the information is new to you, take more time and study it well.

### Graphic Solutions

2-31 Knowing what a parallelogram is and how you can draw one to fit a set of dimensions can help you draw vector diagrams to solve impedance problems. The name *parallelogram* tells you that the figure's opposite sides are parallel.

2-32 Some parallelograms are square or rectangles, but not all. In the vector diagrams for impedance, all the parallelograms you draw will be rectangles, because the vectors for resistance and reactance always form right angles with each other.

2-33 Three common parallelograms are shown in Figure 2.7. A quick comparison of dimensions shows you a very useful fact. The opposite sides of a parallelogram are always equal in length. Think about it for a moment, and the reason will become clear. The length of two opposite sides is determined by the distance between the other two sides. These sides are parallel. That is, they are the same distance apart everywhere.

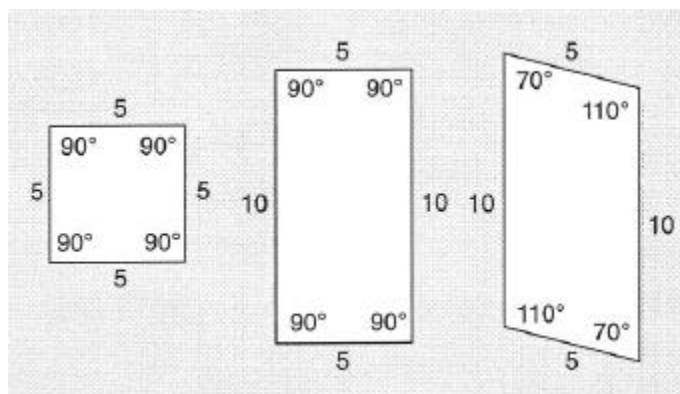


Figure 2.7: Parallelograms

## Graphic Solutions (continued)

- 2-34 Parallelograms and triangles are closely related. You can construct one figure from the other. For example, draw a diagonal line from one corner of a parallelogram in Figure 2.8. The diagonal creates two right triangles that are reversed but otherwise identical. The diagonal serves as the hypotenuse of both triangles.

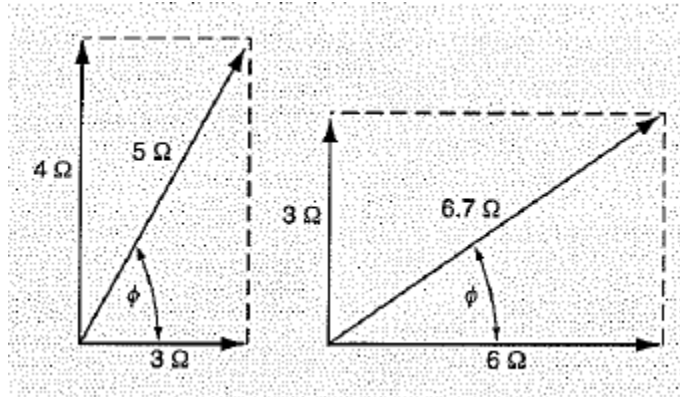


Figure 2.8: Impedance Vectors

- 2-35 You can divide any parallelogram into two such triangles. Likewise, you can draw two identical but reversed triangles sharing a common side to create a parallelogram.
- 2-36 How you can use the triangle-parallelogram combination becomes more apparent in Figure 2.8. In both diagrams, the length of the horizontal line represents resistance values. The vertical line represents the reactance.
- 2-37 In each diagram, the horizontal line and its connecting vertical line form two sides of a parallelogram. The dashed lines complete the two parallelograms. The diagonal of each parallelogram is the resultant vector. Its length represents the impedance in the circuit.
- 2-38 The phase angle,  $\phi$ , is labeled in both diagrams in Figure 2.8. The angle is considered positive if the resultant vector lies above the horizontal line, as in the diagram on the left. It is negative if the resultant lies below the horizontal.
- 2-39 Remember that a positive phase angle indicates that the current lags the potential difference. A negative phase angle indicates that the current leads the potential difference.
- 2-40 Solving impedance problems mathematically requires knowledge of the Pythagorean theorem and knowledge of trigonometry. You need the Pythagorean theorem to calculate the value of the impedance, and trigonometry to calculate the phase angle. If the phase angle is unimportant to you, you can solve the problems with the Pythagorean theorem alone.
- 2-41 The Pythagorean theorem was developed by the ancient Greek mathematician Pythagoras. It expresses the relationship among the lengths of the sides of right triangles. It works for all right triangles.



## Graphic Solutions (continued)

2-42 According to the Pythagorean Theorem, the square of the hypotenuse equals the square of one leg plus the square of the other leg. The following equations describe this relationship:

$$c^2 = a^2 + b^2$$

Or  $c = \sqrt{a^2 + b^2}$

Where  $c$  = Length of the hypotenuse

$a$  = Length of one leg

$b$  = Length of the other leg

2-43 You can use the Pythagorean theorem to calculate the value of the impedance when you know the resistance and the vector sum of the inductive and capacitive reactances. The resistance is one leg of a right triangle, and the vector sum of the reactances is the other leg. You square both these values, add the results, and calculate the square root of the sum.

$$Z = \sqrt{X^2 + R^2}$$

Where  $Z$  = Impedance

$$X = X_L - X_C$$

$R$  = Resistance

You can perform these calculations quickly and easily on a calculator.

2-44 If you do not need to know the phase angle, solving the Pythagorean theorem is as far as you need to go. But if the phase angle is important, you must use some basic trigonometry. The trigonometry you need consists of only a simple definition.

2-45 The definition you need to know concerns the tangent of an angle. The tangent is defined in terms of a right triangle. Specifically, the right triangle you sketch when you use the Pythagorean theorem to calculate the impedance of a circuit.

## Graphic Solutions (continued)

2-46 The *tangent* of the phase angle is the ratio of the side opposite the angle to the side adjacent to the angle. In mathematical form, the definition is written in the following way:

$$\begin{aligned}\tan\phi &= \frac{\textit{side opposite}}{\textit{side adjacent}} \\ &= \frac{X}{R} \\ &= \frac{X_L + X_C}{R}\end{aligned}$$

2-47 Every angle has a unique value for the tangent. Negative angles have negative tangents. The following examples show the unique value of the tangent for three angles.

- An angle of +45° has a tangent of +1.00, because in every right triangle with a 45° angle, the two legs are equal in length.
- An angle of -25° has a tangent of -0.466, because in every right triangle having an angle of 25°, the side opposite the 25° angle is 0.466 times as long as the side adjacent to the angle.
- An angle of +72.5° has a tangent of +3.18, because in every right triangle having an angle of 72.5°, the side opposite the 72.5° angle is 3.18 times as long as the side adjacent to the angle.

2-48 If you know the angle is less than 90°, you can use the unique value of the tangent to calculate the size of an angle. For example, if you know the tangent is 3.18, you know the angle must be 72.5°. There is no other angle less than 90° that has this value for the tangent.

2-49 Finding the angle when you know its tangent is called finding the *inverse tangent*. You write it by adding an exponent of -1 to the abbreviation for tangent, followed by the value of the tangent. For example, you would write the inverse tangent of 3.18 in the following way:

$$\begin{aligned}\phi &= \tan^{-1} 3.18 \\ &= 72.5^\circ\end{aligned}$$

Remember that the inverse tangent is an angle, not a tangent.

2-50 The values of the tangents have been calculated for all angles and are listed in standard tables. In the past, these tables were the only practical way to find the tangent of an angle. You could also use such a table "backward" to find inverse tangents. You would find the value of the tangent, and then see which angle it represented.

## Graphic Solutions (continued)

- 2-51 An easier way to find inverse tangents is to use a scientific calculator. This kind of calculator has a special key for calculating tangent when you key in the value of the angle. It can also calculate the angle if you key in the value of the tangent.
- 2-52 To find the phase angle in a circuit, you should first sketch the right triangle as you do when calculating impedance. After completing your sketch, you should label the phase angle and also the legs of the triangle with the values of the reactance and the resistance.
- 2-53 Next, you calculate the tangent of the phase angle by dividing the reactance by the resistance. Finally, you use a table or a scientific calculator to find the inverse tangent. This value is the phase angle  $\phi$ .
- 2-54 In the example shown in Figure 2.6, the side opposite the phase angle is the reactance in the circuit which is  $41.2\Omega$ . The side adjacent to the phase angle is the resistance in the circuit which is  $101.5\Omega$ . Therefore, you calculate the phase angle as shown below:

$$\tan\phi = \frac{\textit{side opposite}}{\textit{side adjacent}} = \frac{X_L + X_C}{R} = \frac{41.2\Omega}{101.5\Omega} = 0.4059$$

$$\phi = \tan^{-1}(0.4059)$$

$$= 22.1^\circ$$

## Calculating Instantaneous Values

2-55 Most of your work with AC circuits will involve RMS values. You can use these values in equations just as though they were DC values. But sometimes you need to know the value of the potential difference or the current at a specific instant during the AC cycle. To calculate these instantaneous values, you need to use a little more trigonometry.

2-56 In AC power, the values of potential difference and current vary according to a sine curve. Therefore, you can find an instantaneous value by multiplying the peak value by the sine of the proper angle. To make this calculation, you need to know these two values.

2-57 The peak value is easy to calculate if you know the RMS value. The RMS value is 0.707 times the peak value for a sine curve. Therefore, you can calculate the peak value from the following equation:

$$\text{Peak Value} = \frac{\text{RMS value}}{0.707}$$

2-58 For example, the potential difference across a simple circuit is 120 volts RMS. The peak value in this circuit is therefore about 170 V.

2-59 The value of the potential difference at any instant is proportional to the sine of the angle corresponding to that instant. For example, suppose you need to know the instantaneous potential difference at an instant 30 electrical degrees after the cycle starts. You would calculate this value in the following way:

$$E_{inst.} = E_{peak} \times \sin \phi = 170 \text{ V} \times \sin 30^\circ = 170 \text{ V} \times 0.5 = 85 \text{ Volts}$$

2-60 You can use this method for any value of the angle  $\theta$ . When the sine of the angle is negative, the value you calculate will be negative.

2-61 As another example, suppose you are working with a circuit in which the potential difference is 240 Volts RMS and the total impedance is 148  $\Omega$ . The inductance and capacitance in the circuit produces a phase angle of  $+35^\circ$ .

- What is the current in the circuit at the instant the potential difference reaches its peak?
- What is the current when the potential difference is zero?

## Calculating Instantaneous Values (continued)

2-62 To answer these questions, you must first calculate the RMS current and the peak current. Ohm's law enables you to calculate the RMS current. From that value, you can calculate the peak current. These calculations are shown below.

$$I = \frac{E}{Z} = \frac{240 \text{ V}}{148 \Omega} = 1.62 \text{ A RMS} = I_{peak} = \frac{1.62 \text{ A RMS}}{0.707} = 2.29 \text{ A}$$

2-63 Next you must figure out what angles to use for the instants in question. The three instants are identified by dots on the current curve in Figure 2.9.

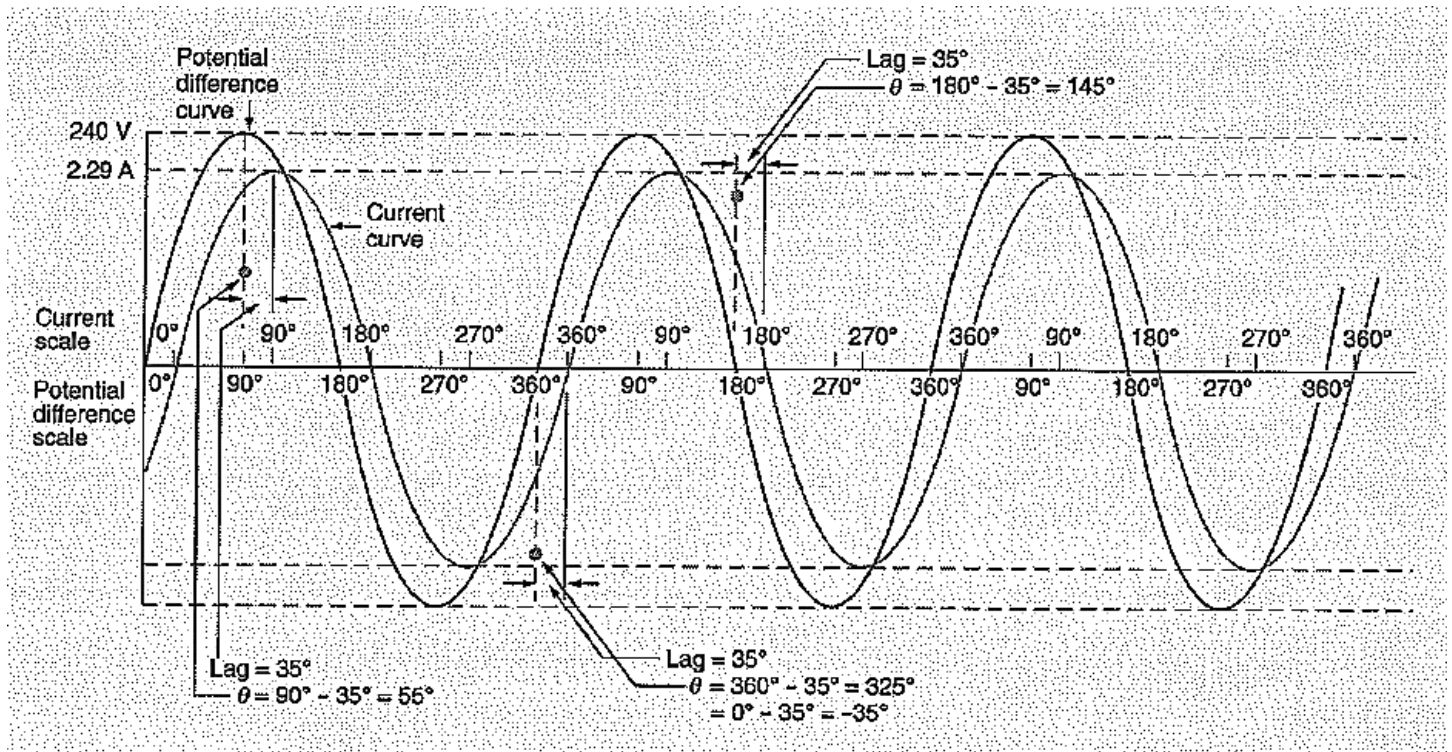


Figure 2.9: Impedance Vectors

2-64 Answering the first question is fairly simple. The peak potential difference occurs when the angle on the potential difference curve is  $90^\circ$ . At that instant, the current curve is at an angle of only  $55^\circ$ , because the current lags the potential difference by  $35^\circ$ . Therefore, you can answer the first question in the following way:

$$I_{inst.} = I_{peak} \times \sin \phi = 2.29 \text{ A} \times \sin 55^\circ = 2.29 \text{ A} \times 0.819 = 1.88 \text{ A}$$

## Calculating Instantaneous Values (continued)

2-65 Answering the second question is more difficult, because there are two answers. The potential difference is zero twice during the AC cycle, once at an angle of  $360^\circ$  when the value is increasing and again at an angle of  $180^\circ$  when the value is decreasing. The current is different at these two times. Both solutions are shown below.

**When  $E = 0$  V (increasing)**

$$I_{inst.} = 2.29 \text{ A} \times \sin (360^\circ - 35^\circ) = 2.29 \text{ A} \times 325^\circ = 2.29 \text{ A} \times (-0.574) = -1.31 \text{ A}$$

**When  $E = 0$  V (decreasing)**

$$I_{inst.} = 2.29 \text{ A} \times \sin (180^\circ - 35^\circ) = 2.29 \text{ A} \times 145^\circ = 2.29 \text{ A} \times -0.574 = +1.31 \text{ A}$$

2-66 As you work on ac circuits, you may need to refresh your memory. Keep this unit in a handy place, and use it as often as necessary.

## Chapter 2 Exercise

Circle the appropriate letter next to the correct answer.

1. An angle is formed where \_\_\_\_\_.
  - a. there are degrees
  - b. There is a circle
  - c. Two lines are parallel
  - d. Two lines meet
  
2. If two interior angles of a triangle are each  $60^\circ$ , how big is the third angle?
  - a.  $20^\circ$
  - b.  $60^\circ$
  - c.  $120^\circ$
  - d.  $240^\circ$
  
3. What is the name of a triangle in which one angle is  $90^\circ$ ?
  - a. Equilateral triangle
  - b. Right triangle
  - c. Unilateral triangle
  - d. Vector triangle
  
4. In a vector diagram, the resistance in the circuit is represented by a \_\_\_\_\_ arrow pointing \_\_\_\_\_.
  - a. Horizontal; toward the left
  - b. Horizontal; toward the right
  - c. Vertical; downward
  - d. Vertical; upward
  
5. When you combine the vectors for resistance, inductive reactance, and capacitive reactance, the resultant represents \_\_\_\_\_.
  - a. Capacitance
  - b. Impedance
  - c. Inductance
  - d. Potential difference

## Chapter 2 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. The vectors for resistance and reactance always form a(n) \_\_\_\_\_ angle.
- a. Acute
  - b. Perfect
  - c. Phase
  - d. Right
7. In a vector diagram, a negative phase angle indicates that the current \_\_\_\_\_ the potential difference.
- a. Equals half
  - b. Is equal to
  - c. Lags
  - d. Leads
8. Which of the following values is calculated from the value of the tangent?
- a. Capacitance reactance
  - b. Inductive reactance
  - c. Phase angle
  - d. Resistance
9. To calculate the instantaneous value of AC potential difference, you multiply the \_\_\_\_\_ by the sine of the proper angle.
- a. Impedance
  - b. Peak value
  - c. Phase angle
  - d. Tangent
10. The peak value equals the RMS value \_\_\_\_\_.
- a. Divided by 0.707
  - b. Divided by  $\tan \phi$
  - c. Multiplied by 0.707
  - d. Multiplied by  $\tan \phi$



## Summary

A graph showing the shape of current or potential difference in ac is called a sine curve. The curve gets its shape from the way the electricity is generated. The angle of each curve is measured in degrees. By looking at the sine curve, you can see where changes occur in each cycle.

A triangle is a figure made from three line segments joined at their ends. Every triangle has three sides and three angles. The sum of the three interior angles is always  $180^\circ$ . If you know any two of the angles, you can easily calculate the third. Any triangle with one angle of  $90^\circ$  is called a right triangle.

When working with sine curves, the direction of any quantity along a line is represented by an arrow called a vector. Each component of a vector is called a component vector. Vector diagrams are used in calculating the total impedance in an ac circuit. Impedance is the combined effect of resistance, inductive reactance, and capacitive reactance in the circuit. By combining the vectors for each value, you find the resultant vector for impedance. If the resultant lies above the horizontal line in the sine curve, the current lags the potential difference. If the resultant lies below the horizontal, the current leads the potential difference.



# Chapter 3: Inductance and Inductive Reactance

## In this Chapter

Inductance	Phase Angles
Factors Affecting Inductance	Calculating Impedance
Counter Electromotive Force (CEMF)	Mutual Induction
Inductive Reactance	Inductors in Series
Inductive Time Delay	Inductors in Parallel

## Objectives

After completing this chapter, you should be able to:

- Name the property of a coil that makes it resist changes in current.
- List the factors that determine inductance in a coil.
- State the definition of counter electromotive force.
- Demonstrate how to convert a frequency in Hz to a frequency in radians per second.

## Terminology

**Inductance:** The property of a coil that makes it resist changes in current

**Resistance:** A circuit's opposition to the flow of electrons

**Henry:** The unit of inductance

**Self-Induction:** When a conductor or coil induces a potential difference in itself

**Mutual Induction:** When a conductor or coil induces a potential difference in another part of the circuit

**Counter emf (CEMF):** An induced potential difference that opposes that of the power supply

**Impedance:** The combination of resistance and reactance in a circuit

**Radian:** A unit of angular measurement

**Time Constant:** A measure of how quickly the current in a circuit rises to its maximum

Every complete electric circuit has some inductance. Transformers, relays, current limiters, and induction furnaces are examples of devices that use the principles of induction.

This lesson explains the causes, effects, and uses of inductance and inductive reactance. You will use this information in everyday electrical maintenance. Such terms as henry, counter electromotive force, impedance, and radian are defined in this lesson.

Electrical maintenance often requires a good understanding of mathematics. This lesson explains how to calculate inductive reactance, current, the time constant of a sine curve, phase angle, impedance, and potential difference in a circuit.

## Inductance

- 3-1 *Inductance* is the property of a coil that makes it resist changes in current. The current in an AC circuit is always changing. But even in a DC circuit, the current changes when you turn the circuit on or off.
- 3-2 The current in a DC circuit may be compared to an object in motion. An object in motion loses energy because of friction, and heat is produced. In a DC circuit, the moving electrons lose energy as they pass through a resistor, and heat is produced. The circuit's opposition to the flow of electrons is called *resistance*, and its value is represented by the letter *R*.
- 3-3 Opening a switch in a DC circuit is like suddenly trying to stop a moving object. There is a delay between the time the switch opens and the time when the current stops. As the switch contacts open, the electrons may keep going across the gap. They form a spark as they jump from one contact to the other. In certain DC circuits, the currents must be reduced before the contacts are opened. Otherwise, a dangerous spark may be formed. Likewise, an electric current cannot be started instantly.
- 3-4 The effects of these time delays are generally not noticeable in the performance of a DC circuit, particularly if the circuit carries a small current.
- 3-5 However, if the circuit includes a conducting path in the shape of a coil, the time delays are important. For example, a DC circuit that includes a large solenoid or an electromagnet can produce a large spark when the contacts open.
- 3-6 The DC current in a coil need not be very high to produce the spark when the switch opens. What matters is how fast the current changes. The faster the change in current, the greater the effect when the switch opens or closes. As long as the current remains steady (zero change), the coil has no effect on the circuit other than its resistive effect.
- 3-7 In an AC circuit, a coil always has an effect because the current is always changing. As the current increases, the coil resists the increase. As the current decreases, the coil resists the decrease. The greater the number of turns of wire, the more the coil opposes changes in the current. The property of the coil that makes it oppose changes in current is called *inductance*.



## Factors Affecting Inductance (continued)

3-16 One *henry* is defined as the inductance of a circuit in which current changing at a rate of 1 ampere (A) per second induces a potential difference of 1 volt (V) across the circuit. Most inductors have inductances measured in fractions of a henry. The *millihenry* equals one-thousandth of a henry, and a *microhenry* equals one-millionth of a henry. Units larger than the henry are not required.

3-17 Inductance depends to a great extent on the physical construction of the inductor. The following factors are especially important in determining the inductance of a coil:

- number of turns
- wire size
- spacing of turns
- number of layers of wire
- coil diameter
- shape of the winding
- core material
- shape of the coil

Wire size does not affect the inductance directly, but it does determine the number of turns that can be wound in a given space.

3-18 All these factors can vary. No single equation can be used for calculating inductance. However, certain general principles apply to the inductance of a coil.

- It increases in proportion to the square of the number of turns
- It increases in direct proportion to the permeability of the core
- It increases in direct proportion to the cross-sectional area of the core
- It decreases as the length of the coil increases, if the number of turns is constant

3-19 Direct current is normally constant when a circuit is operating. Therefore, inductance affects DC circuit only when the circuit is turned on or off. There is usually very little effect on the operations of the circuit.

3-20 Alternating current is always changing. Therefore, an inductor affects an AC circuit at all times. Every electrical circuit has some inductance, but the value depends upon the physical layout of the circuit and on the kinds of electrical devices included in the circuit. In some circuits, the inductance is so small that you can ignore it.

3-21 Inductance is represented in equations by the letter *L*. This symbol is used in equations for both *self induction*, when a conductor or coil induces a potential difference in itself, and *mutual induction*, when a conductor or coil induces a potential difference in another part of the circuit.

3-22 In an AC circuit, inductance produces an effect much like resistance. It impedes the current in the circuit. How much it impedes the current depends in part on the frequency of the power supply. The higher the frequency, the more the inductance impedes the current.

## **Factors Affecting Inductance (continued)**

- 3-23 Self-induction occurs whenever there is a change in current in a conductor. A magnetic field develops around each point on the conductor as current increases from zero to maximum value. Likewise, as the current decreases, the magnetic field decreases. This changing magnetic field induces a potential difference across the conductor. This potential difference opposes the change in the current.
- 3-24 All elements in a circuit, even the connecting wires, show some self induction. For practical purposes, only those elements designed to use this property to advantage are called inductors.
- 3-25 Self induction is much greater in an AC circuit than in a DC circuit. Therefore, the conductor in an AC circuit must have a lower resistance to compensate for the effect of the higher induction.
- 3-26 If you connect an AC machine to a DC source, the effect of self induction is eliminated shortly after you turn the machine on. If the two sources have the same effective potential difference, the DC current will be about 1.57 times the effective AC current. It may burn out the machine.

## **Counter Electromotive Force (CEMF)**

- 3-27 Counter electromotive force (CEMF) is an induced potential difference that opposes that of the power supply. It occurs in all AC circuits, but it has little effect in a low-power circuit, for example, an electric lamp or heater, in which the load is almost pure resistance. But the CEMF across a coil has an important effect on motors, transformers, and other devices that are built to produce strong magnetic effects.
- 3-28 The effect of CEMF is to reduce the effective potential difference across the coil. The effect is to reduce the current below the current that would flow if the coil were not in the circuit. In this sense, the coil has the same effect as a resistor in the circuit. But, unlike a resistor, the coil does not consume any power in impeding the current.

## Inductive Reactance

- 3-29 The effect of induction in an ac circuit is a reduction in the current. This reduction is often thought of as being similar to the effect of resistance. But it is called *inductive reactance* to distinguish it from resistance.
- 3-30 Reactance, like resistance, is the ratio between the potential difference across a circuit and the current in the circuit. It is measured in *ohms*. The combination of resistance and reactance in a circuit is called *impedance*.
- 3-31 In an ac circuit, the rate of change of the current is governed by the frequency of the applied potential difference. The frequency of the potential difference in turn is governed by the angular velocity of the generator.
- 3-32 The angular velocity of the generator is measured in radians per second. The *radian* is a unit of angular measurement, similar to the degree. One radian is defined as the angle between two radii of a circle when they are separated by an arc equal in length to the radius. Figure 3.2, shows this definition and how it compares to the definition of the degree. The following equations compare radians and degrees.

$$2\pi \text{ radians} = 360^\circ$$

$$1 \text{ radian} = 57.3^\circ$$

$$0.0175 = 1^\circ$$

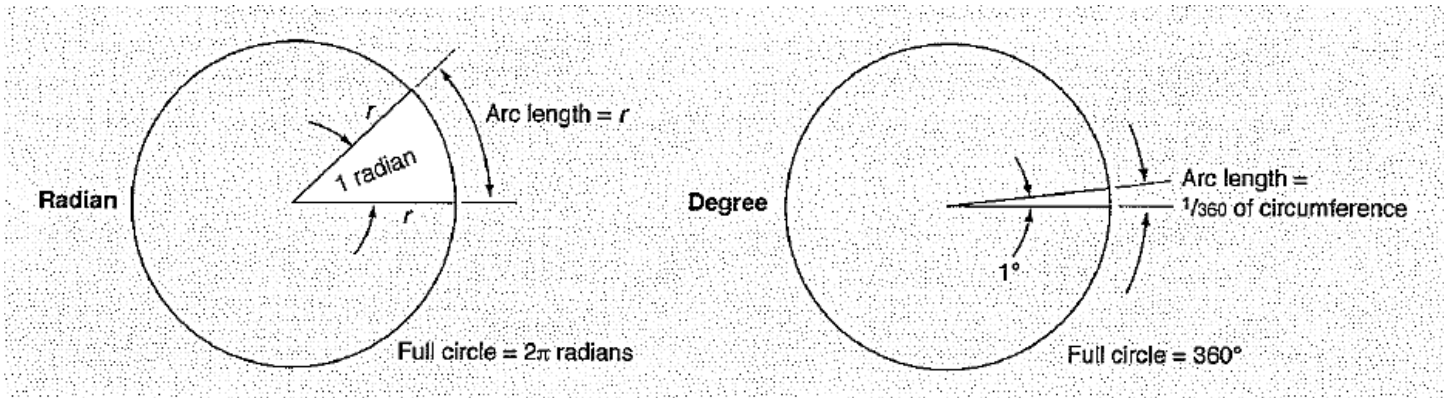


Figure 3.2: Magnetic Field of a Conductor

- 3-33 The radian is used extensively in electrical work. Each electrical cycle equals  $2\pi$  radians. Therefore, you can convert the frequency in hertz to a frequency in radians per second by multiplying by  $2\pi$ . For example, a frequency of 60 Hz equals 377 radians per second.



## Inductive Reactance (continued)

- 3-34 The inductive reactance of a circuit depends on the frequency of the applied potential difference. To calculate the inductive reactance in ohms, you multiply the frequency in radians per second by the inductance in henries. The following equation describes this calculation:

$$X_L = 2\pi fL$$

Where  $X_L$  = Inductive reactance in ohms

$f$  = Frequency in hertz

$L$  = Inductance in henries

- 3-35 Notice in this equation that increasing either the frequency or the inductance increases the inductive reactance. The frequency usually cannot be changed, because it is determined by the speed of the generator at the power station. But the inductance can be changed quite easily by moving an iron core in or out of the center of the coil. Moving the core farther into the coil increases the inductance. Moving it out of the coil decreases the inductance.
- 3-36 Suppose a 20 h coil is connected across a 120 V, 60 Hz power supply. What is the current in the coil? To solve this problem, you begin by calculating the reactance in the following way:

$$X_L = 2\pi fL$$

$$X_L = 2 \times 3.14159 \times 60 \times 20$$

$$X_L = 7540\Omega$$

- 3-37 Next, you calculate the current using Ohm's law.

$$I = \frac{E}{X_L} = \frac{120 V}{7540\Omega}$$

$$I = 0.016 A$$

- 3-38 If the frequency of the power supply increases to 400 Hz, the inductive reactance increases and the current in the coil decreases.

$$X_L = 2 \times 3.14159 \times 400 \times 20$$

$$X_L = 50,265\Omega$$

$$I = \frac{120 V}{50,265\Omega}$$

$$I = 0.0024 A$$

## Inductive Reactance (continued)

3-39 You can see from these examples that inductive reactance limits the current in an AC circuit. In addition, inductance delays the rise and fall of current in the circuit.

## Inductive Time Delay

3-40 Circuits containing inductance and resistance in series are often described by a value called the time constant of the circuit. This value is a measure of how quickly the current in the circuit rises to its maximum value.

3-41 You have learned that an inductor delays the rise in current when a DC potential difference is suddenly applied across the coil. An example of the relationship between the potential difference and the current in the coil is shown in Figure 3.3. This graph is for a circuit consisting of a coil and a resistor in series with a switch and a 100 V DC source. The resistance is  $200\Omega$ .

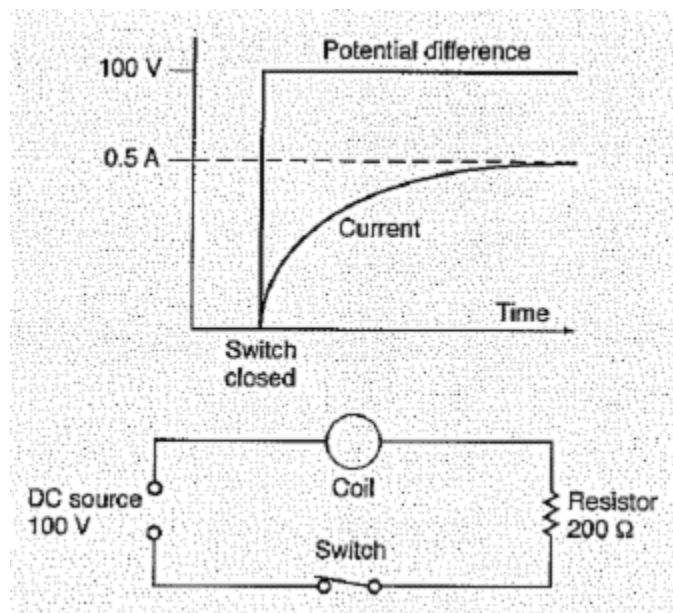


Figure 3.3: Effect of an Inductor in a DC Circuit

3-42 Notice that the potential difference rises from 0 to 100 V at the instant the switch is closed. The current would also rise instantly in a simple resistor. But the coil retards the increase in current.

3-43 The graph of the current has a special shape, called an *exponential curve*. This curve does not increase by equal amounts during equal time intervals. Instead, it increases in a special way. In equal time intervals, the value increases by equal fractions of the *difference* between:

- the value at the beginning of the interval, and
- the maximum value it will reach after a long time.

This characteristic holds no matter how long the time intervals are, provided all the intervals are equal in length.

## Inductive Time Delay (continued)

3-44 For example, if you choose the time interval shown in Figure 3.4, the value of the curve will always increase by half the remaining distance between its value at the beginning of the interval and the maximum possible value. Notice that the time axis is divided into equal intervals. The table shows the values at the end of each of the first five time intervals.

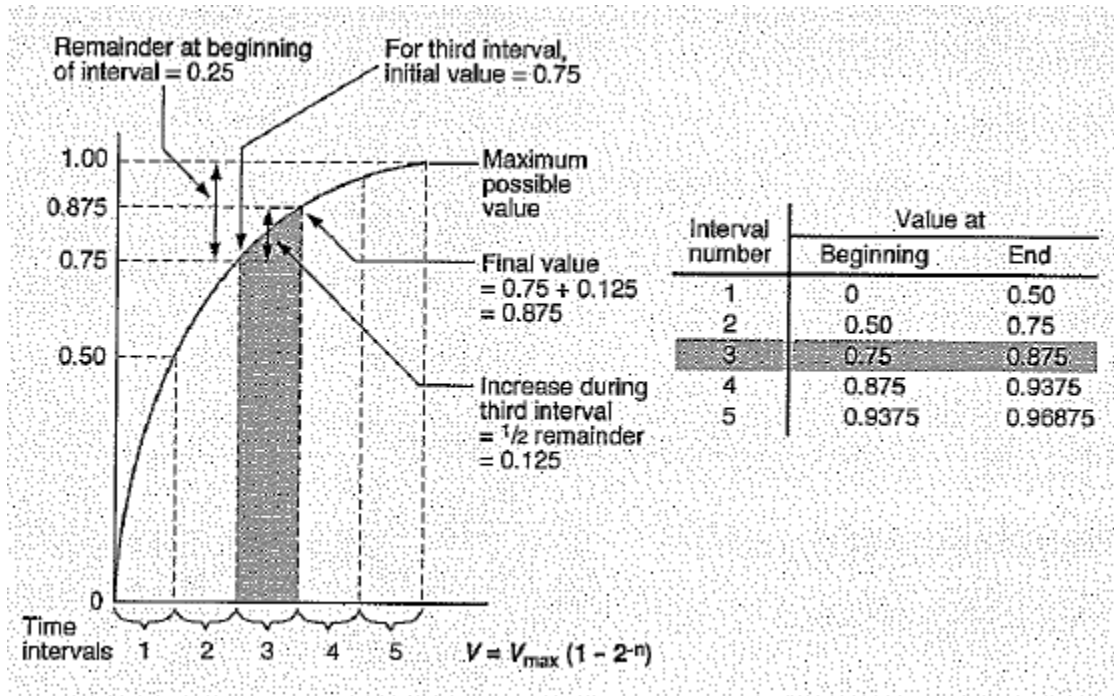


Figure 3.3: Effect of an Inductor in a DC Circuit

3-45 Notice that during each time interval, the value increases by half the amount remaining up to the maximum value. In this example, the maximum value is labeled 1.00, meaning 100% of any maximum value.

3-46 When the intervals are chosen this way, the curve can be described by the following equation:

$$V = V_{max}(1 - 2^{-n})$$

Where  $V$  = Value at the end of any time interval  $n$

$V_{max}$  = Maximum possible value of  $V$

$n$  = Number of time intervals (1,2,3, etc.)

The number two in this equation tells you that the time interval is defined so that during the interval, the value  $V$  increases by one-half (the reciprocal of 2) of the amount remaining up to  $V_{max}$ .

## Inductive Time Delay (continued)

3-47 The real world is not as simple as the example shown in Figure 3.4. In order to write equations for inductors that match the equations that describe other physical devices, the time intervals must be somewhat longer than those shown in Figure 3.4. The intervals must be long enough so that the value always increases by 63.2% of the amount remaining up to the maximum value.

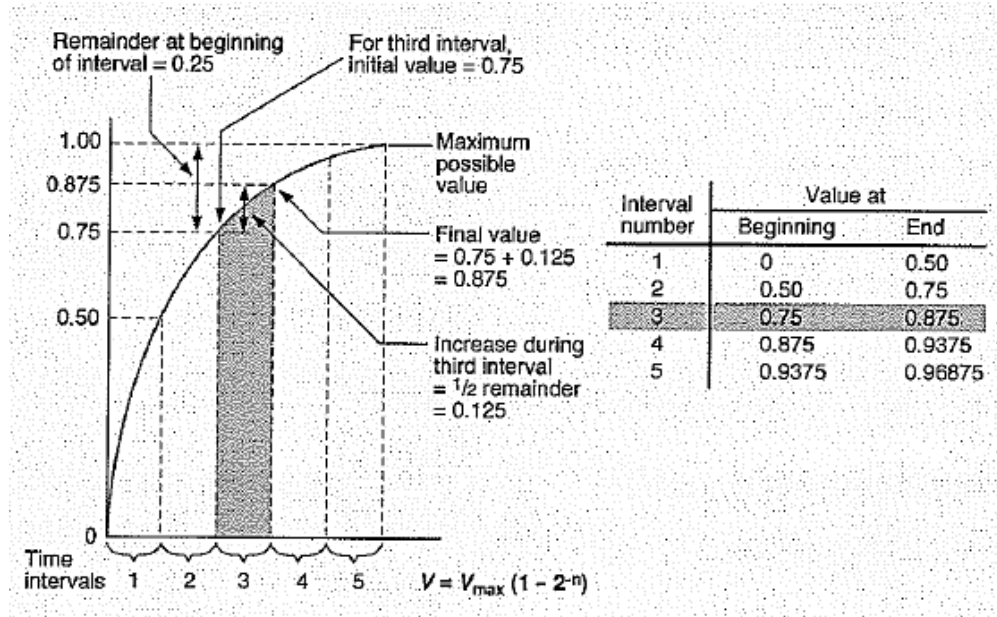


Figure 3.4: Exponential Increase – Short Interval

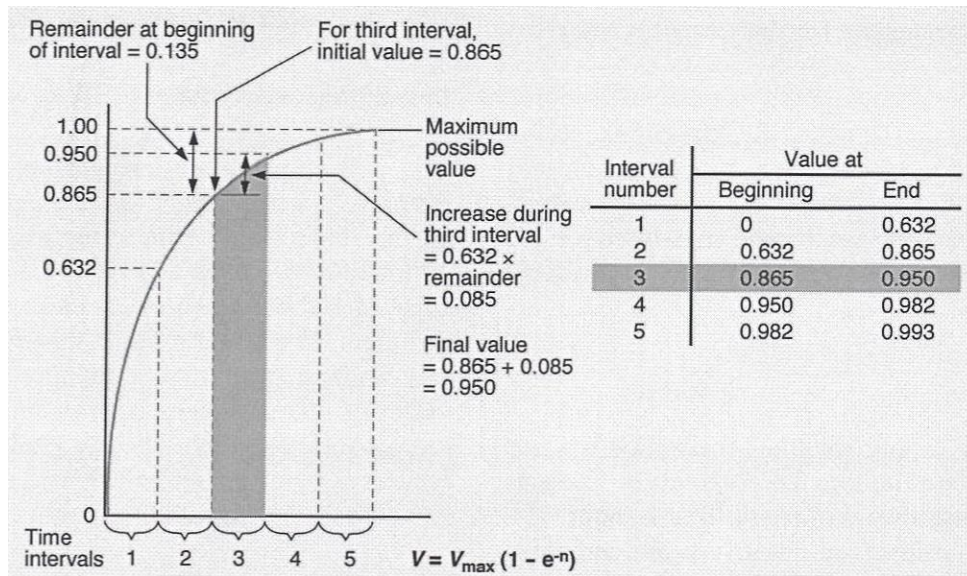
3-48 Figure 3.5 on the following page shows the same curve as in Figure 3.4, but the time axis is divided into these longer time intervals. When the interval is this long, the equation describing the curve can be written in the following way:

$$V = V_{max} (1 - e^{-n})$$

Where  $e$  = The base of the natural logarithms (2.71828...)

The number represented by  $e$  in this equation tells you that the time interval is defined in such a way that, during each interval,  $V$  increases by  $1/e$  (the reciprocal of  $e$ , equal to 0.632) of the amount remaining up to  $V_{max}$ .

## Inductive Time Delay (continued)



**Figure 3.5: Exponential Increase – Short Interval**

3-49 When the time interval is defined in this way, its length is called the time constant of the curve. The time constant is a useful value to know when you are working with an AC circuit.

- If the time constant is short, you know the inductor causes relatively little delay in the circuit.
- If the time constant is long, you know the inductor causes more delay in the circuit.

Unlike the value of inductive reactance, the value of the time constant does not depend on the frequency of the AC source.

3-50 You can easily calculate the time constant for a circuit containing an inductor and a resistor. The value in seconds equals the total inductance in the circuit divided by the total resistance. This relationship is expressed by the equation below:

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

Where  $T$  = Time constant in seconds

$L$  = Inductance in henries

$R$  = Resistance in ohms

3-51 For example, suppose a series circuit includes a 20 h inductor and a total resistance of 100Ω. The time constant for this circuit is 0.2 seconds.

3-52 In a DC circuit, it would take the current about 1 second ( $5T = 5 \times 0.2$  seconds = 1 second) after the switch is closed to reach 99% of its maximum value. The maximum value equals the potential difference of the source divided by the total resistance according to Ohm's law.

## Phase Angles

- 3-53 If an AC circuit includes resistance but no inductance or capacitance, the potential difference and the current are always in phase. That is, both values reach their positive and negative peaks and pass through zero together. The phase angle between the two values is zero.
- 3-54 If the circuit contains inductance but no resistance or capacitance, the phase angle is  $90^\circ$  ( $\pi/2$  radians). The current lags the potential difference by 90 electrical degrees. That is, it reaches its peak one fourth of a cycle later than the potential difference reaches its peak.
- 3-55 In practice, a circuit with no resistance is very rare. It occurs only in circuits made of superconducting material and cooled to a temperature near absolute zero. Ordinary circuits in the plant always have resistance. Therefore, the potential difference and the current are never  $90^\circ$  out of phase.
- 3-56 If the circuit includes both inductance and resistance, the phase angle is somewhere between  $0^\circ$  and  $90^\circ$ . The value depends on the ratio of the inductive reactance to the resistance. If the two values are equal, the ratio is 1 and the phase angle is  $45^\circ$  ( $\pi/4$  radians).
- 3-57 The phase angle is defined as the angle whose tangent equals the ratio of the total reactance to the resistance. In mathematical terms, the angle is expressed by the following equation:

$$\phi = \tan^{-1} \frac{X}{R}$$

Where  $\phi$  = Phase angle

$X$  = Vector sum of the inductive reactance and the capacitive reactance

$R$  = Total resistance in the circuit

## Calculating Impedance

- 3-58 If an AC circuit includes only resistance and inductive reactance, the two values combine to make up the impedance of the circuit. To calculate the impedance, you must add two vectors that make an angle of  $90^\circ$  with each other. There are two ways to add them. You can use the Pythagorean theorem, or you can draw them to scale and measure the resultant vector. If you draw the vector diagram to scale, you can also use it to measure the phase angle,  $\phi$ . The accuracy of your results will depend on how accurately you draw the diagram.
- 3-59 As an example, suppose you need to calculate the current in the circuit shown in Figure 3.6. To do so, you must first calculate the impedance in the circuit, and then use Ohm's law to calculate the RMS current.

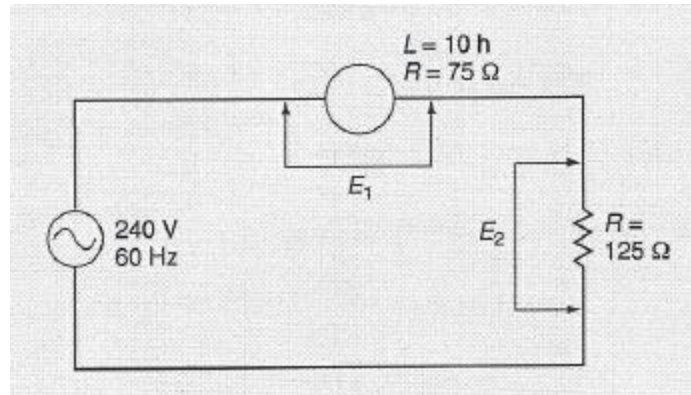


Figure 3.6: Simple Inductive Circuit

- 3-60 The impedance is the vector sum of the resistance and the inductive reactance.
- Notice in Figure 3.6 that the total resistance is  $200\Omega$ , the sum of the resistance of the coil and the additional  $125\Omega$  elsewhere in the circuit.
  - The inductive reactance is  $3770\Omega$ , calculated in the following way:

$$X_L = 2\pi fL$$

$$X_L = 2 \times 3.14159 \times 60 \times 10$$

$$X_L = 3770\Omega$$

## Calculating Impedance (continued)

- 3-61 To calculate the impedance, you can simply apply the Pythagorean theorem to the vector diagram shown in Figure 3.7. The resultant vector has a magnitude of  $3775\Omega$ , which is lower than the algebraic sum of the resistance and reactance. The current in the circuit is  $0.0636\text{ A}$ , calculated from Ohm's law.

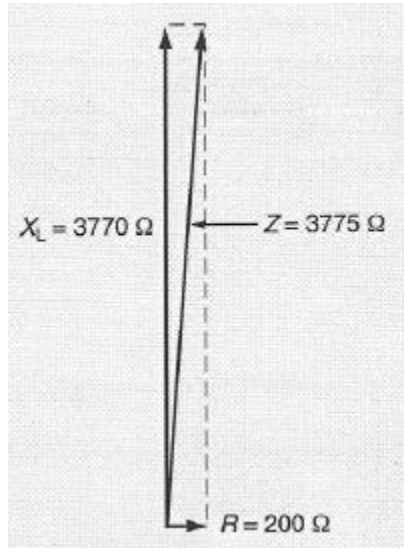


Figure 3.7: Vector Diagram

- 3-62 The potential difference across the single resistor is  $7.947\text{ V}$ , and the potential difference across the coil is  $239.74\text{ V}$ . These potential differences are both calculated from Ohm's law.

$$E_1 = I \times Z = 0.0636\text{ A} \times \sqrt{3770^2 + 75^2} = 239.74\text{ V}$$

$$E_2 = I \times R = 0.0636\text{ A} \times 125\Omega = 7.947\text{ V}$$

- 3-63 You may think these answers are wrong, because the sum of  $E_1$  and  $E_2$  is greater than the potential difference of the source. But if you square each value, add the squares, and take the square root of the sum, you will get a result that is very close to  $240\text{ V}$ . This slight difference is due to rounding in solving the equations.



## Mutual Induction

- 3-64 Mutual induction occurs when the magnetic field of one inductor affects another inductor. The two inductors share the energy produced by one of the inductors. The coils behave like the primary and secondary windings in a transformer. For this reason, mutual induction is often called *transformer action*.
- 3-65 Maximum coupling occurs when two coils are positioned so that all the magnetic field of one coil cuts all the turns of the other. If all the field of one coil cuts only half the turns of the other coil, the coupling is only half as great.
- 3-66 Mutual induction affects the total inductance in a circuit. It may increase or decrease the total inductance. The amount of mutual inductance in a circuit having two coils is calculated by the following equation:

$$M = K\sqrt{L_1 \times L_2}$$

Where M = Mutual inductance

K = Coefficient of coupling

$L_1$  = Inductance of coil number 1

$L_2$  = Inductance of coil number 2

- 3-67 The coefficient of coupling, represented by the letter  $K$ , is the fraction of the magnetic field of one coil that cuts the turns of the other coil. Its maximum value never quite reaches 1, but it approaches this value in certain transformers.

## Inductors in Series

- 3-68 The simplest form of inductive circuit is one with two inductors connected in series, as shown in Figure 3.8. The total inductance in such a circuit is the sum of the two inductances. If the circuit consists of more than two inductors connected in series, the total inductance is the sum of all the individual inductances.

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

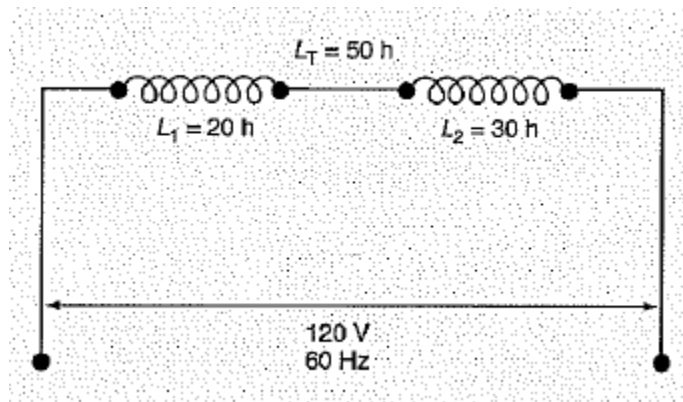


Figure 3.8: Series Inductors

## Inductors in Series (continued)

3-69 This equation works only for circuits in which the inductors are shielded from each other or located so that no mutual inductance occurs between them.

3-70 If mutual inductance does exist between two coils, its influence must be taken into account when you calculate the total inductance. The total inductance is either increased or decreased by  $2M$ , depending on how the coils are arranged physically.

- If they are arranged so that the magnetic field of one adds to the inductance of the other, the total inductance is increased.
- If they are arranged so that the magnetic field of one subtracts from the inductance of the other, the total inductance is decreased.

The following equation expresses this effect for two coils connected in series:

$$L_T = L_1 + L_2 \pm 2M$$

3-71 In some circuits, two coils are arranged so that one can rotate relative to the other. The relative rotation changes the coefficient of coupling, which changes the mutual inductance. The total inductance in the circuit can be varied by such an arrangement.

## Inductors in Parallel

3-72 If inductors are connected in parallel, the total inductance is calculated in the same way as when resistors are connected in parallel, provided the mutual inductance is zero. The following equation describes how to calculate the combined inductance.

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

3-73 As an example, suppose two inductors are connected as shown in Figure 3-9. Their combined inductance is calculated by adding the reciprocals of the individual inductances and then calculating the reciprocal of the sum.

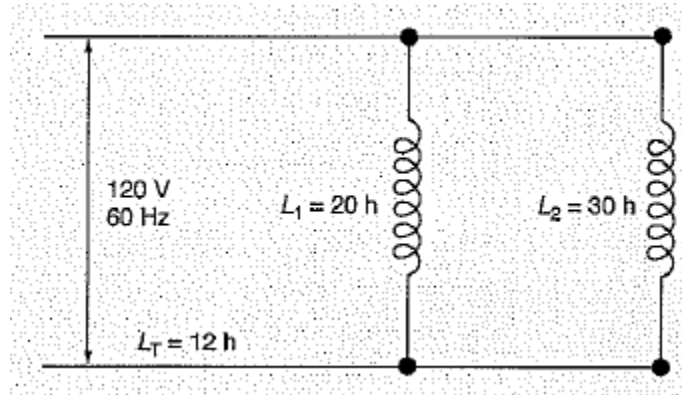


Figure 3.9: Parallel Inductors

$$L_T = \frac{1}{\frac{1}{20 \text{ h}} + \frac{1}{30 \text{ h}}} = \frac{1}{0.05 + 0.033333} = \frac{1}{0.83333} = 12 \text{ h}$$

3-74 Any mutual inductance between parallel inductors reduces their combined inductance. Therefore, little practical use is made of unshielded inductors connected in parallel.

3-75 Combined series and parallel inductors, or groups of inductors in parallel, can be simplified in steps by the same method used with resistances. Figure 3.10 shows a circuit with four inductors. The circuit is simplified in three steps to a circuit having only one inductor. In each step, the circuit always has the same inductance.

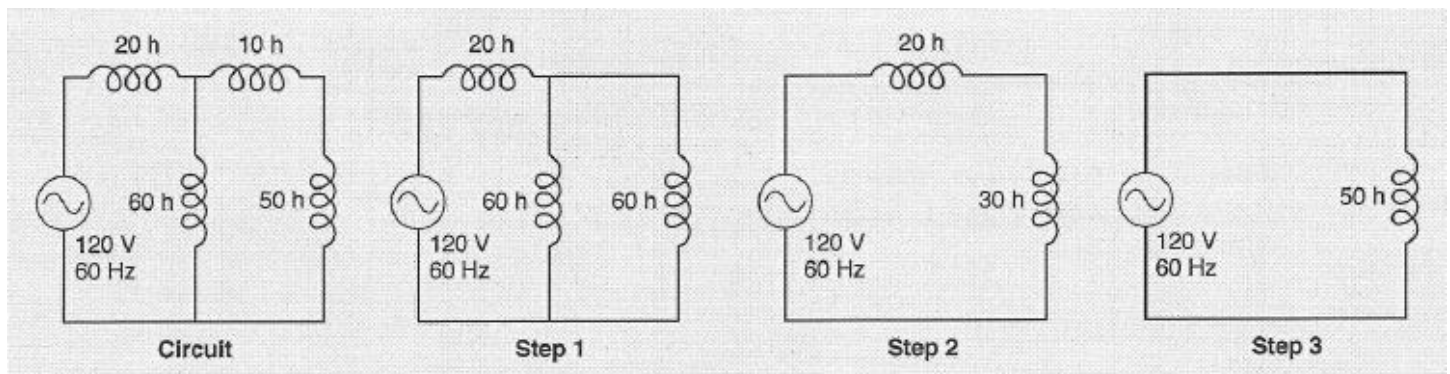


Figure 3.10: Simplifying an Inductive Circuit

## Chapter 3 Exercise

Circle the appropriate letter next to the correct answer.

1. A DC circuit's opposition to the flow of electrons is called \_\_\_\_\_.
  - a. Impedance
  - b. Inductance
  - c. Reactance
  - d. Resistance
  
2. The inductance of a coil decreases if the \_\_\_\_\_.
  - a. Cross-sectional area of the core increases
  - b. Length of the coil increases (number of turns remains constant)
  - c. Number of turns increases (length of the coil remains constant)
  - d. permeability of the core increases
  
3. Which of the following has the greatest self-induction?
  - a. AC circuit
  - b. DC circuit
  - c. AC-DC circuit
  - d. Neither circuit
  
4. What is the name for the angle between two radii of a circle when they are separated by an arc equal to the radius of the circle?
  - a. 0.707
  - b. 3.14
  - c. 189
  - d. 377
  
5. A frequency of 60 HZ equals \_\_\_\_\_ radians per second.
  - a. Capacitance
  - b. Impedance
  - c. Inductance
  - d. Potential difference

### Chapter 3 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. Inductance in an ac circuit is \_\_\_\_\_.
- a. Decreases the current
  - b. Delays the rise and fall of current
  - c. Increases the current
  - d. Speeds up the rise and fall of current
7. In order for the potential difference and the current to be in phase, the circuit must have only \_\_\_\_\_.
- a. Add values
  - b. Add vectors
  - c. Multiply values
  - d. Multiply vectors
8. Which of the following values is calculated from the value of the tangent?
- a. Capacitance reactance
  - b. Inductive reactance
  - c. Phase angle
  - d. Resistance
9. If an inductive circuit consists of more than two inductors connected in series, the combined inductance equals the \_\_\_\_\_.
- a. Average value
  - b. Difference between the values
  - c. Largest value
  - d. Sum of all the values
10. What effect does mutual inductance between two parallel inductors have on their combined inductance?
- a. Decrease it
  - b. Increases it
  - c. No effect
  - d. Impossible to predict

## Summary

Inductance in a coil causes the coil to resist changes in the current. The more turns of wire a coil has, the greater its opposition to the changes in the current. The unit of inductance is the henry. Factors that determine the inductance of a coil include the number of turns, spacing of turns, coil diameter, core material, wire size, number of layers of wire, shape of the winding, and shape of the coil.

Inductive reactance is the reduction in the circuit's current as a result of induction. It is similar to resistance. In an ac circuit, the rate at which the current changes is governed by the frequency of the applied potential difference. The frequency is governed by the angular velocity of the generator. The angular velocity is measured in radians per second. Each electrical cycle equals  $2\pi$  radians.

In inductive circuits, inductors may be connected either in series or in parallel. In series-connected inductors, the total inductance is the sum of all the individual inductances. In parallel-connected inductors, the combined inductance is calculated by adding the reciprocals of the individual inductances and then calculating the reciprocal of the sum.

# Chapter 4: Capacitance and Capacitive Reactance

## In this Chapter

How a Capacitor Works

Units of Capacitance

Factors Controlling Capacitance

Kinds of Capacitors

Discharging Capacitors

Series Capacitors

Parallel Capacitors

Time Constants

Capacitance Reactance

Phase Angle

## Objectives

After completing this chapter, you should be able to:

- Name the parts of capacitors.
- List the factors that affect the amount of charge stored in a capacitor at a given potential difference.
- Demonstrate how to install a multi-section electrolytic capacitor.
- State the definition of capacitive reactance.

## Terminology

**Capacitor:** Two conducting plates separated by a dielectric material

**Farad:** The basic unit of measurement of capacitance

**Dielectric Constant:** The ratio of two capacitances, one for a capacitor having specific material as its dielectric, and the other for a capacitor having a vacuum as its dielectric

**Capacitive Reactance:** The effect of a capacitor on AC current

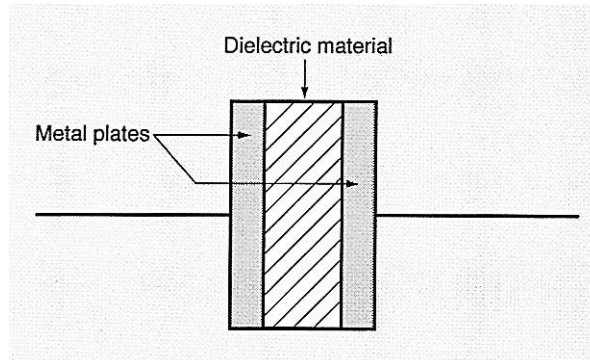
Capacitors are important components of both AC and DC circuits. AC motors, time delays, and communications equipment are examples of devices that use capacitors. Understanding what a capacitor is and its function in electric circuits will help you as you work with electrical equipment and systems in your plant.

In this lesson, you will study how a capacitor works, the different kinds of capacitors and their applications, and how to connect capacitors in series and/or parallel to increase or decrease capacitance in a circuit. The effects of capacitive reactance are also explained.

As you work with capacitors, be aware of the charges stored by these components and follow the instructions included in this lesson for discharging capacitors.

## How a Capacitor Works

- 4-1 A *capacitor* consists of two conducting plates separated by a dielectric (insulating) material, as shown in Figure 4.1. The conducting plates are sometimes called *electrodes*.



**Figure 4.1: Structure of a Capacitor**

- 4-2 When you connect a capacitor to a DC source, electrons from the negative terminal flow onto one plate of the capacitor and remain there. They can go no farther because of the insulation. Electrons are removed from the other plate and flow into the positive terminal of the battery.
- 4-3 One plate has as many extra electrons as the dc source can force onto it. The other plate lacks an equal number of electrons. Thus, one plate has a negative charge, and the other plate has an equal positive charge. When no more current can flow, the capacitor is said to be *charged*.
- 4-4 If a capacitor becomes charged in a circuit and is then removed from the circuit, the capacitor retains its charge. For this reason, a large capacitor with a high potential difference between its plates can be very dangerous. Any connection between the plates allows a high current flow for an instant.
- 4-5 Certain kinds of electronic equipment require high potential differences for their operation. An example is any piece of equipment that includes a *cathode-ray tube*. This kind of tube is used as the picture tube in television sets and as the display tube in oscilloscopes, certain kinds of computer terminals, and other kinds of equipment that provide a visual display.
- 4-6 The power-supply circuit for such a device typically includes one or more large capacitors. The capacitors become charged at high potential differences. They can remain charged for many hours after the equipment is turned off. If you make electrical contact with one or both terminals, you can receive a dangerous shock. Under certain conditions, such a shock can kill you.

### **WARNING**

**Avoid touching the terminals of a large capacitor used in high-voltage equipment. The capacitor may remain charged long after the equipment is disconnected from the power supply. Touching it can give you a dangerous shock.**



## How a Capacitor Works (continued)

- 4-7 In an AC circuit, capacitance alters the relationship between current and potential difference. Each plate is repeatedly charged, discharged, and recharged with the opposite charge. Electrons flow onto one plate and off the other, and then reverse themselves in response to the reversal of the potential difference.
- 4-8 A capacitor acts as an open circuit in a DC circuit. But in an AC circuit, it acts more like a short circuit. The higher the frequency of the ac source, the more the capacitor acts like a short circuit. The lower the frequency, the more the capacitor acts like an open circuit.

## Units of Capacitance

- 4-9 The basic unit of measurement of capacitance is the *farad*, abbreviated *F*. The unit is named in honor of Michael Faraday, an English physicist who made some of the earliest measurements of capacitance in the 1840s. A capacitor has a capacitance of 1 farad if it stores a charge of 1 coulomb when the potential difference between its plates is 1 volt. That is:

$$1 \text{ Farad} = 1 \frac{\text{coulomb}}{\text{volt}}$$

- 4-10 One coulomb is a very large amount of charge. To store that much charge when the potential difference between the plates is only 1 volt would take an enormous capacitor the size of a large room.
- 4-11 The capacitors you see in electric circuits are small enough to hold in the palm of your hand or even on the tip of your finger. Their capacitance is measured in millionths of a farad or microfarads abbreviated  $\mu\text{F}$ , or in millionths of a millionth of a farad or picofarads, abbreviated pF.
- 4-12 You will often see other abbreviations for microfarads and picofarads. The most common abbreviations for units of capacitance are listed below.

<u>Unit</u>	<u>Meaning</u>	<u>Abbreviations</u>
Microfarad	$10^{-6}$ F	$\mu\text{F}$ , mF, MFD
Picofarad	$10^{-12}$ F	$\mu\mu\text{F}$ , mmF, MMFD

## Units of Capacitance (continued)

4-13 You may already be familiar with the symbols shown in Figure 4.2. They are easy to recognize if you note the similarity between the symbol for a fixed capacitor and the cross-section drawing of a fixed capacitor in Figure 4-1.

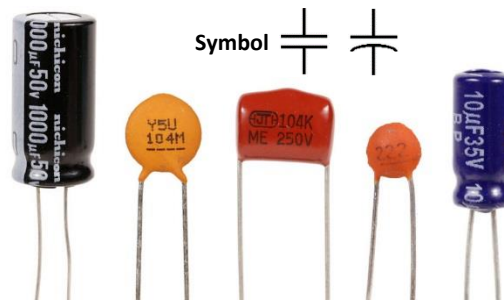


Figure 4.2: Capacitors

## Factors Controlling Capacitance

- 4-14 Applying more potential difference between the terminals forces more charge onto the plates of a capacitor. But the materials used, the area of the plates, and the distance between the plates also affect the amount of charge stored at a given potential difference.
- 4-15 Capacitor plates are usually made of a metal foil. They are often made of aluminum foil. The insulation between the plates can be any one of a number of dielectric materials. The choice depends on which material will serve best in a specific application.
- 4-16 If you compare two capacitors that differ only in the kind of dielectric material between the plates, you will find that their capacitances differ. In order to compare the effectiveness of different dielectrics, a value called the dielectric constant is used.
- 4-17 The *dielectric constant* is the ratio of the capacitances of two capacitors. The two capacitors are identical except for the dielectric material.
- One capacitor has a *vacuum* as the dielectric. This capacitor serves as the standard for comparison.
  - The other capacitor has the *material* as the dielectric.

## Factors Controlling Capacitance (continued)

4-18 The dielectric constant of any material is defined as the ratio of the capacitance of a capacitor having the material as the insulator to the capacitance of an identical capacitor having a vacuum as the insulator.

$$K = \frac{C_m}{C_o}$$

where  $K$  = dielectric constant of a material

$C_m$  = capacitance of the capacitor having the material as an insulator

$C_o$  = capacitance of an identical capacitor having a vacuum as the insulator

4-19 Table 4-1 lists the dielectric constants of several materials. Notice that the value for air is almost identical to the value for a vacuum.

<b>Material</b>	<b>Dielectric Constant</b>
Vacuum	1
Dry air	1.00059
Glass	5 to 10
Mica	6.9 to 7.3
Paraffin	2.25
Polyethylene	2.25
Quartz, fused	3.38
Rubber, vulcanized	2.49
Teflon®	2.1

4-20 In addition to the effect of the dielectric constant, the geometry of a capacitor affects its capacitance.

- Increasing the *area* of the plates increases the capacitance, because more electrons can fit on the negative plate
- Increasing the *separation* of the plates decreases the capacitance, because the two plates have less effect on each other through induction

## Factors Controlling Capacitance (continued)

- 4-21 Figure 4.3 is a diagram of a capacitor. The dielectric is air, and the capacitor is connected to the dc source. As negative charge increases on the left-hand plate, and equal positive charge builds up on the right-hand plate.

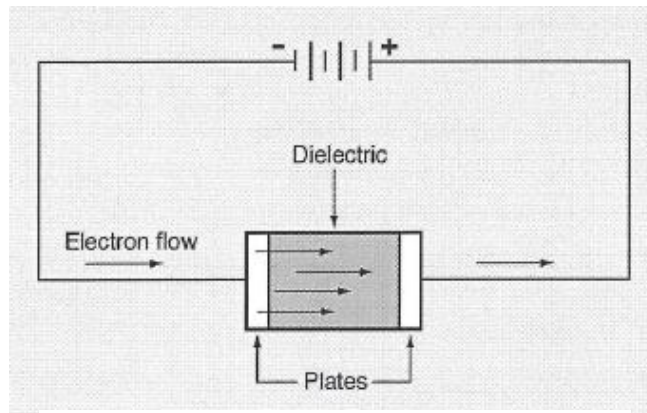


Figure 4.2: Capacitors

- 4-22 Like charges repel each other. Therefore, the increase in electrons on the left repels electrons from the plate on the right. Similarly, the increase in positive charge on the right attracts electrons to the plate on the left.
- 4-23 The effect of the plates on one another increases the amount of charge stored in the capacitor. The capacitance is therefore greater than if the capacitor consisted of only one plate or if the plates were very far apart.
- 4-24 When you consider the effect of the plates on each other, you can see that changing the distance between the plates will change the capacitance of the capacitor.

## Kinds of Capacitors

- 4-25 Capacitors are manufactured in various shapes and sizes and from many different materials. Each kind is named according to the kind of dielectric material used.
- 4-26 The simplest kind of capacitor is the *air capacitor*. It is made of metal plates separated by air. Air capacitors were once used as tuning capacitors in radios, television sets, and other electronic equipment. The range of capacitance values is 1 to 500 pF.
- 4-27 The *mica capacitor* consists of two sheets of thin metal foil separated by a layer of mica which is a mineral that can be split into thin sheets. The capacitance values range from 10 pF to 0.01  $\mu\text{F}$ .
- 4-28 A *paper capacitor* has plates of metal foil separated by a sheet of paper. The paper is coated with wax or impregnated with oil. The capacitance ranges from 250 pF to 1  $\mu\text{F}$ .
- 4-29 An *oil-filled capacitor* has a dielectric of mineral oil or askarel which is a synthetic oil. The capacitance is 1 to 1000  $\mu\text{F}$ .

## Kinds of Capacitors

- 4-30 A *ceramic capacitor* is made by depositing a film of silver on each side of a ceramic wafer. The layers of silver serve as the plates of the capacitor, and the ceramic material serves as the dielectric. Capacitance values range from 1 pF to 0.05  $\mu\text{F}$ .
- 4-31 The physical size of a paper or mica capacitor becomes excessive for capacitance values greater than 1 LCF. Therefore, *electrolytic capacitors* are often used for capacitances in the range of 1 to 1000  $\mu\text{F}$ . One kind of electrolytic capacitor is polarized, with the negative and positive terminals marked. This kind of capacitor is used only in dc circuits.
- 4-32 Electrolytic capacitors may be made with as many as four capacitors in one container. Each capacitor may have a different capacitance and voltage rating. The can is usually the common terminal for all the capacitors.
- 4-33 You must use care when installing a multi-section capacitor. The common terminal is usually the negative side of the capacitor, but some electrolytic capacitors are made with the can as the positive terminal. If you connect the unit backward, the dielectric will break down and cause a short circuit.
- 4-34 The terminals on a multi-section electrolytic capacitor are marked. The information is either stamped or printed on the can. The information on the can will also tell you whether the common terminal is negative or positive.
- 4-35 Never connect an electrolytic capacitor across an AC line. The electrolyte becomes very hot and generates pressure inside. To release this pressure, a safety valve in the bottom of the can should open and vent the capacitor. If this safety valve should fail to open, the capacitor may explode, throwing chemicals and pieces of metal.
- 4-36 A special kind of electrolytic capacitor is made for alternating polarity. It is the only kind that can be used in AC circuits. Unless an electrolytic capacitor is made for use in AC circuits such as a motor-starting capacitor, you must be careful to connect it only in a DC circuit and with the correct polarity.
- 4-37 Capacitors are usually marked with the maximum DC potential difference they can withstand. If no potential difference is indicated, the capacitor is rated for a maximum of 500 Volts.
- 4-38 Voltage ratings are put on capacitors because of the limits of the dielectric. If you apply a potential difference higher than the rated value, the dielectric may break down and cause a short circuit.
- 4-39 When replacing defective capacitors, always try to replace them with capacitors having the same capacitance value and the same voltage rating. You may use a capacitor of a higher voltage rating, but never one of lower rating.

## Discharging Capacitors

- 4-40 Never discharge a capacitor by shorting the terminals with a screwdriver or other conductor. The sudden discharge damages the dielectric and may cause early failure of the capacitor. Instead, discharge the capacitor through a resistor of  $1000\ \Omega$  or more. The resistor allows the capacitor to discharge, or "bleed," slowly.
- 4-41 A large capacitor should have a bleeder resistor permanently connected between its terminals. The resistor should have a value of several thousand ohms. When the circuit is disconnected, the charge on the capacitor "bleeds off" through the resistor and eliminates the danger of shock.
- 4-42 Always be careful when you work on a circuit that includes a large capacitor. If the capacitor has a bleeder resistor, wait at least 5 minutes before touching the circuit to give the charge sufficient time to bleed off. If the capacitor is not equipped with a bleeder resistor, discharge the capacitor through a resistor as described above.

## Series Capacitors

- 4-43 Connecting two or more capacitors in series produces a circuit having lower capacitance than any of the individual capacitors. The effect of connecting capacitors in series is the same as increasing the distance between the plates of a single capacitor.
- 4-44 For example, Figure 4.4 is a diagram of a circuit with three  $10\ \mu\text{F}$  capacitors connected in series. The potential difference across the combination is divided into three equal parts. The charge on each capacitor is therefore only one third as high as it would be on one capacitor if it were connected into the circuit alone.

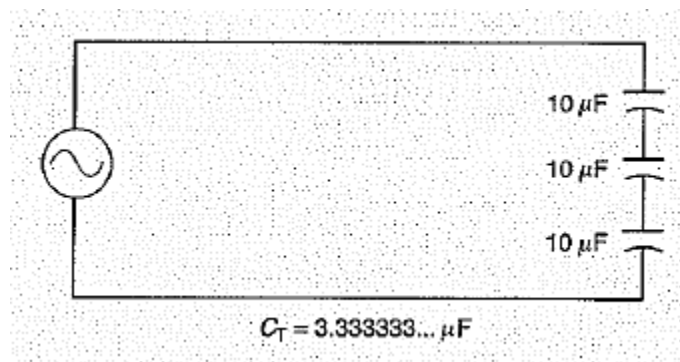


Figure 4.4: Capacitors in Series

- 4-45 The total charge on all three capacitors is the same as the charge on each one individually, because the source "sees" only the two outermost plates. Thus, the amount of charge per volt of potential difference across the combination is only one third as high as it would be if the circuit has only one  $10\ \mu\text{F}$  capacitor.

## Series Capacitors (continued)

4-46 It is very possible that you may need to calculate the total capacitance of capacitors connected in series. The equation to use where two or more capacitors are connected in series is similar to the equations used for resistors and inductors connected in parallel.

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

or

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

where  $C_T$  = Total capacitance

$C_1$  = Capacitance of the first capacitor

$C_2$  = Capacitance of the second capacitor

$C_3$  = Capacitance of the Third capacitor

$C_n$  = Capacitance of the  $n$ th capacitor

4-47 In the example shown in Fig. 4-4, the total capacitance in the circuit is calculated in the following way:

$$C_T = \frac{1}{\frac{1}{10} + \frac{1}{10} + \frac{1}{10}} = \frac{1}{0.3} = 3.333333\dots\mu\text{F}$$

## Parallel Capacitors

- 4-48 Connecting capacitors in parallel increases the total capacitance. All the positive plates are connected together, and all the negative plates are connected together. The effect is the same as increasing the size of both plates in one capacitor.
- 4-49 Figure 4.5 is a diagram of a circuit having three  $10\ \mu\text{F}$  capacitors connected in parallel. Their combined capacitance is  $30\ \mu\text{F}$ .

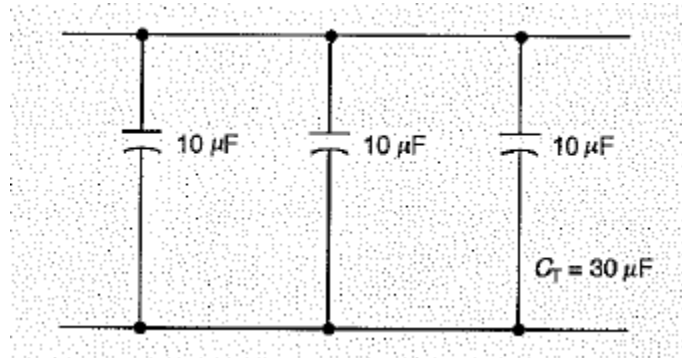


Figure 4.5: Capacitors in Parallel

- 4-50 The equation for calculating the capacitance of parallel capacitors is similar to the equations for resistors and inductors connected in series.



## Time Constants

4-51 The idea of the time constant for inductors is also useful in working with capacitors.

4-52 In Figure 4.6, you can see how the current decreases in a capacitor after a DC potential difference is suddenly applied. The current starts at a maximum value, which depends on how much resistance is in the circuit. As the capacitor charges, the current decreases. When the capacitor is fully charged, the current is zero. The capacitor then acts as an open circuit.

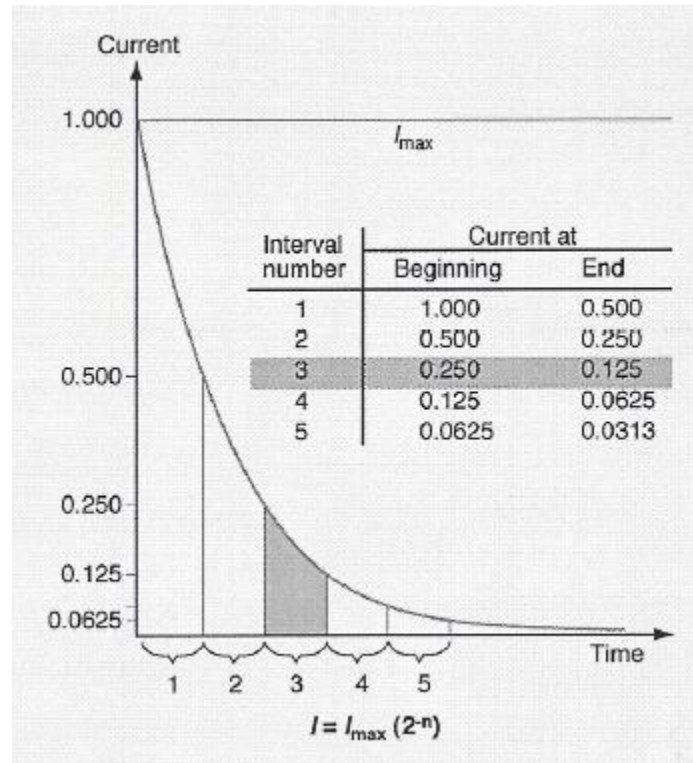


Figure 4.6: Current Decrease – Short Time Intervals

4-53 The graph of the current is an exponential curve. That is, during equal time intervals the current always drops to the same fraction of the value at the beginning of the interval.

4-54 For example, if you choose time intervals of the proper length, the current will always drop to half its value at the beginning of the interval.

- At the end of the first interval, the current has dropped to one half its value at the beginning.
- At the end of the second interval, the current has dropped by half again to one fourth the value at the start of the curve.
- At the end of the third interval, the current has dropped by half again to one eighth the starting value, and so on.

## Time Constants (continued)

- 4-55 The table in Figure 4.6 shows the values of the current at the beginning and end of the first five time intervals. The equation tells you how to calculate the current at the end of any time interval  $n$ . The 2 in the equation tells you the time intervals have been chosen so that the current always drops to one half ( $\frac{1}{2}$ , the reciprocal of two) the previous value during each interval.
- 4-56 Nature is a little more complicated than the equation in Figure 4.6 implies. Yet scientists and engineers like to write simple equations to describe capacitors. In order to do so, the time intervals must be made somewhat longer. The 2 in the equation must be replaced by the number 2.71828 which is the base of the natural logarithms. This number cannot be written exactly, just as the number  $\pi$  (3.14159...) cannot be written exactly. Therefore, it is represented by the letter  $e$  in equations.
- 4-57 Figure 4.7 is the same graph as the one shown in Figure 4.6. The time intervals have been made longer, so that during each interval the current drops to 0.368 times the value at the beginning of the interval. The number 0.368 is the reciprocal of  $e$ . Notice that the equation in Figure 4.7 is exactly like the equation in Figure 4.6, except that the 2 has been replaced by  $e$ .

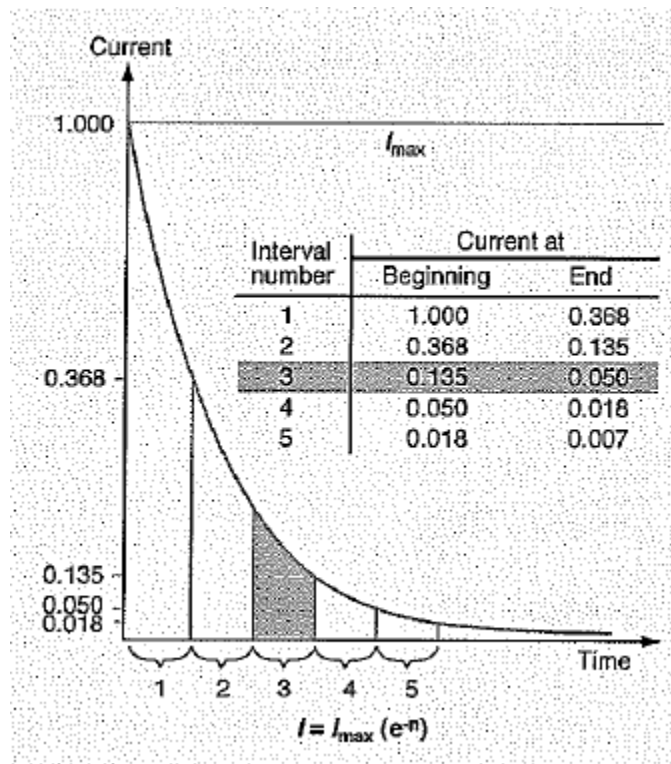


Figure 4.7: Exponential decrease – Standard Time-Constant Intervals

## Time Constants (continued)

4-58 The length of each time interval shown in Figure 4.7 is called the *time constant* of the capacitor. You can calculate its value by multiplying the capacitance in the circuit by the resistance in the circuit. The following equation describes this calculation.

$$T = RC$$

Where  $T$  = Time constant in seconds

$R$  = Resistance in the circuit in ohms

$C$  = Capacitance in the circuit in farads

4-59 For example, suppose the resistance in a circuit is  $200\ \Omega$  and the capacitance is  $25\ \mu\text{F}$ . The time constant for this circuit is 0.005 seconds, calculated in the following way.

$$T = RC = (200\ \Omega) \times (25 \times 10^{-6}\ \text{Farads}) = 5000 \times 10^{-6} = (5 \times 10^3) \times 10^{-6} = 5 \times 10^{-3} = 0.005\ \text{Seconds}$$

4-60 Thus, every 0.005 seconds as the capacitor charges, the current in this circuit will decrease to 36.8% of its value at the beginning of the interval. Within 0.025 seconds (five intervals), the current will have decreased to less than 1% (actually, 0.67%) of its initial value.

4-61 You can speed up the decrease by decreasing either the resistance or the capacitance, or both. You can slow down the decrease by increasing either the resistance or the capacitance, or both.

## Capacitive Reactance

4-62 If an AC potential difference is applied across a capacitor, the current depends on the frequency and on the capacitance.

- If the frequency is low and the capacitor has low capacitance (small plates), the capacitor carries very little current. It acts like an open circuit.
- If the frequency is high and the capacitor has high capacitance (large plates), the capacitor carries very high current. It acts like a short circuit.

4-63 For any combination of frequency and capacitance, the effect of the capacitor is similar to the effect of a resistor. At low frequency and low capacitance, the capacitor acts like a high resistance. At high frequency and high capacitance, the capacitor acts like a low resistance.

4-64 The effect of a capacitor on current is called *capacitive reactance*. It is similar to resistance and is measured in ohms. But the capacitor does not produce heat or consume electrical energy. In this respect, the capacitor is similar to an inductor. It controls the current in a circuit without wasting energy.

## Capacitive Reactance (continued)

4-65 The equation for calculating capacitive reactance is the following:

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

Where  $X_C$  = Capacitive reactance in ohms

$f$  = Frequency in Hertz

$C$  = Capacitance in farads

4-66 You can see from this equation that the value of  $X_C$  is high when the frequency and the capacitance are low. That is, the capacitor acts like an open circuit under these conditions. The value of  $X_C$  is low when the frequency and the capacitance are high. That is, the capacitor acts like a short circuit under these conditions.

4-67 As an example, suppose a circuit includes a capacitor having a capacitance of  $10 \mu\mu\text{F}$ . Suppose further that the circuit operates at a frequency of 2000 Hz. What is the reactance of the capacitor in this circuit?

4-68 To calculate the reactance of this capacitor, you start by using the equation for capacitive reactance.

$$\begin{aligned} X_C &= \frac{1}{2\pi fC} \\ &= \frac{1}{2 \times 3.14159 \times 2000 \times (10 \times 10^{-12})} \\ &= \frac{10^{+12}}{125,663.37} \\ &= 7.96 \times 10^{-6} \times 10^{+12} \\ &= 7.96 \times 10^{+6} \Omega \\ &= 7,960,000 \Omega \end{aligned}$$

4-69 For comparison, suppose another circuit includes a capacitor having a capacitance of  $25 \mu\text{F}$ . This circuit operates at a frequency of 50 Hz. What is the reactance of this capacitor in the circuit?

## Capacitive Reactance (continued)

4-70 To calculate the reactance, you use the same equation as before.

$$\begin{aligned}X_C &= \frac{1}{2\pi fC} \\&= \frac{1}{2 \times 3.14159 \times 50 \times (25 \times 10^{-6})} \\&= \frac{10^6}{7853.98} \\&= 1.2732 \times 10^{-4} \times 10^6 \\&= 1.2732 \times 10^2 \Omega \\&= 127.32 \Omega\end{aligned}$$

4-71 Notice that this large capacitor operating at low frequency has a low reactance. If the frequency were still lower—say, 1 Hz—the reactance would be higher (almost 7000  $\Omega$ ). Then the capacitor would behave less like a short circuit.

## Phase Angle

- 4-72 To calculate the phase angle in a capacitive circuit, you start by sketching a vector diagram with the capacitive reactance directed downward and the resistance directed toward the right. Figure 4.8 is an example of such a vector diagram.

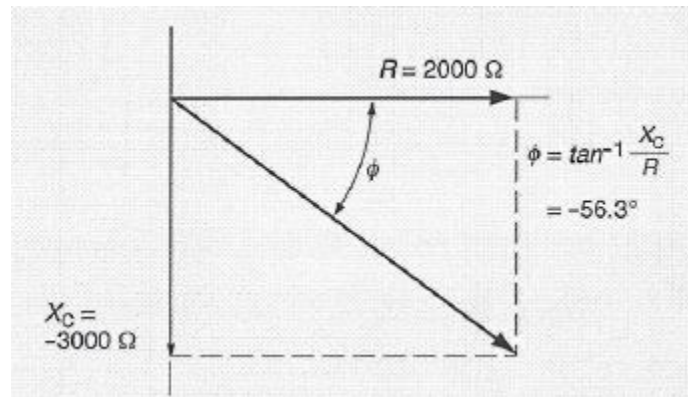


Figure 4.8: Vectors for Capacitance AC Circuits

- 4-73 Next, find the angle that has a tangent equal to the ratio of the reactance to the resistance. If the circuit includes no inductor, the ratio will be negative because the capacitive reactance is negative. The negative tangent indicates that the phase angle is negative.

- 4-74 The vector diagram in Figure 4.8 indicates a phase angle of  $-56.3^\circ$ . It is calculated in the following way:

$$\phi = \tan^{-1} \frac{X_C}{R} = \tan^{-1} \frac{-3000 \Omega}{2000 \Omega} = \tan^{-1} -1.5 = -56.3^\circ$$

- 4-75 As another example, suppose the capacitive reactance shown in Figure 4.8 is only  $1000 \Omega$ . What is the phase angle between the potential difference and the current in this circuit?

$$\phi = \tan^{-1} \frac{X_C}{R} = \tan^{-1} \frac{-1000 \Omega}{2000 \Omega} = \tan^{-1} -0.5 = -26.6^\circ$$

## Phase Angle (continued)

4-74 A negative angle indicates that the current leads the potential difference as seen in Figure 4.9. In a circuit having no resistance, the phase angle will be  $90^\circ$  which means the current leads the potential difference by one fourth of a cycle.

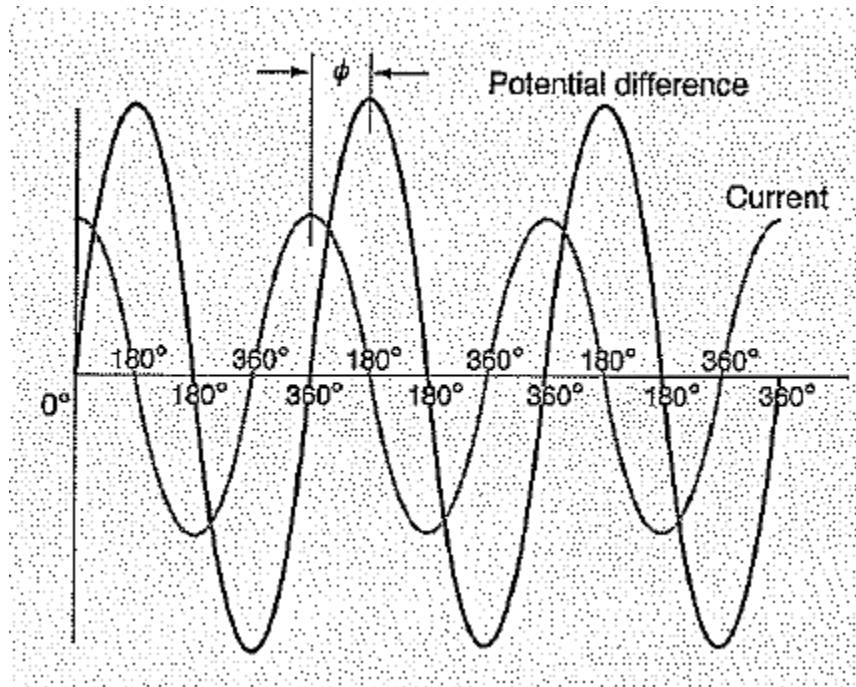


Figure 4.9: Waveforms in Capacitive AC Circuits

## Chapter 4 Exercise

Circle the appropriate letter next to the correct answer.

1. If a charged capacitor is removed from a circuit, the capacitor \_\_\_\_\_ its charge.
  - a. Loses all of
  - b. Loses most of
  - c. Loses some of
  - d. Retains
  
2. A capacitor acts like an open circuit in a(n) \_\_\_\_\_ circuit.
  - a. AC
  - b. DC
  - c. Parallel
  - d. Series
  
3. The amount of charge stored in a capacitor at a given potential difference is *not* affected by the \_\_\_\_\_.
  - a. Ambient temperature
  - b. Area of the plates
  - c. Distance between the plates
  - d. Materials used
  
4. The simplest kind of capacitor uses \_\_\_\_\_ as the dielectric.
  - a. Air
  - b. Ceramic
  - c. Mica
  - d. Paper
  
5. You should never connect an electrolytic capacitor \_\_\_\_\_.
  - a. Across a DC line
  - b. Across an AC line
  - c. With the common terminal negative
  - d. With the common terminal positive



## Chapter 4 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. If no potential difference is indicated, a capacitor is rated for a maximum of \_\_\_\_\_ Volts.
- a. 250
  - b. 500
  - c. 1000
  - d. 2000
7. A capacitor should be discharged through (a) \_\_\_\_\_.
- a. Any piece of metal
  - b. Pair of pliers
  - c. Resistor
  - d. Screwdriver
8. Connecting two or more capacitors in series produces a combined capacitance that is \_\_\_\_\_.
- a. Double the individual capacitances
  - b. Equal to the highest capacitance
  - c. Greater than the highest capacitance
  - d. Lower than the lowest capacitance
9. Connecting capacitors in parallel produces the same effect as increasing the \_\_\_\_\_.
- a. Amount of dielectric
  - b. Circuit resistance
  - c. Distance between the plates
  - d. Size of the plates
10. If an AC potential difference is applied across a capacitor, the resulting current depends on the \_\_\_\_\_.
- a. Area of the plates
  - b. Distance between the plates
  - c. Frequency and capacitance
  - d. Kind of dielectric material

## Summary

The capacitor is a component widely used in electric circuits. It consists of two conducting plates separated by a dielectric material which serves as an insulator between the plates.

The larger the capacitor, the greater the charge retained after it is disconnected from the power source. For this reason, you should be careful not to touch the capacitor until it has been completely discharged. To discharge the capacitor, you should bleed it through a resistor of 1000 watts or more. Large capacitors have permanently attached bleeder resistors for this purpose.

There are several ways to change capacitance in a circuit. Increasing the area of the plates increases the capacitance as does connecting capacitors in parallel. To decrease capacitance, you can increase the separation between the plates or connect capacitors in series.

Capacitors are named according to the type of dielectric material used. Common dielectrics are air, mica, paper, oil, and ceramic materials.

# Chapter 5: Impedance

## In this Chapter

Impedance in Series

Resonance in Series Circuits

Phase Angles

Impedance in Parallel Circuits

## Objectives

After completing this chapter, you should be able to:

- State the definition of impedance.
- Explain how to calculate the impedance in a series AC circuit.
- Demonstrate how to find the value of a phase angle for a circuit.
- Explain how to calculate the impedance in a parallel circuit.

## Terminology

**Impedance:** The combined effect of resistors, inductors, and capacitors in an AC circuit

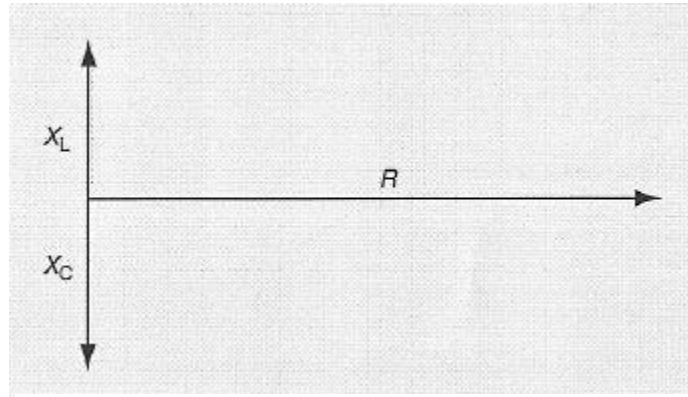
**Resonance:** A condition in an AC circuit in which the inductive reactance and the capacitive reactance are equal.

Chapters Three and Four explained the ideas of inductive reactance and capacitive reactance. They explained how each kind of reactance combines with resistance to restrict the current in an AC circuit. This Chapter explains these combined effects—called impedance—in both series and parallel circuits.

The Pythagorean theorem and Ohm's law are important in calculating impedance in a circuit. This lesson includes problems that provide the opportunity to practice finding values of resistance, inductance, and capacitance. Phase angles and resonance in AC circuits are also explained.

## Impedance in Series Circuits

- 5-1 The combined effect of resistors, inductors, and capacitors in restricting the current in an AC circuit is called *impedance*. The word *impede* means "to interfere with" the progress of something. In an AC circuit, the resistors, inductors, and capacitors interfere with the current in the circuit. Therefore, their combined interference is called impedance. The symbol for impedance is  $Z$ .
- 5-2 To calculate impedance in a series ac circuit, you must perform a *vector addition* of the three components. In a vector diagram, the inductive reactance ( $X_L$ ) is directed upward, the capacitive reactance ( $X_C$ ) is directed downward, and the resistance ( $R$ ) is directed toward the right. These three directions are shown in Figure 5.1.



**Figure 5.1: Vectors for Calculating Impedance**

- 5-3 To find the impedance of the circuit, you can use either the Pythagorean theorem or a scale drawing. In either case, you first add the vectors for the two reactances. The vector sum is the difference between the two values, because they have opposite directions. Then, you combine the total reactance with the resistance to find the impedance in the circuit.
- 5-4 All AC circuits are solved in the same way.
- You always start by drawing a vector diagram, with the three arrows pointing in the direction shown in Figure 5.1.
  - Next, you always add the inductive reactance and the capacitive reactance (by vector addition) to find the total reactance.
  - Finally, you always add the total reactance and the resistance (also by vector addition) to find the impedance in the circuit.

## Impedance in Series Circuits (continued)

5-5 For example, suppose you need to find the RMS current in the circuit shown in Figure 5.2. You can calculate the current by first calculating the impedance, and then applying Ohm's law. The following paragraphs explain the calculations.

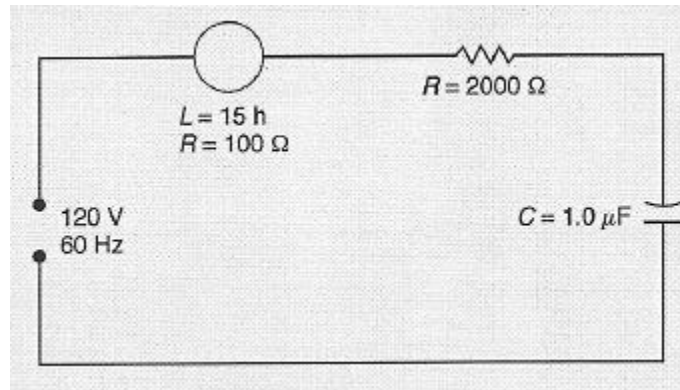


Figure 5.2: Series AC Circuit

5-6 To begin, you must sketch the vector diagram, as shown in Figure 5.3. You do not need to sketch the vectors to scale, but you should draw them in the right directions.

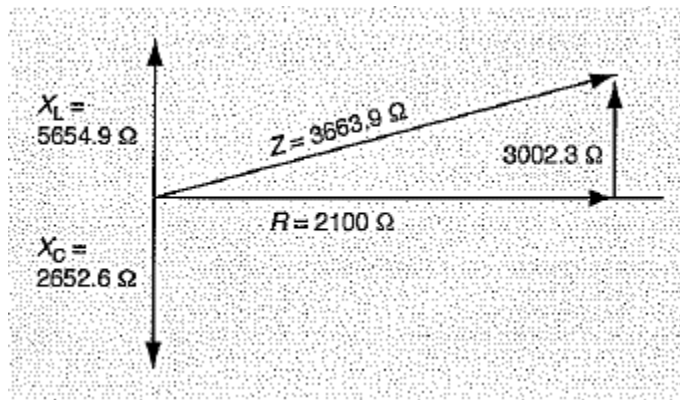


Figure 5.3: Vector Diagram for a Series AC Circuit

5-7 Next, you calculate the inductive reactance and the capacitive reactance, and combine them to find the total reactance.

$$X_L = 2\pi fL = 5654.9 \Omega$$

$$X_C = \frac{1}{2\pi fC} = 2652.6 \Omega$$

$$X_L + X_C = 5654.9 \Omega - 2652.6 \Omega = 3002.3 \Omega$$

## Impedance in Series Circuits (continued)

5-8 You can now use the Pythagorean theorem to calculate the impedance of the circuit.

$$Z = +\sqrt{X^2 + R^2} = \sqrt{3002.3^2 + 2100^2} = 3663.9 \Omega$$

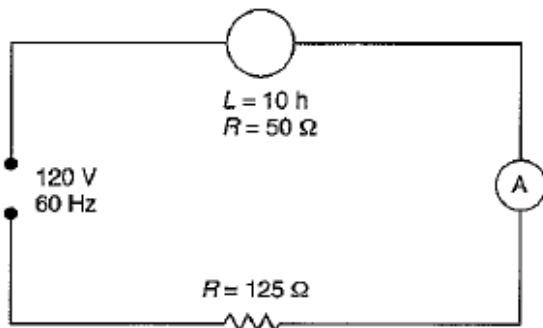
5-9 Finally, you can calculate the current from Ohm's law.

$$I = \frac{E}{Z} = \frac{120V}{3663.9 \Omega} = 0.033 \text{ A RMS}$$

5-10 The problems on this page and on the next page are intended to give you practice in calculating the impedance of circuits. In each problem, examine the circuit diagram and find what values of resistance, inductance, and capacitance are included. Then, calculate the reactances and use vector addition to find the impedance of the circuit. Finally, use Ohm's law to calculate the current indicated by the ammeters shown in the circuits.

5-11 Use the blank area next to each diagram for your sketches and calculations. Write your answers in the spaces provided below each problem. Check your answers on page 88 of this chapter.

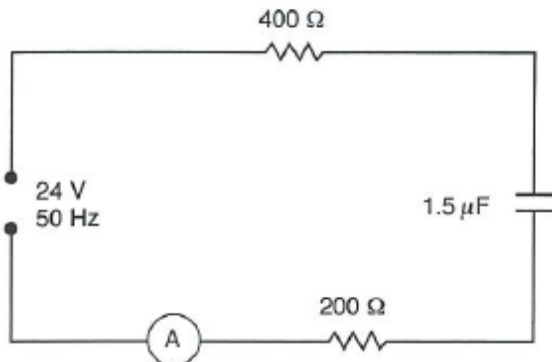
### Problem 5-1



$Z =$  \_\_\_\_\_

$I =$  \_\_\_\_\_

### Problem 5-2

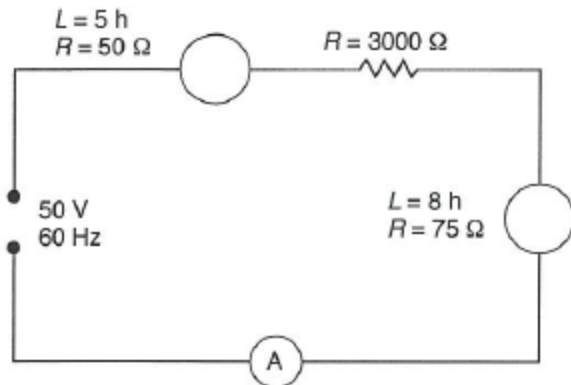


$Z =$  \_\_\_\_\_

$I =$  \_\_\_\_\_

## Impedance in Series Circuits (continued)

### Problem 5-3



$Z =$  \_\_\_\_\_

$I =$  \_\_\_\_\_

## Phase Angles

5-12 Your vector diagram is the basis for calculating the value of the phase angle and for determining whether the current leads or lags the potential difference.

- The phase angle is positive when the impedance vector is above the horizontal. A positive phase angle tells you the current lags the potential difference.
- The phase angle is negative when the impedance vector is below the horizontal. A negative phase angle tells you the current leads the potential difference.

5-13 To calculate the value of the phase angle, you find the angle whose tangent equals the total reactance divided by the resistance in the circuit. You can use either a scientific calculator or a trigonometry table for finding the angle. A calculator is usually faster and more accurate.

## Phase Angles (continued)

- 5-14 As an example, suppose you need to find the phase angle for the circuit shown in Figure 5.4. The vector diagram is the basis for the calculation. You can see from the vector diagram that the phase angle is positive, because the inductive reactance is greater than the capacitive reactance. Their vector sum is positive.

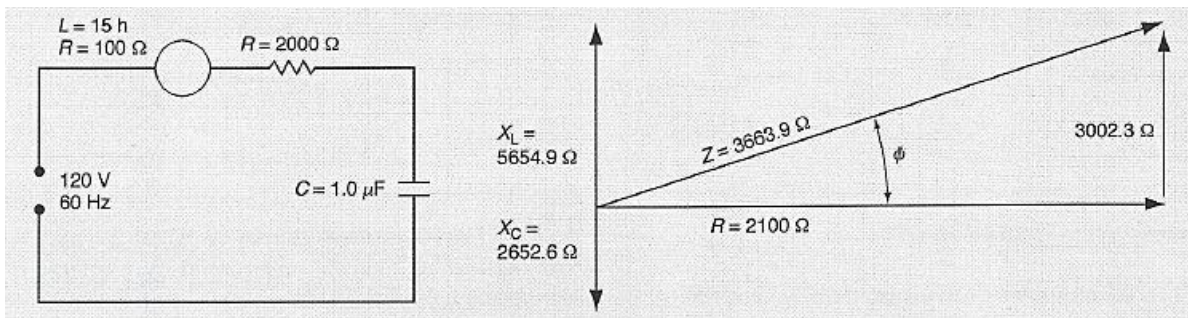


Figure 5.4: Series AC Circuit and Vector Diagram

- 5-15 To find the value of the phase angle, you divide the total reactance by the resistance in the circuit.

$$\phi = \tan^{-1} \frac{\text{reactance}}{\text{resistance}} = \tan^{-1} \frac{3002.3 \Omega}{2100 \Omega} = \tan^{-1} 1.42967 = 55.0^\circ$$

- 5-16 Use the same vector diagrams you drew in calculating the impedances to calculate the phase angles for the problems on pages 86 and 87. Write your answers in the spaces provided below. Use an "X" to indicate whether the current leads or lags the potential difference. Then, check your answers on page 82.

Problem	Phase Angle	Check whether Lead or Lag
5-1	_____	_____
5-2	_____	_____
5-3	_____	_____

- 5-17 The potential difference across any single component in an ac series circuit equals the product of the current in the component and the impedance of that component alone. If the circuit consists of a pure inductor (having no resistance), a pure capacitor, and a resistor, the potential difference across the circuit as a whole equals the vector sum of the potential differences across the components.



## Phase Angles (continued)

5-18 Figure 5.5 shows an example of such a circuit. This circuit is the same as the one shown in Figure 5.2, except that the coil has no resistance and the resistor has a resistance of  $2100\ \Omega$ . The vector sum of the potential differences is shown at the right of the diagram.

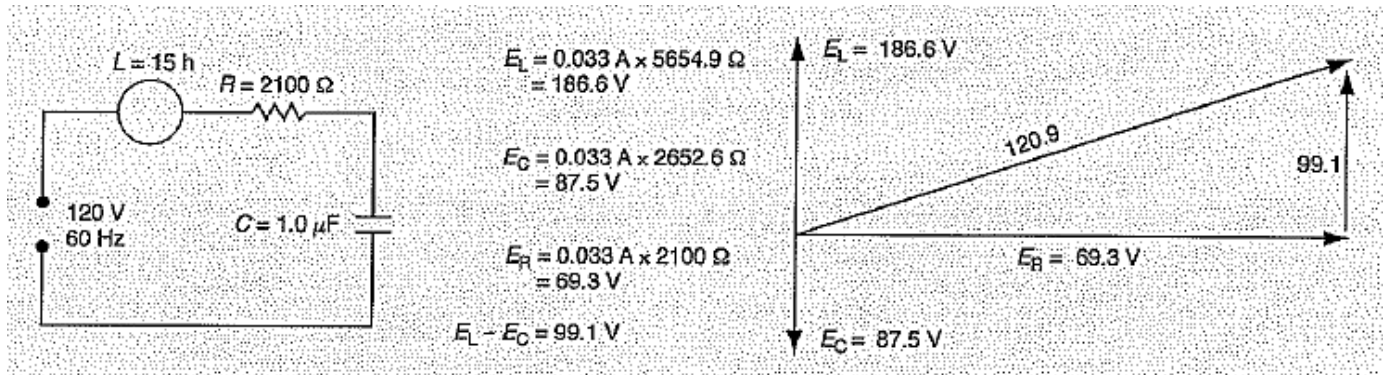


Figure 5.5: Vector Diagram for Calculating Potential Differences

- 5-19 Physically, the resultant must equal the potential difference applied to the circuit. In this example, the mathematical resultant is slightly higher (by 0.9 V) because of the combined effects of rounding off during the solution of the original problem and during this vector addition.
- 5-20 Notice that the potential difference across the coil is much higher than the applied potential difference. You may think this result makes no sense physically, but it does. If you were to measure the ac potential difference across the coil, you would find that the value actually is almost 190 V RMS. This effect can occur in any AC circuit that includes both an inductor and a capacitor.

### WARNING

**Be careful when working on AC circuits that contain both inductors and capacitors, especially if the resistance is low. The potential difference across an inductor capacitor can greatly exceed the potential difference of the source. If you touch a terminal in such a circuit, you can receive a severe shock, even with the power disconnected.**

## Resonance in Series Circuits

- 5-21 In any series circuit containing both inductance and capacitance, the current is greatest when  $X_L$  and  $X_C$  are equal. In a vector diagram, the two reactances balance each other, and the impedance ( $Z$ ) equals the resistance. In a circuit where the reactances are unequal, the impedance is greater than the resistance, and the current is lower.
- 5-22 If  $X_L$  and  $X_C$  are equal, then  $E_L$  and  $E_C$  are also equal. The circuit is then said to be *at resonance*.
- 5-23 Figure 5.6 is an example of a series circuit at resonance. The calculations on the following page illustrate the conditions in this circuit. Notice that the potential differences across the inductor and the capacitor are much higher than the potential difference across the circuit as a whole.

$$X_L = 2\pi fL = 2 \times 3.14159 \times 60 \times 0.352 = 132.7 \Omega$$

$$X_C = \frac{1}{2\pi fC} = \frac{10^6}{2 \times 3.14159 \times 60 \times 20} = 132.63 \Omega$$

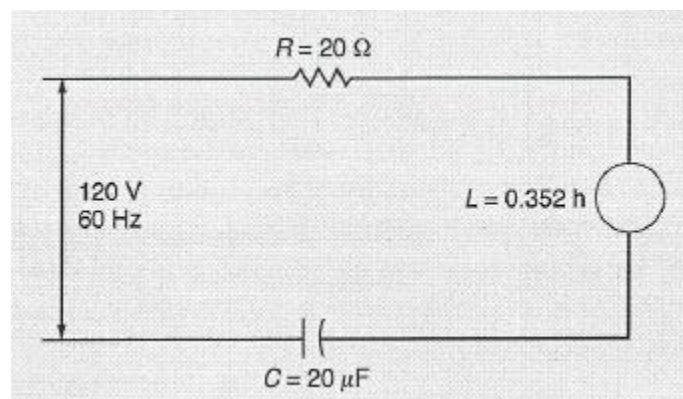
$$Z = \sqrt{(X_L + X_C)^2 + R^2} = 20 \Omega$$

$$I = \frac{E}{Z} = \frac{120 \text{ V}}{20 \Omega} = 6 \text{ A RMS}$$

$$E_L = I \times X_L = 6 \times 132.70 = 796.2 \text{ V RMS}$$

$$E_C = I \times X_C = 6 \times 132.63 = 795.8 \text{ V RMS}$$

- 5-24 The slight differences between  $X_L$  and  $X_C$ , and between  $E_L$  and  $E_C$ , are caused by rounding off during the calculations. In practice, you can consider the values equal on both pairs.



**Figure 5.6: Series Resonant Circuit**

- 5-25 You should realize that this circuit is at resonance only at a frequency of 60 Hz. The same circuit would not be at resonance if it were operated at 50 Hz or at any other frequency. The reason is that both  $X_L$  and  $X_C$  change when the frequency changes. One value increases while the other decreases. In any ac circuit, there is only one frequency at which the two values are equal. This frequency is called the resonant frequency.

## Impedance in Parallel Circuits

- 5-26 Series circuits are not practical for operating equipment in a plant. Adding a load changes the potential difference across every other load in the circuit. The change in potential difference changes the current in each load, thus changing the output of the load. If you were to compensate by changing the potential difference across the circuit, you would need to make a change every time someone started a machine, turned on a lamp, or added any other device to the circuit.
- 5-27 The parallel circuit is much more practical. Adding a load does not affect the potential difference or the current in any other load. The only limitation is the system's ability to carry enough current for all the equipment.
- 5-28 Vector diagrams are very useful in solving parallel ac circuit problems. In solving these problems, you use the vector diagram to represent the current in the circuit, rather than the impedance or the potential difference.
- 5-29 As an example, suppose you need to find the current in the circuit shown in Figure 5.7. You start by finding the inductive reactance ( $X_L$ ) and the current in each branch.

$$X_L = 2\pi fl = 2 \times 3.14159 \times 60 \times 0.08 = 30.16 \Omega$$

- 5-30 You can then use this value in Ohm's law to calculate the current in the inductive branch, as shown below:

$$I_L = \frac{E}{X_L} = \frac{120 V}{30.16 \Omega} = 3.98 A$$

- 5-31 You can also use Ohm's law to calculate the current in the resistive branch.

$$I_R = \frac{E}{R} = \frac{120 V}{40 \Omega} = 3.0 A$$

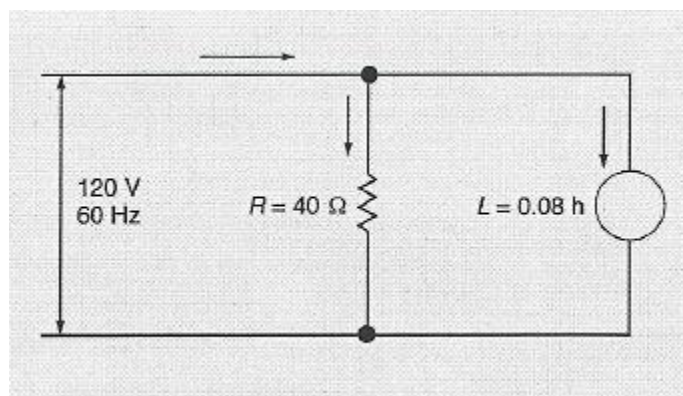


Figure 5.6: Series Resonant Circuit

## Impedance in Parallel Circuits (continued)

5-32 The two calculations shown in paragraphs 5-30 and 5-31 provide the basis for constructing the vector diagram shown in Figure 5.8. For a parallel circuit, the vector for the current in the resistor is drawn horizontally. The vector for the current in the inductor is drawn vertically upward. The resultant of these two vectors is the total current in the circuit. You can use the Pythagorean theorem to calculate the resultant vector, which represents the current in the circuit as a whole.

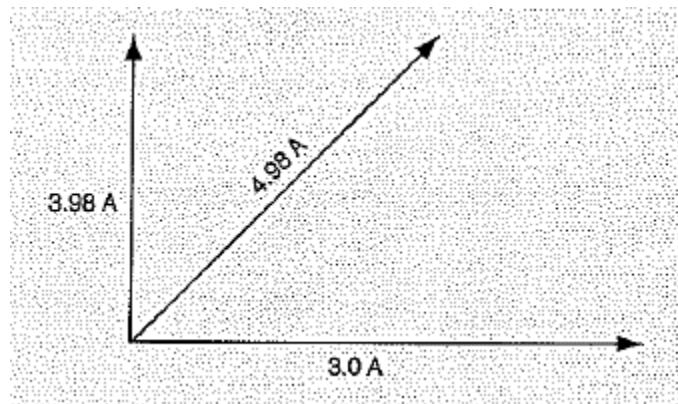


Figure 5.8: Vector Diagram for a Circuit without Capacitance

$$I = \sqrt{I_L^2 + I_R^2} = \sqrt{3.98^2 + 3^2} = 4.98 \text{ A}$$

5-33 From the current and the potential difference applied to the circuit, you can calculate the circuit's impedance by applying Ohm's law. The impedance for the circuit in this example is  $24.1 \Omega$  and is calculated as follows:

$$Z = \frac{E}{I} = \frac{120 \text{ V}}{4.98 \text{ A}} = 24.1 \Omega$$

Notice that the impedance of this parallel circuit is lower than either the resistance or the reactance in the circuit, just as in a circuit consisting of parallel resistors.

- 5-34 All circuits that include *either* inductance or capacitance, in parallel with resistance, have an impedance lower than any of the values on the parallel branches. But if a circuit includes *both* inductance and capacitance, the circuit's impedance may be higher than on any branch, because the inductance and capacitance have opposite effects.
- 5-35 The current in the resistor is in phase with the potential difference of the source. The current in the inductor lags the potential difference of the source by  $90^\circ$ . The overall current in the circuit lags the applied potential difference by an amount somewhere between  $0$  and  $90^\circ$ .

## Impedance in Parallel Circuits (continued)

5-36 You can calculate the exact phase angle by trigonometry. The ratio of the current in the inductor ( $I_L$ ) to the current in the resistor ( $I_R$ ) equals the tangent of the phase angle ( $\phi$ ). In this example, the phase angle is  $53^\circ$ .

$$\phi = \tan^{-1} \frac{3.98}{3} = \tan^{-1} 1.3267 = 52.992^\circ$$

Just as in the vector diagrams described earlier, the fact that the angle is positive indicates that the current lags the potential difference.

5-37 If the circuit contains a capacitor in parallel with either a resistor or an inductor, or both, you use the same basic method to calculate the current in the circuit. The only difference is that the vector for the current in the capacitor is directed vertically downward.

5-38 For example, suppose you need to calculate the current in the circuit shown in Figure 5.9 on the following page.

- You begin by calculating the reactances of the inductor and the capacitor.
- Then, you calculate the current in each one using Ohm's law.
- Next, you calculate the current in the resistor using Ohm's law.
- Finally, you sketch a vector diagram and add all three currents by vector addition.

$$X_L = 2\pi fL = 2 \times 3.14159 \times 60 \text{ Hz} \times 0.8 \text{ h} = 30.16 \Omega$$

$$I_L = \frac{E}{X_L} = \frac{120 \text{ V}}{301.6 \Omega} = 0.398 \text{ A RMS}$$

$$X_C = \frac{1}{2\pi fC} = \frac{1}{2 \times 3.14159 \times 60 \times 4.5 \times 10^{-6}} = \frac{10^6}{1696.46} = 589.46 \Omega$$

$$I_C = \frac{120 \text{ V}}{589.46 \Omega} = 0.204 \text{ A RMS}$$

$$I_R = \frac{120 \text{ V}}{400 \Omega} = 0.300 \text{ A RMS}$$

$$I = \sqrt{(I_L + I_C)^2 + I_R^2} = \sqrt{(0.398 + 0.204)^2 + 0.300^2} = \sqrt{0.194^2 + 0.300^2} = 0.357 \text{ A RMS}$$

## Impedance in Parallel Circuits (continued)

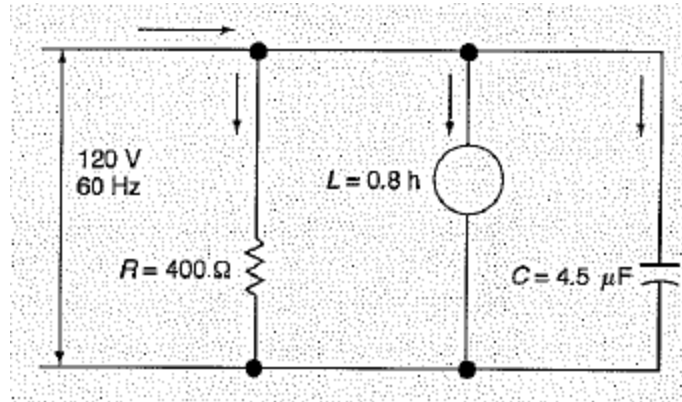


Figure 5.9: Vector Diagram for a Circuit with Capacitance

5-39 The following steps show these calculations. The vector diagram is shown in Figure 5.10.

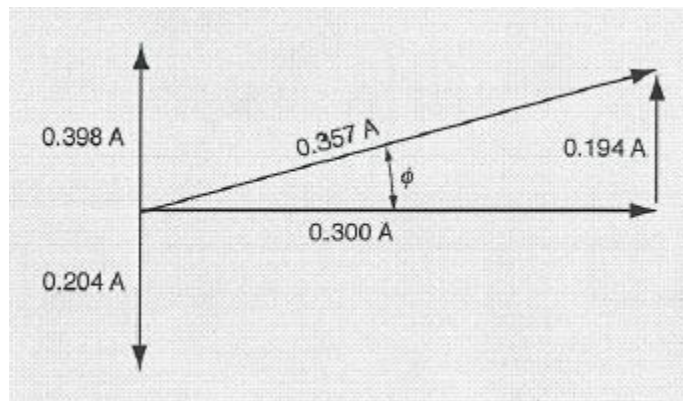


Figure 5.10: Vector Diagram for a Circuit with Capacitance

5-40 You can use the same vector diagram to calculate the phase angle for this circuit. The tangent of the phase angle equals the vector sum of the currents in the inductor and capacitor divided by the current in the resistor.

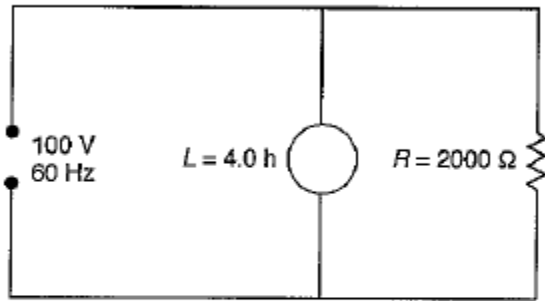
$$\phi = \tan^{-1} \frac{I_L + I_C}{I_R} = \tan^{-1} \frac{0.194}{0.300} = 32.89^\circ$$

The fact that the angle is positive tells you that the current lags the potential difference.

5-41 The problems on the following page are intended to give you practice in solving parallel-circuit problems. For each problem, calculate the current in the circuit, the impedance of the circuit, and the phase angle. Tell whether the current leads or lags the potential difference. Do your work in the blank area next to the problem and write your answers in the spaces provided. Then check your answers on page 80 of this Chapter.

## Impedance in Parallel Circuits (continued)

### Problem 5-4



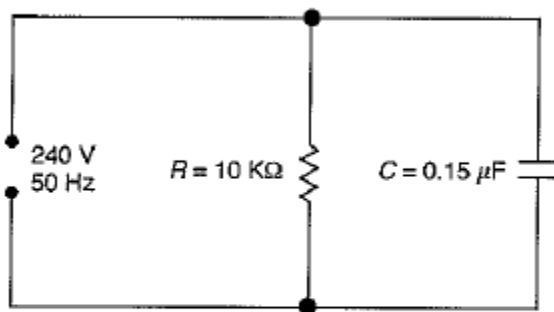
$Z =$  \_\_\_\_\_

$I =$  \_\_\_\_\_

$\phi =$  \_\_\_\_\_

Lead or lag? \_\_\_\_\_

### Problem 5-5



$Z =$  \_\_\_\_\_

$I =$  \_\_\_\_\_

$\phi =$  \_\_\_\_\_

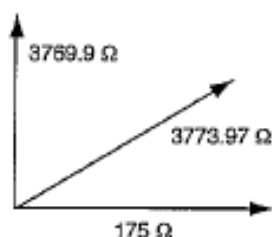
Lead or lag? \_\_\_\_\_

### Answers to Problems 5-1—Page 70

$$X_L = 2\pi fL = 3769.9 \Omega \quad R = 175 \Omega$$

$$Z = \sqrt{X_L^2 + R^2} = 3773.96 \Omega$$

$$I = \frac{E}{Z} = \frac{120 \text{ V}}{3773.96 \Omega} = 0.0318 \text{ A}$$

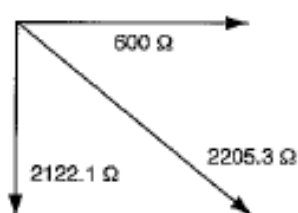


### Answers to Problem 5-2—Page 71

$$X_C = \frac{1}{2\pi fC} = 2122.1 \Omega \quad R = 600 \Omega$$

$$Z = \sqrt{X_C^2 + R^2} = 2205.3 \Omega$$

$$I = \frac{E}{Z} = \frac{24 \text{ V}}{2205.3 \Omega} = 0.0109 \text{ A}$$



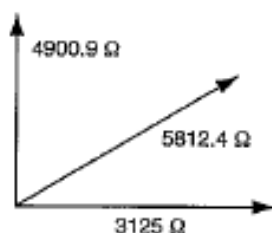
### Answers to Problem 5-3—Page 71

$$L = 5\text{h} + 8\text{h} = 13\text{h} \quad X_L = 2\pi fL = 4900.9 \Omega$$

$$R = 3125 \Omega$$

$$Z = \sqrt{X_L^2 + R^2} = 5812.4 \Omega$$

$$I = \frac{E}{Z} = \frac{50 \text{ V}}{5812.4 \Omega} = 0.0086 \text{ A}$$



### Answers to Problems 5-4—Page 78

$$X_L = 2\pi fL = 1507.96 \Omega$$

$$I_L = \frac{100}{1507.96} = 0.0663 \text{ A}$$

$$I_R = \frac{100}{2000} = 0.05 \text{ A}$$

$$I = \sqrt{(I_L)^2 + I_R^2} = 0.083 \text{ A}$$

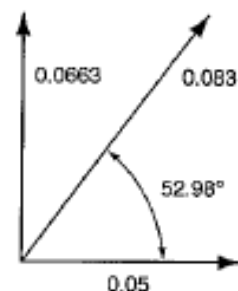
$$Z = \frac{E}{I} = 1204.8 \Omega$$

$$\phi = \tan^{-1} \frac{I_L}{I_R}$$

$$= \tan^{-1} 1.326$$

$$= 52.98^\circ$$

Current *lags* potential difference.



### Answers to Problems 5-5—Page 78

$$X_C = \frac{1}{2\pi fC} = 21,221 \Omega$$

$$I_C = \frac{240}{21,221} = 0.0113 \text{ A}$$

$$I_R = \frac{240}{10 \text{ k}\Omega} = 0.024 \text{ A}$$

$$I = \sqrt{(I_L) + I_C^2 + I_R^2} = 0.0265 \text{ A}$$

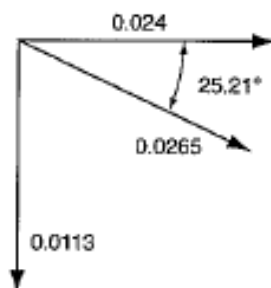
$$Z = \frac{E}{I} = 9056.6 \Omega$$

$$\phi = \tan^{-1} \frac{I_L + I_C}{I_R}$$

$$= \tan^{-1} -0.47083$$

$$= -25.21^\circ$$

Current *leads* potential difference.





## Chapter 5 Exercise

Circle the appropriate letter next to the correct answer.

1. Impedance in an AC circuit is the combined effect of inductors, capacitors and \_\_\_\_\_.
  - a. Rectifiers
  - b. Relays
  - c. Resistors
  - d. Rheostats
  
2. The symbol for inductive reactance is \_\_\_\_\_.
  - a.  $R$
  - b.  $X_C$
  - c.  $X_L$
  - d.  $Z$
  
3. The total reactance in an AC circuit equals \_\_\_\_\_.
  - a. Reactance plus the resistance
  - b. Sum of the capacitive reactance and the resistance
  - c. Vector sum of the resistance and the reactance
  - d. Vector Sum of the two reactances
  
4. If  $X_L$  is  $4000\ \Omega$  and  $X_C$  is  $2000\ \Omega$ , what is the total reactance?
  - a.  $2000\ \Omega$
  - b.  $4000\ \Omega$
  - c.  $4472\ \Omega$
  - d.  $6000\ \Omega$
  
5. When the phase angle in a vector diagram is positive, it means the current \_\_\_\_\_ the potential difference.
  - a. Is greater than
  - b. Is in phase with
  - c. Lags
  - d. leads

## Chapter 5 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. To find the value of the phase angle, you divide which of the following values by the resistance in the circuit?
- a. Capacitive reactance
  - b. Impedance
  - c. Inductive reactance
  - d. Total reactance
7. In any series circuit containing both inductance and capacitance, the current is greatest when \_\_\_\_\_.
- a.  $X_C$  is greater
  - b.  $X_L$  is greater
  - c.  $X_L$  and  $X_C$  are equal
  - d.  $X_L$  and  $R$  are equal
8. When using vector diagrams in solving parallel AC circuit problems, use the vectors to represent \_\_\_\_\_.
- a. Capacitance
  - b. Current
  - c. Impedance
  - d. Potential difference
9. In a vector diagram for a parallel circuit, the vector for the current in the resistor is drawn \_\_\_\_\_.
- a. Diagonally
  - b. Horizontally
  - c. Vertically downward
  - d. Vertically upward
10. In a diagram for a parallel ac circuit, the vector that is drawn vertically downward represents the current in the \_\_\_\_\_.
- a. Capacitor
  - b. Inductor
  - c. Resistor
  - d. Total circuit

## Answers to Problems on Page 88

Problem	Phase Angle	Check whether Lead or Lag	
5-1	<u>87.3°</u>	<u>          </u>	<u>  X  </u>
5-2	<u>74.2°</u>	<u>  X  </u>	<u>          </u>
5-3	<u>57.5°</u>	<u>          </u>	<u>  X  </u>

## Summary

Most AC circuits have some resistance, inductance and capacitance. The combined effect of these is restricting the current in an AC circuit and is called impedance.

To find impedance in a series AC circuit, you start by drawing a vector diagram, then add the inductive reactance and the capacitive reactance, by vector addition, to find the total reactance. Finally, you calculate the impedance in the circuit by adding the total reactance and the resistance.

The vector diagram is also used for determining whether the phase angle is positive or negative. The phase angle is positive when the impedance vector is above the horizontal. This means the current lags the potential difference. The phase angle is negative when the impedance vector lies below the horizontal. A negative phase angle means the current leads the potential difference. To find the value if the phase angle, the total reactance is divided by the resistance in the circuit.

Vector diagrams are also used for calculating impedance in parallel circuits. However, the vector diagram is used to calculate tie current in the circuit rather than the impedance or the potential difference.



# Chapter 6: Power and Energy in AC Circuits

## In this Chapter

Work and Energy

Power

Power in Resistive Circuits

Power in Inductive Circuits

Power in Capacitive Circuits

Importance of the Power Factor

Power Factor Correction

Power Capacitors

Capacitor Installation

## Objectives

After completing this chapter, you should be able to:

- State the definition of Power.
- Demonstrate how to calculate power in an inductive circuit.
- State the reason why capacitors are added to circuits to increase the power factor.
- Explain how to install capacitors correctly.

## Terminology

**Mechanical work:** The force on an object multiplied by the distance the object moves in the direction of the force

**Potential difference:** The difference in electrical potential energy per unit of charge between two points

**Power:** The rate of doing work

**Power factor:** The ratio between the effective power and the RMS power in a circuit

Power in an AC circuit is the product of the potential difference and the current in the circuit. But this product alone does not represent real power. The power factor determines how much power is actually available to the plant.

The amount of power produced in an AC circuit varies depending on how much resistance, capacitance, and inductance the circuit contains. This lesson explains how to correct and control resistance, capacitance, and inductance in AC circuits.

Capacitors are often used to achieve the required power factor, but they must be installed correctly to be effective. You will study how to select, install, and maintain capacitors to get maximum results and service life.

## Work and Energy

- 6-1 The idea of energy is closely related to the idea of *mechanical work*. Mechanical work is defined as the force exerted on an object multiplied by the distance the object moves.
- 6-2 For example, suppose a lift truck raises a crate against the force of gravity. The lift truck does work as it raises the crate. If the gravitational field exerts a force of 500 pounds on the crate, and the lift truck raises it 10 feet against this force, it does 5000 ft-lb of work on the crate. The crate gains 5000 ft-lb of gravitational potential energy in the process.
- 6-3 If the lift truck then lowers the crate back to the starting point, the crate does 5000 ft-lb of work on the lift truck. It loses 5000 ft-lb of gravitational potential energy as it does so.
- 6-4 In the metric system, force is measured in *newtons* and distance is measured in *meters*. Therefore, mechanical work is measured in newton-meters. Any gain or loss of potential energy is also measured in *newton-meters*. For convenience, 1 newton-meter is called 1 *joule*.
- 6-5 The definition of mechanical work forms the basis for many different ideas that share the name "energy." Electrical energy is one example. Electrical energy is defined in terms of the work done in moving a charged particle against the force exerted on it by an electric field.
- 6-6 The electric field exerts a force that depends on the electric charge of the particle. If something moves the particle against this force, the particle gains electrical potential energy. The amount of gain equals the amount of force multiplied by the distance the particle moves.
- 6-7 The amount of electrical potential energy gained or lost by the particle depends in part on the charge of the particle. If the charge doubles, the amount of energy gained or lost doubles. But the energy per unit of charge remains constant.
- 6-8 The difference in energy per unit of charge from one point to another is called the *potential difference* between the two points. It is determined by the strength of the electric field and the distance between the two points, but not by the amount of charge on the moving particle.
- 6-9 If the energy gained or lost is measured in *joules*, and the charge is measured in *coulombs*, the potential difference is measured in *joules per coulomb*. For convenience, 1 joule per coulomb is called 1 volt (V).
- 6-10 If a great many charged particles move from one point to another, the amount of energy gained or lost depends on the total amount of charge carried by all the particles. The total amount of charge depends on how much charge each particle has and on how many of them go from one point to the other during the time they are allowed to move.

## Work and Energy (continued)

6-11 To say it another way, the total charge depends on two factors:

- the current (how much charge moves per unit of time), and
- the length of time the current continues.

The amount of energy gained or lost depends on these two factors and on the potential difference between the two points.

6-12 For example, suppose a current of 2 A (2 coulombs per second) flows through a resistor for 1 second. Suppose further that the potential difference across the resistor is 10 V. The amount of energy lost by the electrons moving through the resistor is calculated in the following way.

$$\text{Total charge moved} = 2 \frac{\text{coulombs}}{\text{second}} \times 1 \text{ second} = 2 \text{ coulombs}$$

$$\text{Energy lost} = 10 \frac{\text{joules}}{\text{coulomb}} \times 2 \text{ coulombs} = 20 \text{ joules}$$

6-13 This method works for all combinations of current, time, and potential difference. The following equation summarizes the method of calculating energy changes, taking into account all three factors.

$$\text{Energy change} = E \times I \times t$$

Where  $E$  = Potential difference between two points

$I$  = Current from one point to the other

$t$  = Time the current last

## Power

6-14 *Power* is defined as the rate of doing work. That is, power is the rate at which energy changes in a system. The following equations express this definition:

$$P = \frac{\textit{work}}{\textit{time}} = \frac{\textit{energy change}}{\textit{time}}$$

6-15 If the amount of work is measured in *joules*, and the time is measured in *seconds*, the amount of power is measured in *joules per second*. One joule per second is called 1 *watt* (W).

6-16 If you combine the equation for power with the equation for electrical energy change, you can see that the power is simply the product of the potential difference and the current.

$$P = \frac{E \times I \times t}{t} = E \times I$$

6-17 If you multiply the units according to this equation, you find that the product of the potential difference (in joules per coulomb) and the current (coulombs per second) gives you the proper units for power (joules per second).

$$P = \frac{\textit{joules}}{\textit{coulomb}} \times \frac{\textit{coulombs}}{\textit{second}} = \frac{\textit{joules}}{\textit{second}} = \textit{watts}$$

6-18 Potential difference and current each have direction. When you multiply them together, the product also has a direction, but the direction has a different meaning than that of potential difference or current.

6-19 Power is the rate at which energy is transferred from one object to another. If you define the positive direction as meaning that energy is transferred from object A to object B, then the negative direction means that energy is transferred from object B to object A. This meaning differs from the usual meaning of direction, because direction usually indicates an orientation in space.

6-20 When you solve the equation for power, the power will be positive if the current and the potential difference are in the same direction (either positive or negative). If they are in opposite directions, the power will be negative.

6-21 A positive value for power means that energy is being transferred from the source to the load. If the load is resistive, its temperature rises.

6-22 A negative value for power means that energy is being transferred from the load to the source. Such a negative transfer occurs only in reactive loads— inductors and capacitors.

6-23 Reactive loads can store energy in the form of a magnetic or electric field, and return it as electrical energy when the field strength decreases. A resistor can only produce heat, which it cannot recover in the circuit.



## Power in Resistive Circuits

- 6-24 In a DC circuit, both the potential difference and the current are constant. Therefore, the power in a resistor is constant. As electricity flows through the resistor, the resistor generates heat. Its temperature rises, and it transfers heat to the cooler surroundings.
- 6-25 In an AC circuit, both the potential difference and the current are always changing. Therefore, the power in a resistor is always changing. You can calculate the power at any instant, but the value will be different at another instant.
- 6-26 Figure 6.1 shows the potential difference across a resistor, the current through it, and the power the resistor consumes. Notice that the current is *in phase* with the potential difference. That is, there is no instant when the two values have opposite signs. They are both positive for half the cycle, and then both negative for the other half.

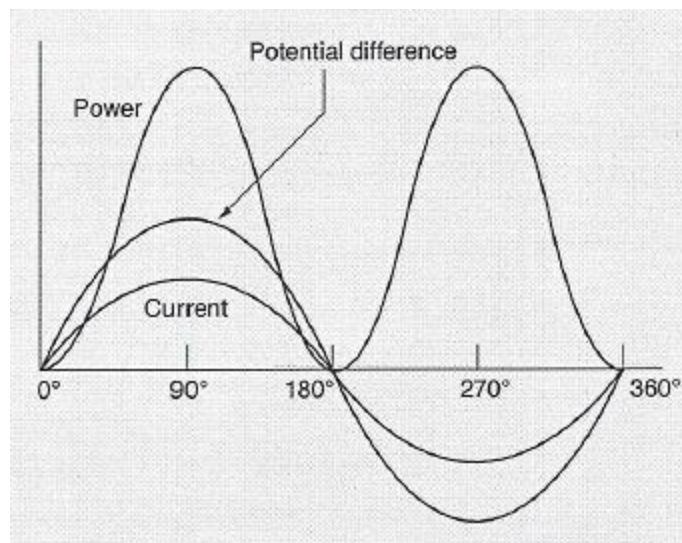
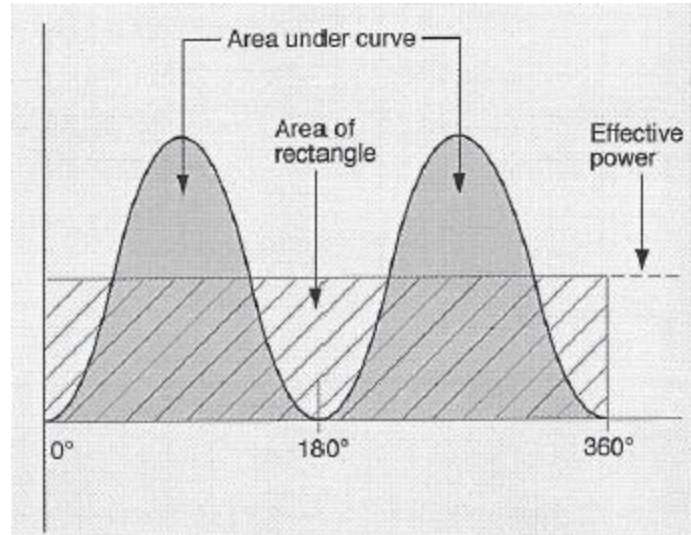


Figure 6.1: AC Power in a Resistor

- 6-27 When the potential difference and the current are in phase, the power is never negative. Energy is always going from the source to the resistor. The rate of energy change keeps rising to a maximum and falling to zero as the potential difference and the current rise and fall.
- 6-28 The power curve is positive during the first half cycle, because both the current and the potential difference are positive. During the second half of the cycle, both current and potential difference are negative. Two negative values multiplied together give a positive product. Therefore, the power is positive during the second half of the cycle as well as during the first. The power curve rises and falls like the curves for current and the potential difference, but with twice the frequency.

## Power in Resistive Circuits (continued)

6-29 To calculate the effective power in the circuit, you must find a constant value that defines a rectangular area equal to the area under the power curve for one complete cycle of the AC source. In Figure 6.2, this value is represented by the horizontal line. Notice that the rectangular area below this line equals the area under the power curve for one complete AC cycle.



**Figure 6.2: Power in an Inductor with Resistance**

6-30 The effective power equals the RMS potential difference multiplied by the RMS current. Its value is therefore equal to half the peak value of the instantaneous power, as shown by the following calculation:

$$P_{RMS} = E_{RMS} \times I_{RMS} = \frac{\sqrt{2}}{2} E_{peak} \times \frac{\sqrt{2}}{2} I_{peak} = \left( \frac{\sqrt{2}}{2} \right) (E_{peak} \times I_{peak}) = \frac{2}{4} P_{peak} = 0.5P_{peak}$$

## Power in Inductive Circuits

6-31 In a circuit with pure inductance, the current lags the applied voltage by  $90^\circ$  as shown in Figure 6.3. To calculate the power at any instant, you multiply the potential difference by the current at that instant, just as you do for a resistive circuit.

- The power is *zero* at any instant when either the potential difference or the current is zero, meaning no energy is being transferred.
- The power is *positive* whenever the potential difference and the current have the same sign, meaning the source is supplying energy to the inductor
- The power is *negative* whenever the potential difference and the current have opposite signs, meaning the inductor is returning energy to the source.

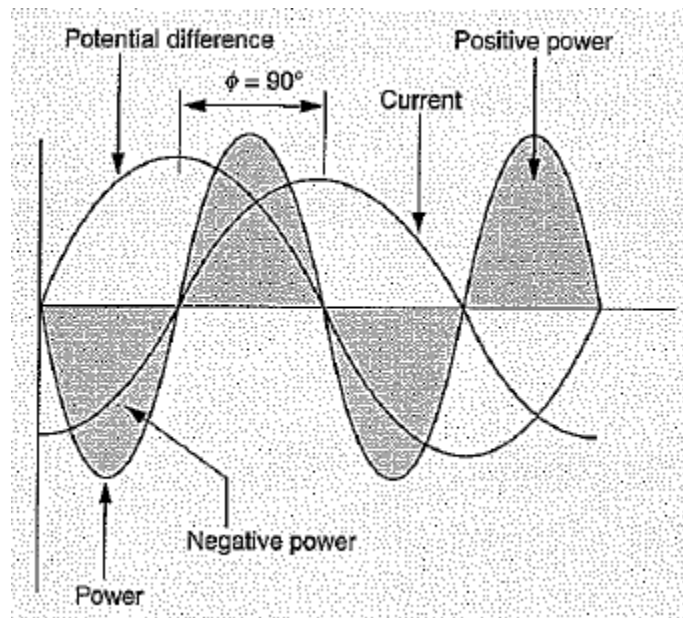


Figure 6.3: Power in an Inductor

6-32 Notice that the negative portion of the power curve in Fig. 6-3 equals the positive portion. The effective power is therefore zero. All the energy the inductor receives from the source is returned to the source. A wattmeter connected in the circuit will read zero.

## Power in Inductive Circuits (continued)

6-33 No inductor in the plant is completely free of resistance. Therefore, the phase angle is always less than  $90^\circ$ . As a result, the power curve looks something like the curve in Figure 6.4. There is more area under the positive portion of the curve than under the negative portion. The effective power in the circuit is positive. A wattmeter connected in the circuit will give a reading greater than zero.

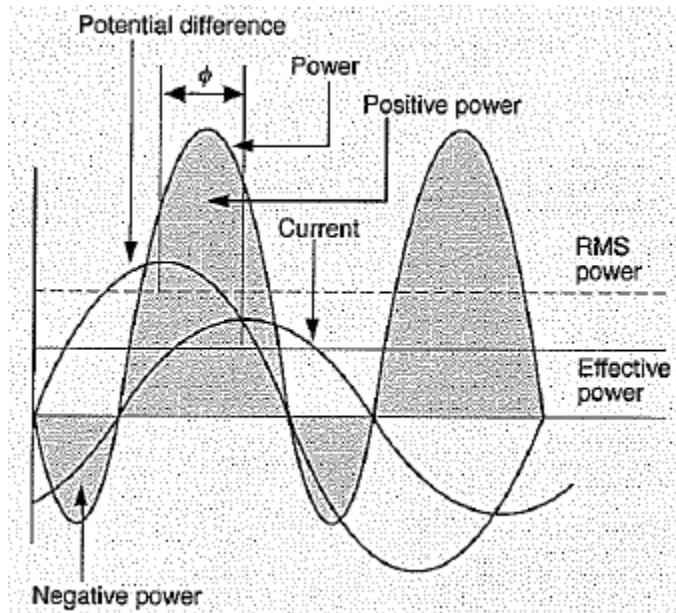


Figure 6.4: Power in an Inductor with Resistance

6-34 The greater the resistance in the circuit compared to the inductive reactance, the more nearly the effective power approaches the RMS power for a purely resistive circuit. The ratio between the effective power and the RMS power in a resistive circuit is called the *power factor*. It is expressed mathematically by the following equation:

$$\text{Power Factor} = \frac{\text{Effective Power}}{\text{RMS Power}}$$

6-35 You can divide the RMS current in the circuit into two components, as shown in Figure 6.5. One component is the current in the resistor. The other is the current in the inductor. In a vector diagram, the two currents act at an angle of  $90^\circ$  to each other.

## Power in Inductive Circuits (continued)

- 6-36 The current in the inductor is not important in calculating power, because an inductor consumes no power. All the power consumed in the circuit is consumed by the resistor. Therefore, the current to use in calculating effective power is the resistive component of the RMS current. In Figure 6.5, the resistive component is the horizontal vector,  $I_R$ .

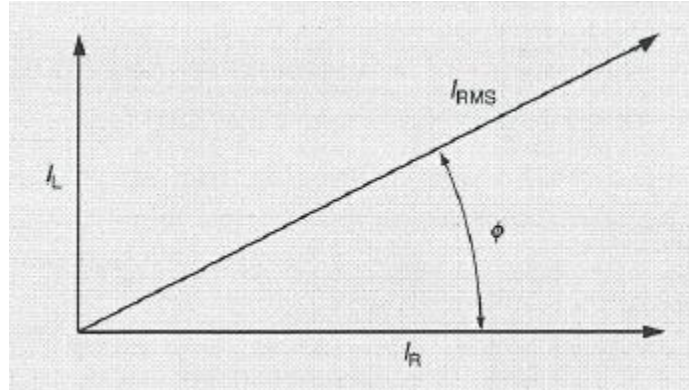


Figure 6.5: Vectors for current in an Inductor

- 6-37 According to the definition of the cosine of an angle, the ratio of the resistive component of the current to the RMS current equals the cosine of the phase angle, as described below.

$$\cos \phi = \frac{\text{Adjacent}}{\text{Hypotenuse}} = \frac{I_R}{I_{RMS}}$$

- 6-38 If you solve this equation for  $I_R$  and use the result in calculating the effective power, the power factor turns out to equal the cosine of the phase angle.

$$\text{Power Factor} = \frac{E_{RMS} \times I_R}{E_{RMS} \times I_{RMS}} = \frac{E_{RMS} \times (I_{RMS} \cos \phi)}{E_{RMS} \times I_{RMS}} = \cos \phi$$

## Power in Capacitive Circuits

6-39 In a capacitive circuit with no resistance, the current leads the potential difference by  $90^\circ$ , as shown in Figure 6.6. If you calculate the instantaneous power, and graph the results, the graph looks like the power curve in Figure 6.6.

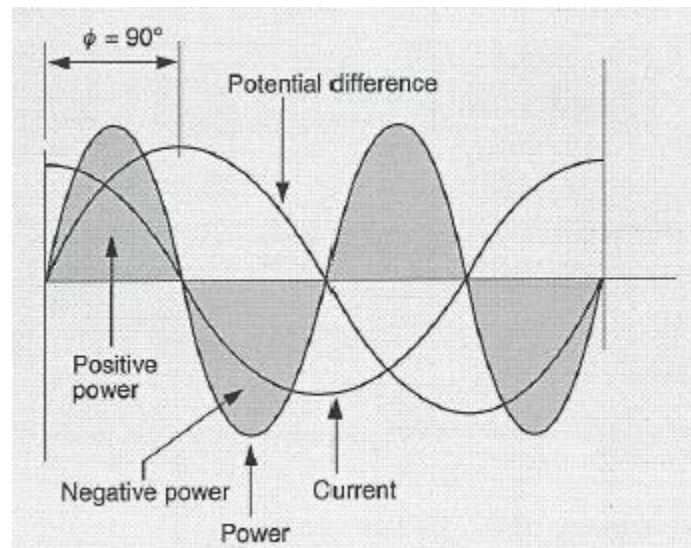


Figure 6.6: Power in a Capacitor

6-40 Notice that the power curve is exactly the opposite of the power curve in a purely inductive circuit. The effective power is zero, because the area under the positive parts of the curve exactly equals the area under the negative parts. All the energy the capacitor receives from the source is returned to the source later in the AC cycle. A wattmeter connected to this circuit will read zero.

6-41 It is possible to keep the resistance in a capacitive circuit very low. Unlike the inductor, the capacitor does not consist of a long wire that has resistance. However, many capacitive circuits include resistors as well as capacitors.

## Power in Capacitive Circuits (continued)

6-42 The analysis of the capacitive circuit with resistance is similar to the analysis of the inductive circuit with resistance. The graph of power looks somewhat like the graph in Figure 6.7, depending on the size of the phase angle. There is more area under the positive part of the curve than under the negative part, so the effective power is greater than zero. A wattmeter connected to this circuit will give a positive reading.

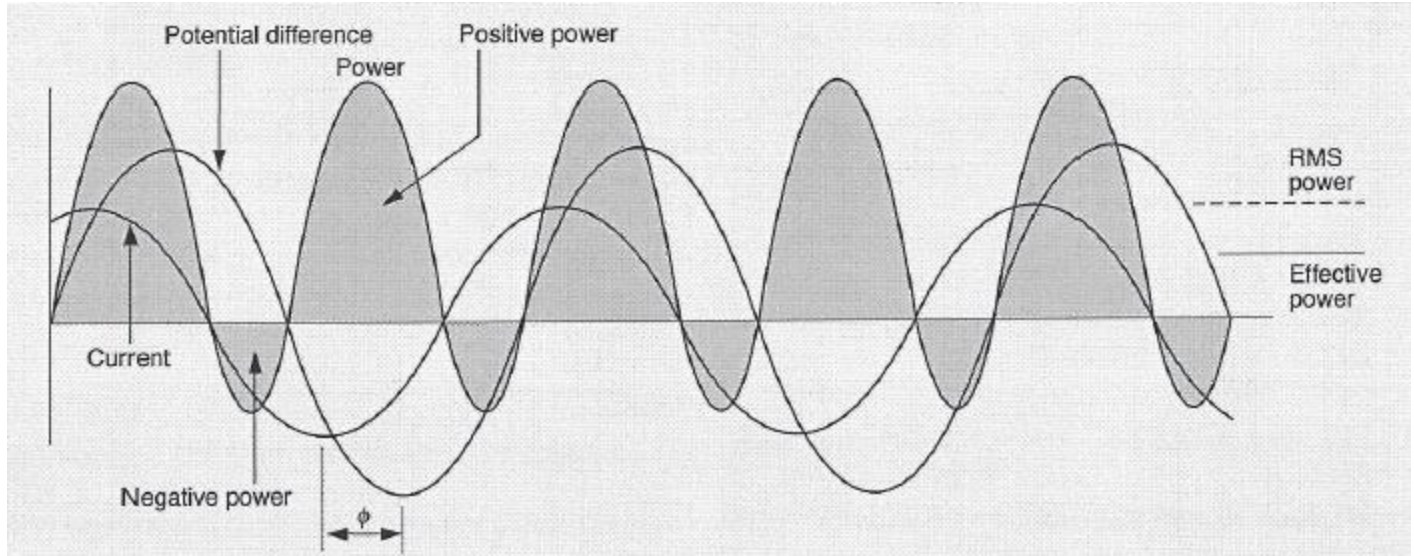


Figure 6.7: Power in a Capacitive Circuit with Resistance

6-43 You can calculate the power factor for a capacitive circuit just as you can for an inductive circuit. The value of the effective power equals the product of the RMS potential difference and the current in the resistor. The capacitor consumes no power.

6-44 To calculate the current in the resistor, you break the RMS current into a capacitive component ( $I_C$ ) and a resistive component ( $I_R$ ), as shown in Figure 6.8, on the following page. From the definitions of the power factor and the cosine of the phase angle, you can see that the power factor equals the cosine of the phase angle, just as for the inductive circuit.

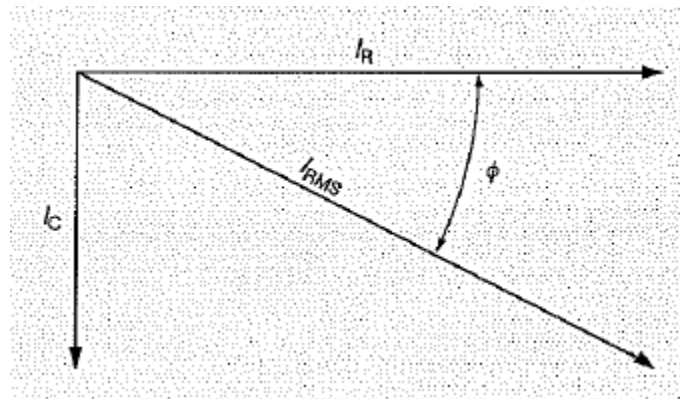


Figure 6.8: Vector Diagram for Current in a Capacitor

## Importance of the Power Factor

6-45 Many of the ac loads in a plant include both inductance and resistance, but not much capacitance. As a result, the inductance in the plant as a whole is high enough to make the current lag the potential difference by a significant amount. As the phase angle increases, the power factor decreases.

6-46 If the power factor becomes too low, several problems may occur.

- The RMS current must be higher to deliver the same effective power as if the power factor were 1.00. The higher current produces greater power loss in the distribution lines.
- The utility company may charge a penalty.
- The maximum power the plant can draw from the transformer substation is reduced.

6-47 As an example, suppose the phase angle in your plant is  $35^\circ$ . Suppose further that the maximum power that can be delivered by the transformer substation is 500 kW at 480 V RMS. What is the maximum effective power in the plant, and how is the power loss in the lines affected?

6-48 In order to answer these questions, you must first calculate the power factor. This calculation is quite simple. You use a scientific calculator to find the cosine of the phase angle,  $35^\circ$ .

$$\text{Power Factor} = \cos \phi = \cos 35^\circ = 0.819$$

6-49 This value equals the ratio of the effective power to the RMS power. Therefore, the maximum effective power available in the plant is only 409.6 kW. This value is 18% less than the maximum power available from the substation.

6-50 With the plant operating at the maximum effective power, the RMS current is 1041.7 A. If the phase angle were zero, the same effective power (409.6 kW) would require only 853.3 A RMS. The power loss in the distribution lines is almost 50% higher when the phase angle is  $35^\circ$  than when the phase angle is zero, because the power loss increases with the square of the current.



## Power Factor Correction

- 6-51 The most practical and economical way to increase the power factor is to add capacitors to the circuits in the plant. Capacitors increase the power factor because the effects of capacitance are exactly opposite those of inductance. Adding capacitors to an inductive circuit counteracts the effect of the circuit's inductance, lowering the reactive power in the circuit.
- 6-52 Capacitors are rated to indicate their ability to increase the power factor. The rating is measured in VAR (volt-amperes, reactive) or kVAR (kilovolt-amperes, reactive). It indicates the amount of inductive power the capacitor can offset at a given frequency and potential difference. For example, a 10 kVAR capacitor will offset 10 kW of inductive power.
- 6-53 You can calculate the rating of the capacitor that should be added to correct a power factor. To do so, you need to sketch two vector diagrams and make a few calculations using trigonometry. If you use a scientific calculator, the calculations are quite easy.
- 6-54 For example, suppose a measurement shows that a motor circuit in your plant has a power factor of only 0.70. The motor draws 2400 W of effective power. What capacitor should you add to the circuit in order to increase the power factor to 0.95?
- 6-55 To solve this problem, you must first sketch two vector diagrams similar to the diagram shown in Figure 6.9. In each diagram, the effective power is a horizontal vector, and the reactive power is a vertical vector. The RMS power is the resultant of the two vectors. The phase angle is the angle from the horizontal to the resultant vector.

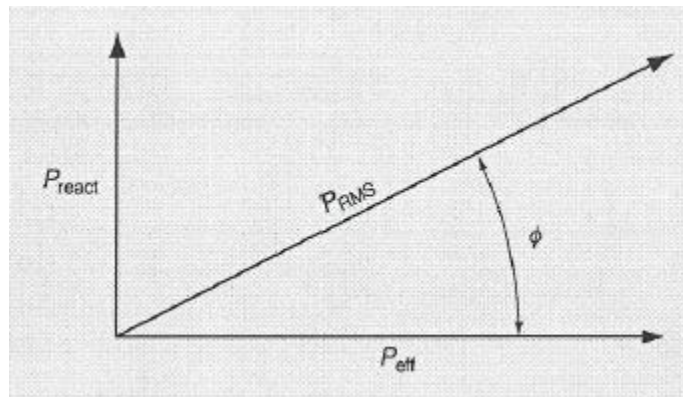


Figure 6.9: Vector for Power-Factor Problems

## Power Factor Correction (continued)

6-56 Before correction, the vector diagram of the motor circuit looks like the diagram shown on the left in Figure 6.10.

6-57 After correction, the vector diagram looks like the diagram shown on the right in Figure 6.10.

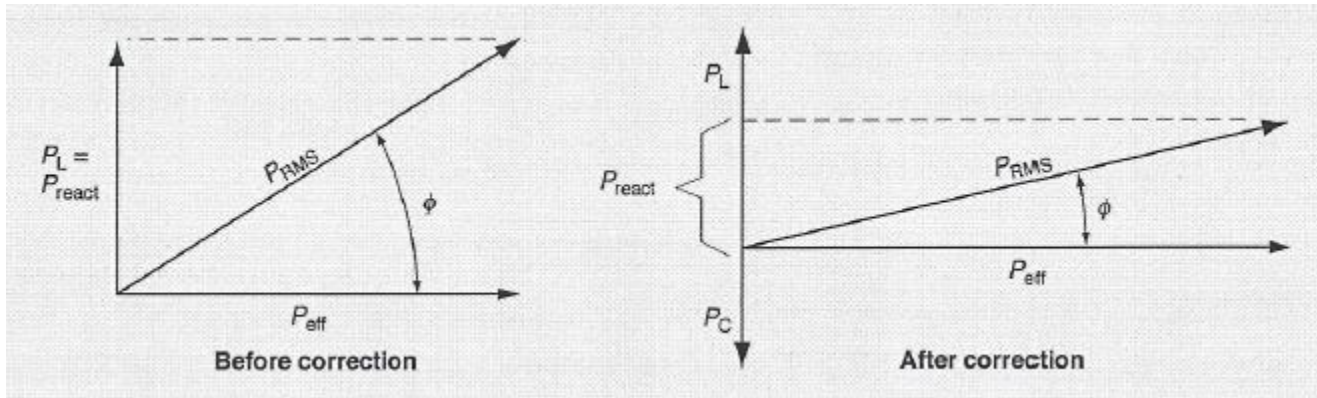


Figure 6.10: Vector Diagrams for Correcting Power-Factor

6-58 You can see that in order to increase the power factor from 0.70 to 0.95, you must reduce the reactive power ( $P_{react}$ ) from 2448.5 W to 788.8 W. Therefore, you must add a capacitor with a rating of at least 1659.7 VAR to the circuit.

6-59 However, the capacitor must not add more than 2448.5 VAR to the circuit. At 2448.5 VAR, the power factor will be 1.00. A capacitor with a higher rating will overcorrect the circuit, reducing the power factor and causing the current to lead the potential difference.

6-60 Table 6-1 on the following page, eliminates the need to make these calculations. To use the table, you find the value corresponding to the present power factor (in the example, 0.70) and the desired power factor (in the example, 0.95). You multiply this value by the effective power in the circuit. The product is the rating of the capacitor you must add to the circuit to raise the power factor to the desired level. In the example, you would multiply 2400 W by 0.691 to find the value of the added capacitance, 1658.4 VAR.

## Power Factor Correction (continued)

Existing Power Factor	Desired Power Factor			
	0.85	0.90	0.95	1.00
0.60	0.713	0.849	1.	1.333
0.62	0.646	0.782	0.	1.266
0.64	0.581	0.717	0.	1.201
0.66	0.518	0.654	0.	1.138
0.68	0.458	0.594	0.	1.078
0.70	0.400	0.536	0.	1.020
0.72	0.344	0.480	0.	0.964
0.74	0.289	0.425	0.	0.909
0.76	0.235	0.371	0.	0.855
0.78	0.182	0.318	0.	0.802
0.80	0.130	0.266	0.	0.750
0.82	0.078	0.214	0.	0.698
0.84	0.026	0.162	0.	0.646

- 6-61 By increasing the power factor to 0.95, you decrease the RMS power required. Before you add the capacitor, the RMS power delivered to the motor circuit is 3428.6 W. Afterward, the RMS power delivered is 2526.3 W, a reduction of 26.3%.
- 6-62 The frequency and potential difference specified for the capacitor must be the same as the frequency and potential difference of the power source for the plant. Capacitors offset different amounts of reactive power at different frequencies and potential differences.

## Power Capacitors

- 6-63 Capacitors are easy to install and maintain. They have no moving parts, and they do not vibrate. They require no auxiliary equipment. Capacitors are made for indoor or outdoor installations at any desired voltage level.
- 6-64 Manufacturers usually guarantee capacitors for one year. Their actual service life is usually 10 to 20 years, depending on the operating conditions.
- 6-65 Capacitors for power-factor correction can be installed almost anywhere in any quantity. Capacitors are available to fit all motors. They can be placed at various points on a loaded line, either between the line and the load or between the line and electrical ground. No special support or foundation is required.
- 6-66 Capacitors consume almost no power. However, they should be disconnected from the circuit as the inductive loads are disconnected. If a capacitor remains in the circuit, its effect remains in the circuit. The capacitor then decreases the power factor, because its capacitive reactance has no inductive reactance to offset it. Instead of the lag caused by excessive inductive reactance, excessive capacitive reactance causes the current to lead the potential difference.

## Capacitor Installation

- 6-67 Capacitors have a long service life and require very little maintenance. However, proper installation of capacitors is important.
- 6-68 Capacitors should be located in areas where temperatures do not exceed 40°C (104°F). At full load, capacitors generate heat which must be removed. Good air circulation is needed to hold the temperature down and to extend the life of the capacitor.
- 6-69 Capacitors may be installed in groups at convenient points in the plant circuit. They can also be installed at the locations of individual inductive loads. If they are installed at individual loads, they can be connected and disconnected with the same switching devices that control the loads. This arrangement prevents excess capacitance from remaining in the circuit when inductive loads are disconnected.
- 6-70 Avoid mounting capacitors closely together. The heat from one will affect adjacent capacitors. Follow the manufacturer's instructions for mounting to reduce the danger of overheating.
- 6-71 Dielectric breakdown in the capacitor will cause a short circuit. Therefore, power capacitors should always be fused to protect the distribution system. Use fuses rated at 165 to 250 percent of the capacitor's rated current. These values will allow for maximum operating conditions and for any momentary surges of current that may occur. Other equipment near the capacitor should also be protected because of the damage a short circuit in the capacitor could create.
- 6-72 Blown fuses will disconnect a shorted capacitor from the circuit before internal gas pressure builds up. The gas pressure can become severe enough to break the seams of the capacitor case. The blown fuse will remove the defective capacitor from the circuit without interrupting service.

## Chapter 6 Exercise

Circle the appropriate letter next to the correct answer.

1. If gravity exerts a force of 300 lb on a crate, and a lift truck raises it 12 feet, how much work is done?
  - a. 0 lb-ft
  - b. 300 lb-ft
  - c. 312 lb-ft
  - d. 3600 lb-ft
  
2. The rate at which energy changes in a system is called \_\_\_\_\_.
  - a. Potential energy
  - b. Power
  - c. Resistance
  - d. Work
  
3. When energy is transferred from the load to the source, there is a \_\_\_\_\_.
  - a. Negative power load
  - b. Positive power load
  - c. Resistive load
  - d. Temperature rise
  
4. In a DC circuit, which of the following is *not* constant?
  - a. Current
  - b. Potential difference
  - c. Power in a resistor
  - d. Reactance
  
5. All the power consumed in a circuit is consumed by the \_\_\_\_\_.
  - a. Capacitor
  - b. Inductor
  - c. Reactor
  - d. Resistor

## Chapter 6 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. If the power factors become too low, which if the following will *not* happen?
- a. Maximum power available will decrease
  - b. Phase angle will decrease
  - c. Department may be charged a penalty
  - d. RMS current will increase
7. What is the most practical and economical way to increase a power factor?
- a. Add capacitors to the circuits
  - b. Increase the inductance in the circuits
  - c. Use less power
  - d. Use more power
8. If you need to correct a power factor, where should you *not* install a capacitor?
- a. Across any two lines
  - b. Between the line and electrical ground
  - c. Between the line and the load
  - d. On the loaded line
9. To provide a long service life, capacitors require \_\_\_\_\_.
- a. Ambient temperatures lower than 60° F
  - b. Frequent maintenance
  - c. Proper installation
  - d. Regular lubrication
10. To protect the distribution system, power capacitors should always be fused at \_\_\_\_\_% of their rated capacity.
- a. 50 to 100
  - b. 100 to 200
  - c. 165 to 250
  - d. 200 to 265

## Summary

Work, energy and power are closely related in the AC circuit. Work is defined as the force exerted on an object multiplied by the distance to object moves. Electrical energy is defined in terms of work done in moving a charged particle against the force exerted in it by an electric field. Power is defined as the rate of doing work. It is the rate at which energy changes in a system.

In an AC resistive circuit, the power is always changing because the potential difference and the current are always changing. In a circuit with pure inductance, the current lags the applied voltage by  $90^\circ$ . In a capacitive circuit with no resistance, the current leads the potential difference by  $90^\circ$ .

The ratio between the effective power and the RMS power in resistive circuit is called the power factor. When the inductance in the plant is high enough to make the current lag the potential difference by a large amount, the phase angle increases and the power factor decreases.

If the power factor becomes too low, there may be a large power loss in the distribution lines, the utility company may charge a penalty for the low power factor and the amount of power that can be drawn from the transformer substation will be reduced. The easiest way to correct the power factor is to add capacitors to the circuits. The capacitors increase the power factor because the effects of the capacitance are opposite those of the inductance.





# Chapter 7: Three-Phase Circuits

## In this Chapter

Three-Phase Alternators

Y-Connected Alternators

Delta-Connected Alternators

Power in Three-Phase Circuits

Power Factor Correction

Measuring Power in Three-Phase Circuits

## Objectives

After completing this chapter, you should be able to:

- List the main advantages of the Three-Phase AC system.
- State the definition of phase sequence.
- Demonstrate how to calculate the RMS power in a three-phase circuit.
- Explain how to measure the total power consumed by the load in a three-phase circuit.

## Terminology

**Phase sequence:** The order in which the potential differences of the phases reach their peaks

**Effective power:** The RMS power multiplied by the power factor

**Wattmeter:** An instrument used for measuring electrical power

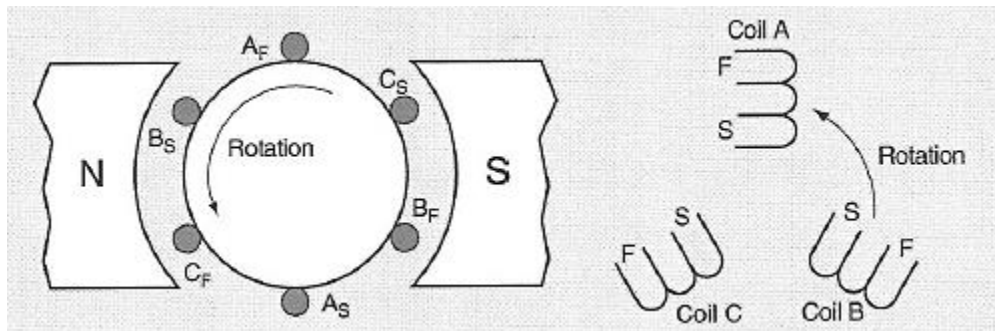
**Three-phase circuit systems are widely used in plants in the United States and other countries. Machines that operate on three-phase current are smaller than single-phase machines, yet they have better operating characteristics and higher power ratings.**

**In order for three-phase systems to operate properly, they must be connected correctly. This lesson explains Y-connected and delta-connected alternators, load connections, and how to calculate important values in three-phase systems.**

**The section on measuring power in three-phase circuits explains the use of wattmeters, how to connect them in order to take measurements, and what various readings mean in determining the power factor in three-phase circuits.**

## Three-Phase Alternators

- 7-1 The three-phase system is the most common alternating current system used in the United States and in many other countries. There are two key reasons why it is so widely used.
- It provides equal potential differences between electrical ground and all three lines.
  - It provides two potential differences between pairs of lines.
- 7-2 Three-phase potential differences are generated by three coils rotating in a magnetic field, as shown in Figure 7.1. The start of each coil is indicated by the subscript S (as in  $A_S$ ). The finish of each coil is indicated by the subscript F (as in  $A_F$ ). The three coils A, B, and C are positioned 120 electrical degrees apart.



**Figure 7.1: Elements of a Three-Phase Alternator**

- 7-3 It is possible to bring out a pair of wires from each coil, forming three single-phase AC sources. However, the coils are usually connected to each other at one end, forming a single source that produces three sine waves.
- 7-4 *Phase sequence* is the order in which the potential differences reach their peaks with respect to one another. In Figure 7.1, the phase sequence is A, B, C. This sequence is the order in which the coils pass any given point as they rotate.
- 7-5 The sine curves representing the potential difference across each of the coils are shown in Figure 7.2 on the following page. If you examine these sine curves closely, you can see that the sum of all three values is always zero. For example, when one potential difference is zero, the other two are exactly opposite to each other in value. One is positive, and the other is negative.
- 7-6 You can use the vertical components of three rotating vectors to represent the three potential differences, as shown in Figure 7.3 on the following page. The vectors are 120° apart because the coils are 120 electrical degrees apart. The sum on the three vertical components is zero because the sum of the three vectors is zero. The sum remains zero as the vectors rotate.

## Three-Phase Alternators (continued)

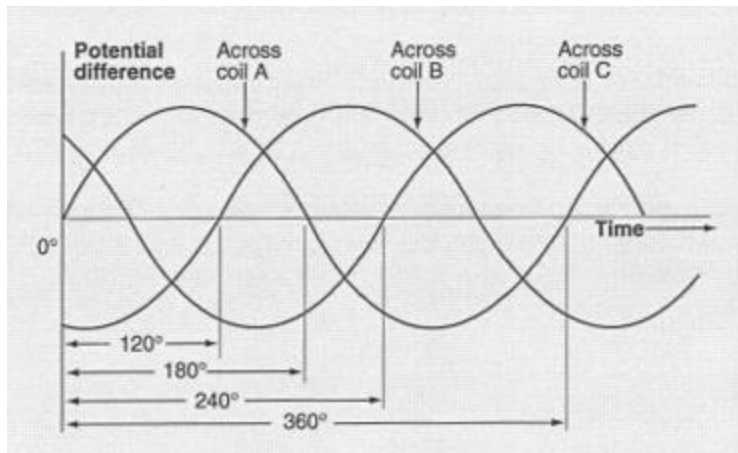


Figure 7.2: Potential Differences Across Coils

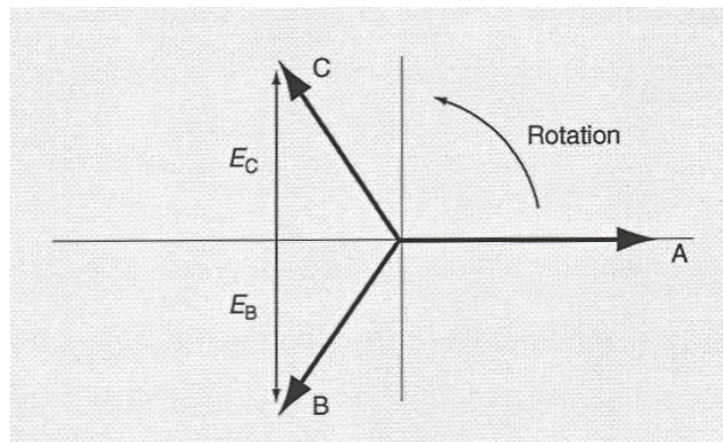
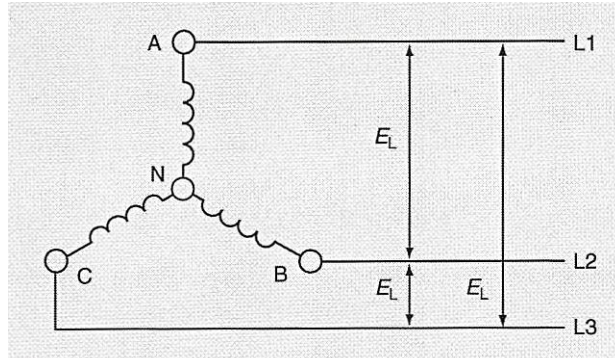


Figure 7.3: Vector Diagram for Potential Difference

## Y-Connected Alternators

7-7 The three coils shown in Figure 7.1 can be connected at one end as shown in Figure 7.4. The three S terminals are connected to form a common junction, labeled N. This kind of connection is called a *Y connection*, or sometimes a *star connection*.

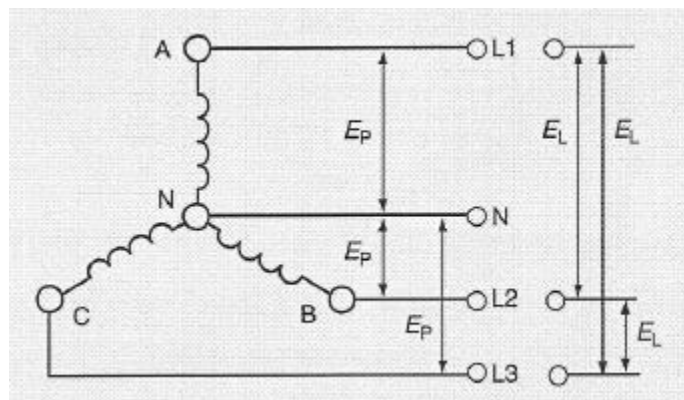
7-8 Usually only three wires (labeled A, B, and C) come out to the external circuit, as shown in Figure 7.4. Such a system is called a three-wire system. But sometimes a neutral wire (labeled N) is connected to the junction of the three coils and brought out. The addition of this wire creates a three-phase, four-wire system, as shown in Figure 7.5.



**Figure 7.4: Three Wire Y-Connected Alternator**

7-9 The potential difference generated across each coil in an alternator is called the *phase voltage* or the *coil voltage*. It is labeled  $E_p$ . If the neutral connection is brought out of the alternator,  $E_p$  is measured from any "hot" terminal (A, B, or C) to the neutral terminal (N). The potential difference between any pair of hot terminals is called the line voltage. It is labeled  $E_L$ .

7-10 You can probably see from Figure 7.5 that  $E_L$  is greater than  $E_p$ . Both values are always changing according to a sine curve. But the curve for  $E_L$  rises to higher peaks than does the curve for  $E_p$ . Therefore, the RMS value of  $E_L$  is higher than the RMS value of  $E_p$ .



**Figure 7.5: Four Wire Y-Connected Alternator**

## Y-Connected Alternators (continued)

- 7-11 The peak and RMS values of  $E_L$  are 1.732 times the peak and RMS values of  $E_p$ . This value may seem odd, but it is not. It is the square root of three, and also twice the sine of  $60^\circ$ . The reason why  $E_L$  equals the square root of 3 times  $E_p$  is explained in the following paragraphs.
- 7-12 The peak of the curve for  $E_L$  occurs when the instantaneous values of  $E_p$  for the two coils are equal and opposite, as shown in Figure 7.6. You can prove this statement to yourself by calculating  $E_L$  for various instantaneous values of  $E_p$ . The peak occurs twice — once when the vectors  $E_1$  and  $E_2$  are in the positions shown in Figure 7.6, and again after each vector rotates  $180^\circ$ . One peak is a maximum, and the other is a minimum on the  $E_L$  curve.
- 7-13 The phase voltage across each coil is the vertical component of the vector labeled  $E_1$  or  $E_2$ . The value of  $E_L$  is the *vector difference* between the two vertical components of  $E_1$  and  $E_2$ . These vertical components are labeled  $E_{P1}$  and  $E_{P2}$  in Figure 7.6. Their vector difference is twice the value of either one, because the two vertical components are in opposite directions.

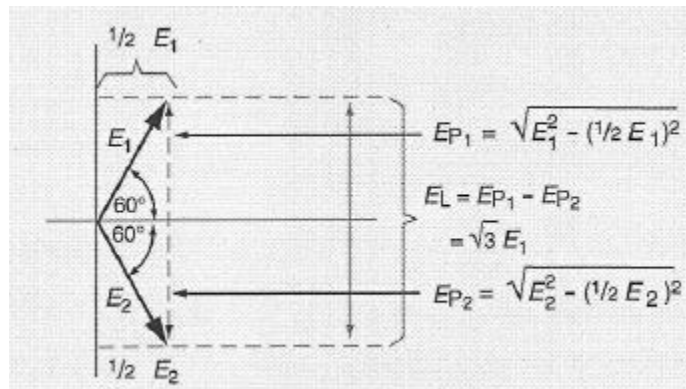


Figure 7.6: Vector Diagram for Calculating  $E_L$

- 7-14 If you have studied geometry, you may remember that in a 30-60-90° triangle, the side opposite the 30° angle is half as long as the hypotenuse. You can use this fact, and the Pythagorean theorem, to calculate the vertical components of  $E_1$  and  $E_2$ .

$$E_{P1} = \sqrt{E_1^2 - \left(\frac{1}{2}E_1\right)^2} = \sqrt{\frac{3}{4}E_1^2} = \sqrt{\frac{3}{2}}E_1$$

$$E_{P2} = -\sqrt{E_2^2 - \left(\frac{1}{2}E_2\right)^2} = -\sqrt{\frac{3}{4}E_2^2} = \sqrt{\frac{3}{4}}E_2 = -\sqrt{3}E_2$$

- 7-15 The vector difference,  $E_L$ , between these two vertical components is twice the value of one component, as shown by the vector on the right in Figure 7.6

$$E_L = 2 \times \frac{\sqrt{3}}{2}E_1 = \sqrt{3}E_1$$

## Y-Connected Alternators (continued)

7-16 The peak value of  $E_{P1}$  equals  $E_1$ , because when the vector  $E_1$  points straight up its vertical component equals the vector itself. Therefore, the peak value of  $E_L$  is the square root of 3 times the peak value of  $E_P$ .

$$E_L = \sqrt{3}E_P$$

7-17 The RMS potential difference is proportional to the peak potential difference. That is, if the peak potential difference changes, the RMS potential difference changes in proportion. Therefore, the RMS value of  $E_L$  is the square root of 3 times the RMS value of  $E_P$ .

7-18 The current in each line from terminals A, B, and C must equal the current in the coil connected to the line. In other words, the line current ( $I_L$ ) in any line equals the phase current ( $I_P$ ) in the coil to which the line is connected. As the equation, it can be stated as follows:

$$I_L = I_P$$

## Delta-Connected Alternators

7-19 Some alternators are connected so that the three coils form a continuous loop. Their ends are connected together in series as shown in Figure 7.7. Such an alternator is said to be *delta-connected* because in a diagram, the three coils make a triangular shape that looks like the Greek capital letter *delta*.

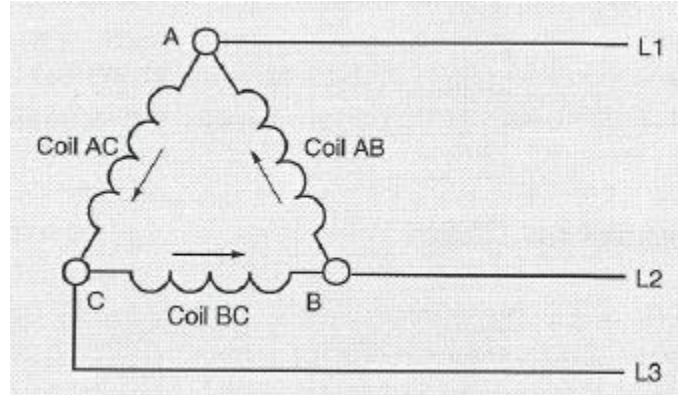


Figure 7.7: Three-Phase Delta-Connected Alternator

7-20 Line connections are made at the junctions between coils, as shown in Fig. 7-7. Because of these connections, the potential difference between any two terminals equals the potential difference across a single coil.

7-21 The three coils are positioned 120 electrical degrees apart, just as in a Y-connected alternator. Therefore, the potential differences across the coils are out of phase with each other by 120°. The vector sum of the three potential differences is always zero, just as in a Y-connected alternator.

## Delta-Connected Alternators (continued)

- 7-22 If you reverse the connections to one coil in a delta-connected alternator, one of the sine curves for the output will be inverted. The combined potential difference for the three coils will then no longer equal zero. It will equal twice the potential difference across a single coil. This potential difference will produce a high current in the coils even without an external connection between the terminals. This current will damage the coils.
- 7-23 The phase currents of a delta-connected alternator are shown by the arrows in Figure 7.7. The vector diagram representing these currents is shown in Figure 7.8. To calculate the current in lines L1, L2, or L3, you must add the currents in the two coils connected to the line. This addition is a vector addition of the vertical components of the two current vectors.

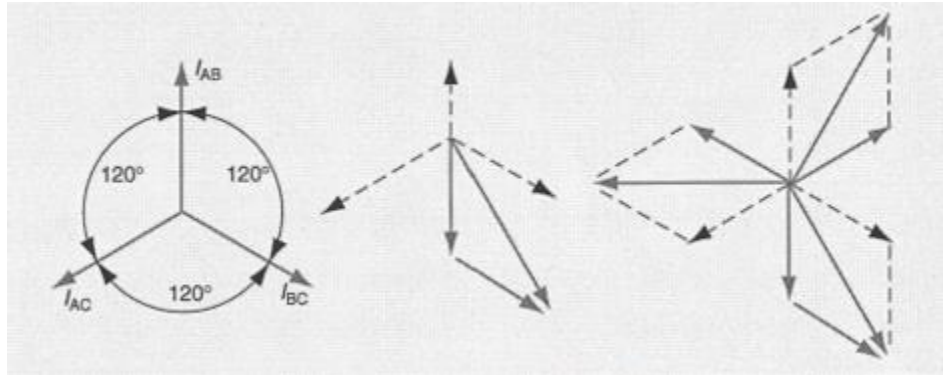


Figure 7.8: Vector Diagram for Currents

- 7-24 For example, suppose you need to know the current in line L1. This current is the difference between the vertical components of the rotating current vectors for the two coils connected to line L1.

$$I_L = I_{AB} - I_{AC}$$

- 7-25 The lengths of the rotating vectors ( $I_{AB}$  and  $I_{AC}$ ) are equal and the directions of the vectors are  $120^\circ$  apart. Therefore, the vector difference between the peak values of current is 1.732 times the peak value of the current in any one coil.

$$I_L = \sqrt{3}I_{AB} = 1.732 I_{AB}$$

The same relationship exists between the RMS values of the currents.

- 7-26 The peak current occurs at the instant when one of the two rotating current vectors is  $60^\circ$  above the horizontal axis, and the other is  $60^\circ$  below the horizontal axis. The vectors are shown in these positions in Figure 79.

## Delta-Connected Alternators (continued)

- 7-26 The peak current occurs at the instant when one of the two rotating current vectors is  $60^\circ$  above the horizontal axis, and the other is  $60^\circ$  below the horizontal axis. The vectors are shown in these positions in Figure 7.9.

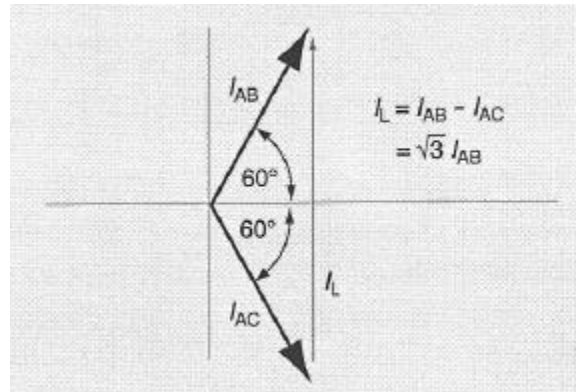


Figure 7.9: Vector Diagram for Calculating  $I_L$

## Power in Three-Phase Circuits

- 7-27 In single-phase circuits, the *RMS power* ( $P_{RMS}$ ) is calculated by multiplying the RMS potential difference by the RMS current. The *effective power* ( $P_{eff}$ ) is defined as the RMS power multiplied by the power factor. Remember that the power factor equals the cosine of the phase angle.
- 7-28 The effective power developed in a single coil of a three-phase circuit, whether Y- or delta-connected, is the product of the potential difference across the coil and the current through it, multiplied by the cosine of the phase angle between the potential difference and current. In mathematical terms, the effective power is expressed by the following equation.

$$P = E I \cos \phi$$

- 7-29 The effective power developed in all three coils of a balanced three-phase alternator is three times the amount developed in one coil.

$$\text{Total } P_{eff} = 3 \times P_{eff} = 3 \times E_p I_p \cos \phi$$



## Power in Three-Phase Circuits

7-30 In the plant, you can easily measure the current and potential difference in the line. But measuring the current and potential difference in the coils is much more difficult. Therefore, it is an advantage to use equations developed previously as a basis for substituting for  $E_p$  and  $I_p$  in the power equation. You must substitute in two different ways, depending on whether the alternator is Y-connected or delta-connected.

- For a Y-connected alternator  $I_p = I_L$

$$E_p = \frac{E_L}{\sqrt{3}}$$

- For a delta-connected alternator  $I_p = \frac{I_L}{\sqrt{3}}$

$$E_p = E_L$$

7-31 When you make substitutions, you find that the resulting power equations are identical for Y-connected and delta-connected alternators.

$$\text{Total } P_{eff} = \sqrt{3} E_L I_L \cos \phi$$

7-32 The value of  $\cos \phi$  equals the power factor. Therefore, the product of the remaining terms on the right side of the equation is the RMS power produced by the generator.

$$\text{Total } P_{RMS} = \sqrt{3} E_L I_L$$

7-33 The values of  $P_{eff}$  and  $P_{RMS}$  in these equations are in watts. However, the generators in plants and in electric utility generating stations generate power measured in thousands of watts. To convert the values of  $P_{eff}$  and  $P_{RMS}$  into kilowatts, you simply divide by 1000.

7-34 The problems on the following pages will show you how to calculate certain values for Y-connected and delta-connected alternators. Study each problem and its solution carefully. If you are in doubt about why certain equations are used, go back and read the necessary parts of this lesson again.

## Power in Three-Phase Circuits (continued)

### Problem 1

A three-phase Y-connected alternator produces a potential difference of 480 V RMS between each pair of hot lines. It delivers a current of 300 A RMS in each line, and the current lags the potential difference by 45°. What is the *potential difference* across each coil in the alternator? What is the *current* in each coil? What is the *RMS power* and the *effective power* delivered by the alternator?

- Potential difference across each coil

$$E_p = \frac{E_L}{\sqrt{3}} = \frac{480 \text{ V RMS}}{1.732} = 277 \text{ V RMS}$$

- Current in each coil

$$I_p = I_L = 300 \text{ A RMS}$$

- RMS power

$$\text{Total } P_{RMS} = \sqrt{3} E_L I_L = 1.732 \times 480 \text{ V RMS} \times 300 \text{ A RMS} = 249,408 \text{ W} = 249.4 \text{ kW}$$

- Effective power

$$\text{Total } P_{eff} = P_{RMS} \times \cos \phi = 249.4 \text{ kW} \times 0.7071 = 176.4 \text{ kW}$$

### Problem 2

A three-phase delta-connected alternator delivers 240 V RMS to the terminals. The current in each coil is 100 A RMS at a power factor of 60% lagging. Find the potential difference between pairs of lines, the current in each line, and the RMS power and the effective power delivered by the alternator.

- Potential difference between pairs of lines

$$E_L = E_p = 240 \text{ V RMS}$$

- Current in each line

$$I_L = \sqrt{3} I_p = 1.732 \times 100 \text{ A RMS}$$

- RMS power

$$\text{Total } P_{RMS} = \sqrt{3} E_L I_L = \sqrt{3} \times (240 \text{ V RMS}) \times (\sqrt{3} \times 100 \text{ A RMS}) = 72,000 \text{ W} = 72 \text{ kW}$$

- Effective power

$$\text{Total } P_{eff} = P_{RMS} \times \text{power factor} = 72 \text{ kW} \times 0.60 = 43.2 \text{ kW}$$

## Load Connections

- 7-35 The loads connected to a three-phase alternator can be connected in either the Y or delta arrangement. Examples of loads typically connected to three-phase alternators include motors, transformers, and lamps.
- 7-36 The equations for calculating currents, potential differences, and power apply to the loads as well as to the alternators. In applying the equations, you should treat the loads like the coils in the alternator. The following problems demonstrate how to solve typical problems concerning three-phase loads.

### Problem 3

Three resistors are connected across pairs of lines in a three-phase Y-connected circuit, as shown in Figure 7.10. The potential difference between pairs of lines is 240 V RMS. The resistors are  $15 \Omega$  each. What is the *current in each resistor*, the *current in each line* from the alternator, and the *effective power* consumed by the three resistors? Remember that the current in a resistor is in phase with the potential difference. That is, the phase angle between the current and the potential difference is zero.

- Current in each resistor

$$E_P = \frac{E_L}{\sqrt{3}} = \frac{240 \text{ V RMS}}{\sqrt{3}} = 138.6 \text{ V RMS across each resistor}$$

$$I_P = \frac{E_P}{R_P} = \frac{138.6 \text{ V RMS}}{15 \Omega} = 9.24 \text{ A RMS in each resistor}$$

- Current in each line

$$I_L = I_P = 9.24 \text{ A RMS}$$

- Power consumed by the three resistors

$$\text{Total } P_{eff} = 3P_{eff} = 3 \times E_P I_P \cos \phi = 3 \times 138.6 \text{ V RMS} \times 9.24 \text{ A RMS} \times \cos 0^\circ = 3842 \text{ W} = 3.8 \text{ kW}$$

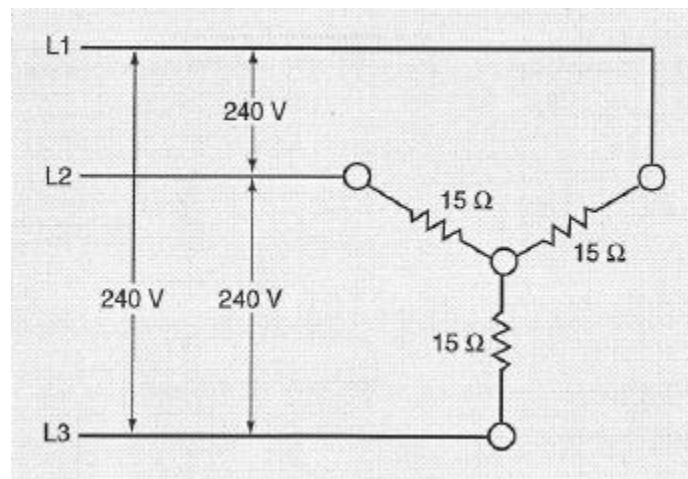


Figure 7.10: Three-Phase Y-Connected Resistors

## Load Connections (continued)

7-37 Another common Y-connected circuit is the four-wire circuit shown in Figure 7.11. The fourth wire is a grounded neutral wire. In this system, the potential difference between any line and the neutral line is less than the potential difference between a pair of hot lines. The ratio between the two potential differences equals the square root of 3.

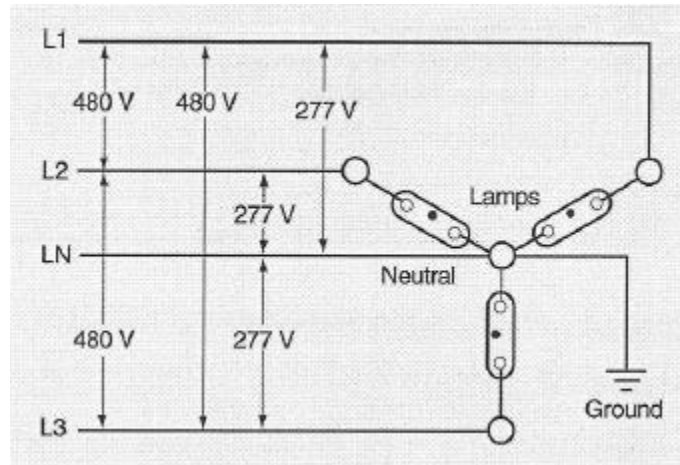


Figure 7.11: Dual-Voltage Three-Phase Circuits

7-38 If the potential difference between pairs of hot lines is 480 V RMS, the potential difference between a hot line and the neutral line is 277 V RMS. The 480 V lines can be used for running motors, and the 277 V lines can be used for operating fluorescent lighting circuits.

## Load Connections (continued)

### Problem 4

Suppose three inductive loads are connected in a delta circuit, as shown in Figure 7.12. The impedance of each load is  $45 \Omega$ , and the power factor is 72%. What is the *current in each load* and *in each line*? What is the *RMS power delivered*, and what is the *effective power consumed*?

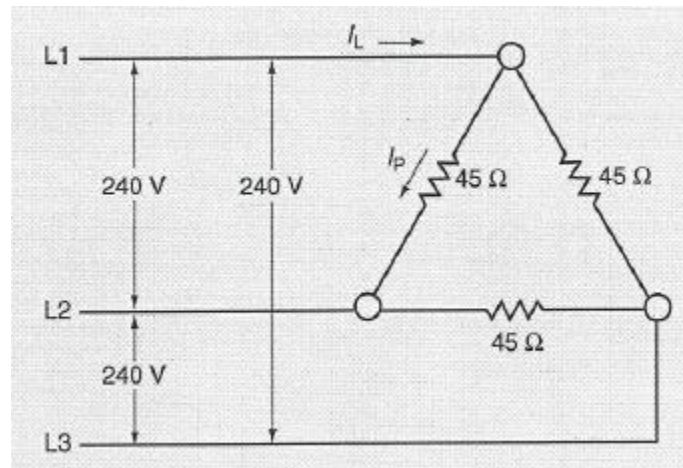


Figure 7.12: Three-Phase Delta-Connected Loads

- Current in each load

$$E_P = E_L$$

$$I_P = \frac{E_P}{Z_P} = \frac{240 \text{ V RMS}}{45 \Omega} = 5.33 \text{ A RMS}$$

- Current in each line

$$I_L = \sqrt{3} I_P = 1.732 \times 5.33 \text{ A RMS} = 9.24 \text{ A RMS}$$

- RMS power in all three loads

$$\text{Total } P_{RMS} = \sqrt{3} E_L I_L = 1.732 \times 240 \text{ V RMS} \times 9.24 \text{ A RMS} = 3841 \text{ W} = 3.8 \text{ kW}$$

- Effective power in all three loads

$$\text{Total } P_{eff} = P_{RMS} \times \text{power factor} = 3.8 \text{ kW} \times 0.72 = 2.7 \text{ kW}$$

## Load Connections (continued)

### Problem 5

A 15 horse power three-phase induction motor rated at 480 V draws a full-load current of 20 A RMS per terminal. What is the RMS power drawn by the motor? If the power factor is 85%, what is the effective power drawn by the motor?

- RMS power

$$\text{Total } P_{RMS} = \sqrt{3} E_L I_L = 1.732 \times 480 \text{ V RMS} \times 20 \text{ A RMS} = 16,627.2 \text{ W} = 16.6 \text{ kW}$$

- Effective power

$$\text{Total } P_{eff} = P_{RMS} \times \text{power factor} = 16.6 \text{ kW} \times 0.85 = 14.1 \text{ kW}$$

## Measuring Power in Three-Phase Circuits

7-39 The instrument used for measuring power is called the *wattmeter*. It is connected into a circuit in such a way that both the current in the load and the potential difference across it affect the reading. When the current is out of phase with the potential difference, the reading is automatically reduced by the proper amount to indicate the effective power in the circuit.

7-40 In a three-phase circuit, the total power consumed by the load is the sum of the power in the three individual lines. You can measure the total power in two different ways.

- You can use three wattmeters—one on each line.
- You can use only two wattmeters—each connected to two lines.

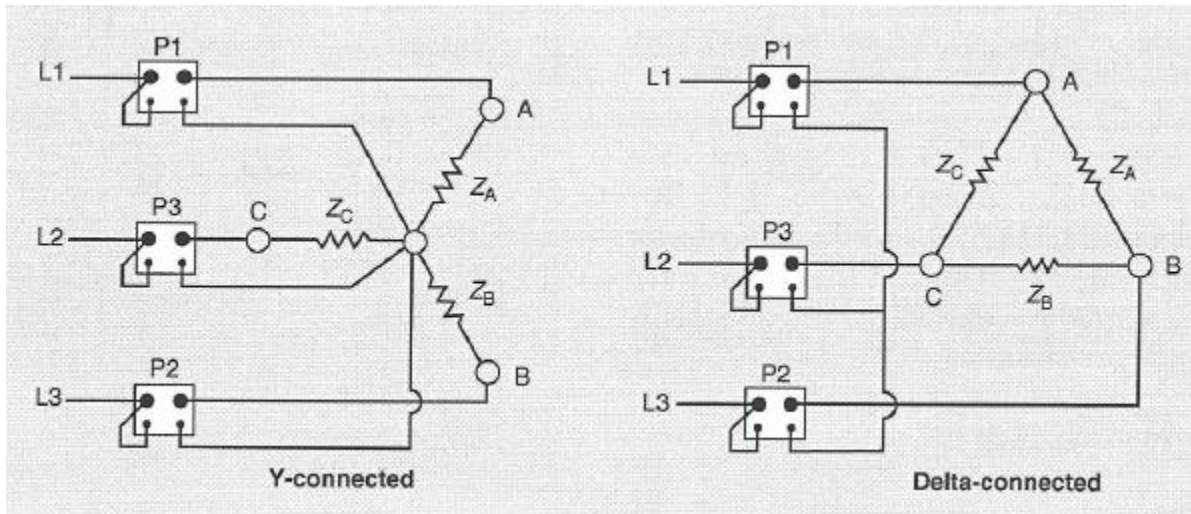
In each way, the total power consumed by the load equals the sum of the readings on the wattmeters.

7-41 If you use three wattmeters, you connect one on each line as shown in Figure 7.13 on the following page. Notice that the only difference is in how one voltage terminal is connected on each meter in the Y-connected load compared to the delta-connected load. Each kind of load requires measuring the potential difference from each line to a common point.

- In a Y-connected load, the common point is the junction where the three loads join.
- In the delta-connected load, there is no common point in the circuit. Therefore, you must create a common point by connecting one voltage terminal from each meter to a common line.

7-42 To measure the total effective power using the three-wattmeter method, you simply add the values indicated on the three wattmeters. If the loads are not balanced, the three meters may read three different values. Even so, you simply add them together to find the total effective power consumed by the circuit.

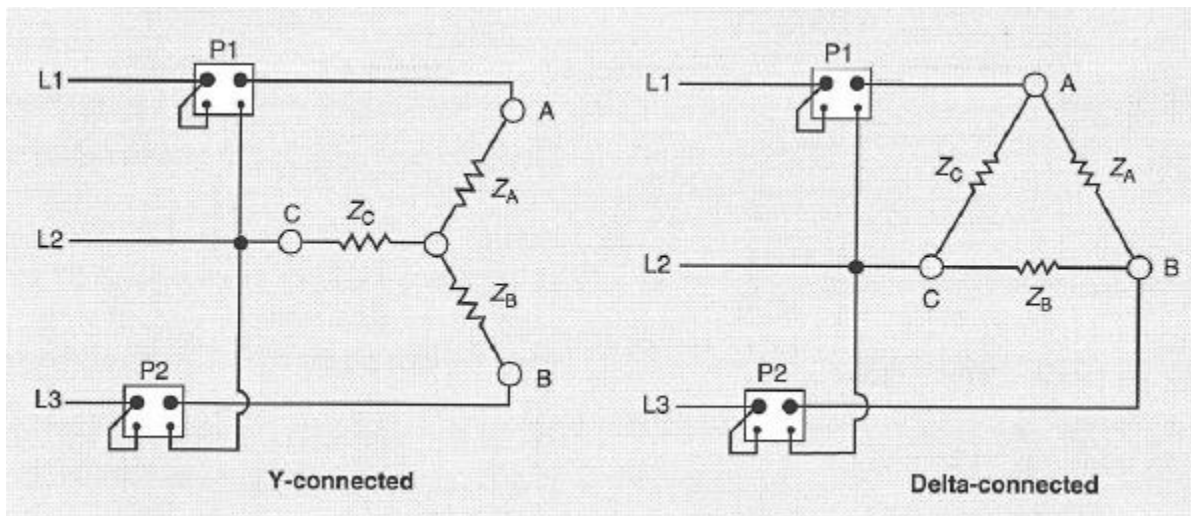
## Measuring Power in Three-Phase Circuits (continued)



**Figure 7.13: Three-Wattmeter Method for Measuring Three-Phase Power**

7-43 To measure the power with only two wattmeters, you must connect them as shown in Figure 7.14. Notice that the connections are exactly the same for a Y-connected load as for a delta-connected load. To find the power, you must combine the two readings.

- If the power factor is 100%, each wattmeter will read half the total power going to the load.
- If the power factor is only 50%, one wattmeter will read zero. The other will then read the total power.
- If the power factor is 50 to 100%, one meter will read more than the other, and the total power will be the sum of the two readings.
- If the power factor is less than 50%, one wattmeter will give a negative reading. Then, either the current connections or the voltage connections must be reversed to get a useful reading. In order to compensate for the reversal of the connections, you must subtract the value on that meter from the other in calculating the total effective power.



**Figure 7.14: Two-Wattmeter Method for Measuring Three-Phase Power**

## Chapter 7 Exercise

Circle the appropriate letter next to the correct answer.

1. How far apart are the coils placed in a three-phase alternator?
  - a. 60°
  - b. 120°
  - c. 270°
  - d. 360°
  
2. Line voltage is the potential difference between \_\_\_\_\_.
  - a. A hot terminal and a neutral terminal
  - b. Any pair of coils in the alternator
  - c. Any pair of hot terminals
  - d. Any pair of neutral terminals
  
3. When energy is transferred from the load to the source, there is a \_\_\_\_\_.
  - a. A single coil
  - b. Two coils
  - c. All three coils
  - d. The coil junctions
  
4. If you reverse the connections to one coil in a delta-connected alternator, the result will be \_\_\_\_\_.
  - a. A high current in the coils
  - b. A low current in the coils
  - c. A short circuit
  - d. No current in the coils
  
5. The effective power developed in all three coils of a balanced three-phase alternator is \_\_\_\_\_.
  - a. Zero
  - b. Half the amount developed in one coil
  - c. Twice the amount developed in one coil
  - d. Three times the amount developed in on coil



## Chapter 7 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. What is the potential difference across each coil in a three-phase Y-connected alternator that produces a potential difference of 480 V between each pair of hot lines?
- a. 160 W
  - b. 277 W
  - c. 480 W
  - d. 600 W
7. A three-phase delta-connected alternator delivers 240V RMS to the terminals. The current in each coil is 100 A RMS at a power factor of 60% lagging. What is the potential difference between pairs of lines?
- a. 120 V RMS
  - b. 196 V RMS
  - c. 240 V RMS
  - d. 720 V RMS
8. A 15 horse power three-phase induction motor rated at 480 V draws a full-load current of 29 A RMS per terminal. What is the approximate RMS power drawn by the motor?
- a. 831 W
  - b. 3200 W
  - c. 9600 W
  - d. 16,600 W
9. In a three-phase circuit, the total power consumed by the load equals the power in \_\_\_\_\_.
- a. Any one line
  - b. Any two lines
  - c. All three lines together
  - d. All three lines multiplied by the square root of three
10. If you connect two wattmeters to a three-phase circuit and one meter reads zero, you know the power factor is \_\_\_\_\_.
- a. Less than 50%
  - b. 50%
  - c. 50 to 100%
  - d. 100%

## Summary

The three-phase system is the most common AC system in use today. Three-phase potential differences are generated by three coils rotating in a magnetic field. The coils are usually connected to each other at one end, forming a single source that produces three sine waves. If they are connected to form a common junction, they are said to be Y-connected. If the coils are connected so that they form a continuous loop, they are said to be delta-connected.

The effective power developed in a single coil in any three-phase circuit is the product of the potential difference across the coil and the current through it, multiplied by the cosine of the phase angle between the potential difference and the current. The effective power developed in all three coils of a balanced three-phase alternator is three times the amount developed in one coil.

The wattmeter is used for measuring power in three-phase circuits. It is connected into a circuit so that both the current in the load and the potential difference across it affect the reading. Three wattmeters—one on each line, or two wattmeters—each one connected to two lines, can be used to measure the total power consumed by the load. The sum of the readings on the wattmeters is the total power consumed.

# Chapter 8: Principles of Transformers

## In this Chapter

Magnetic Field

No-Load Operation

Construction of Transformers

Variable Transformers

Transformer Losses and Efficiency

Autotransformers

Instrument Transformers

## Objectives

After completing this chapter, you should be able to:

- Explain the difference between the primary winding and the secondary winding in a transformer.
- Explain how the windings are positioned in a core-type transformer.
- List the kinds of losses that occur in transformers.
- State the definition of a current transformer.
- List the functions of an instrument transformer.

## Terminology

**Primary winding:** The transformer winding that receives current from the supply

**Secondary winding:** The transformer winding connected to the load

**Step-up transformer:** A transformer that is used for increasing the potential difference

**Step-down transformer:** A transformer that is used for decreasing the potential difference

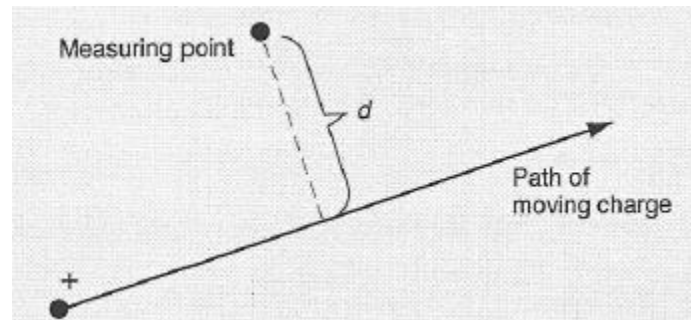
**Autotransformer:** A transformer in which a single winding serves as both the primary and secondary windings

Different electrical devices require different voltages. Some require 120 V, some 240 V, others 480 V. The transformer enables us to have power generated at a convenient voltage. Depending on how the windings are connected to the supply and to the load, the transformer can increase or decrease potential difference as needed.

In this lesson, you will study the basic operating principles and characteristics of transformers. Understanding transformer losses will help you to calculate the efficiency of the transformers in your plant. You will also study how to use instrument transformers and test instruments.

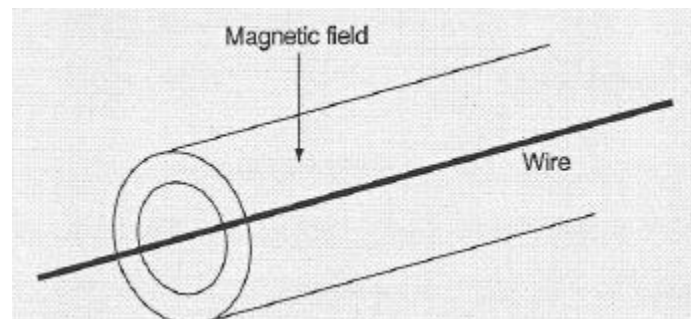
## Magnetic Field

- 8-1 A moving electric charge creates a magnetic field. The strength of the field at any point in space depends on the amount of charge, on how fast the charge is moving, and on the distance of the charge from the point where the field strength is measured. Figure 8.1 shows these variables. Doubling the charge, or doubling its speed, doubles the strength of the magnetic field. Doubling both multiplies the field strength by four. Doubling the distance of the charge from the point of measurement divides the strength of the magnetic field by four.



**Figure 8.1: Creation of a Magnetic Field**

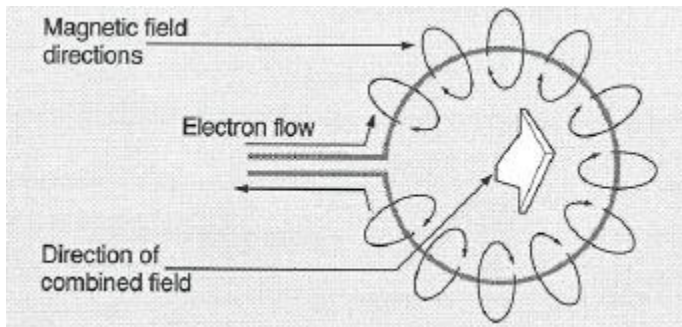
- 8-2 The moving charge may be either positive or negative. It may exist on particles flying through a vacuum, as shown in Figure 8.2, or on particles moving through a conducting material. The most common example of a moving charge is the current in a wire. It consists of negatively charged electrons jumping from atom to atom in the metal.



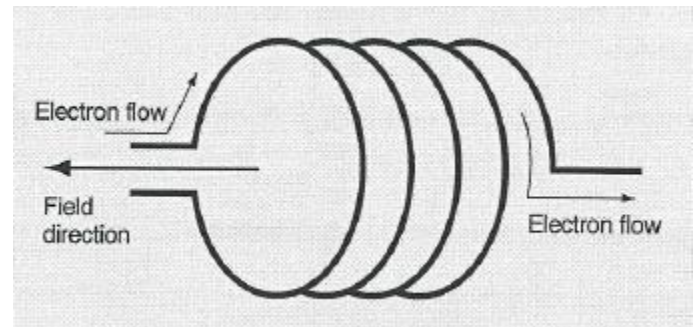
**Figure 8.2: Magnetic Field of a Current-Carrying Wire**

## Magnetic Field (continued)

8-3 If the wire is bent into a loop, as shown in Figure 8.3, the magnetic field inside the loop increases in strength. The reason is that more moving charges are near the points inside a loop than inside a straight wire. If a long wire is coiled into many loops, as shown in Figure 8.4, the field inside the coil becomes even stronger because more charges are moving near the points inside the loop.



**Figure 8.3: Magnetic Field of a Loop of Wire**



**Figure 8.4: Magnetic Field of Multiple Loops**

8-4 Inserting a core of iron, nickel, cobalt, or some other magnetic material into the coil further increases the strength of the magnetic field. The reason is that the magnetic field of the coil aligns the magnetic domains inside the material. The fields of these magnetic domains then add to the field produced by the current in the coil.

8-5 If a second coil is brought near the current-carrying coil, a current can be induced in it. The current can be induced in several ways, provided there is a change in the relationship between the second coil and the magnetic field of the first. For example, a current will be induced in the second coil if any of the following events occurs.

- One coil moves toward or away from the other.
- One coil rotates while the other remains stationary.
- The core moves into or out of either coil.
- The current changes in the first coil.

8-6 If the ends of the second coil are not connected electrically, current cannot exist in the coil. Instead, a potential difference will be created between the ends. If the ends are connected through a resistor, a capacitor, or another coil, both current and potential difference will be created between the ends of the coil.

8-7 A simple transformer consists of two coils mounted in fixed positions relative to each other. One coil is supplied by an alternating current. As the current alternates, the magnetic field it produces also alternates. This alternating field induces an alternating current in the second coil which supplies a load.

## Magnetic Field (continued)

- 8-8 A simple transformer consists of two coils wound on a closed iron core as seen in Figure 8.5. The winding connected to the supply is called the *primary winding*. The winding connected to the load is called the *secondary winding*.

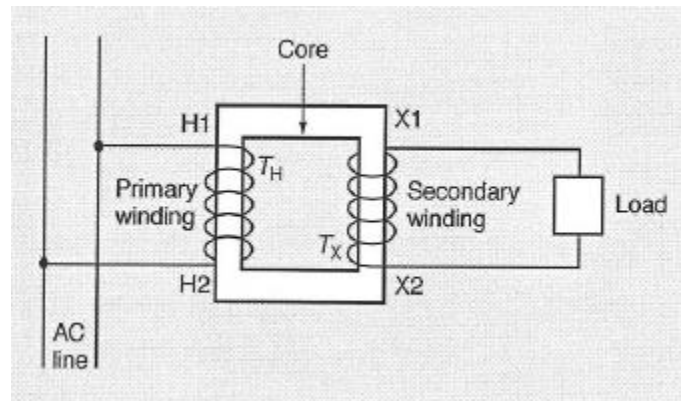


Figure 8.5: Simple Transformer

- 8-9 If the transformer is used for increasing the potential difference, it is called a *step-up transformer*. In this kind of transformer, the low-voltage winding is the primary. If the transformer is used for decreasing the potential difference, it is called a *step-down transformer*. In this case, the high-voltage winding is the primary.
- 8-10 Standard markings are used for transformer terminals. The terminals of the high-voltage winding are marked H1, H2 and so on. The low-voltage terminals are marked X1, X2 and so on. The number of turns in each winding is abbreviated  $T_H$  or  $T_X$ . All these markings are shown in Figure 8.5.

## No-Load Operation

- 8-11 Suppose an alternating current is supplied in the high-voltage (H) winding if the step-down transformer shown in Figure 8.5. No load is connected to the secondary winding. The RMS current in the primary winding is very small, because the winding is an almost pure inductive load. The more turns of wire included in the primary winding, the closer the winding is to a purely inductive load and the lower its RMS current.
- 8-12 The AC supply sets up an alternating magnetic field in the core. As the field alternates, it induces a potential difference in the secondary winding. The amount of potential difference induced per turn in the secondary winding equals the amount applied per turn in the primary. Therefore, the ratio of potential differences from primary to secondary equals the ratio of turns in the two windings. The following equation expresses the equality of the two ratios.

$$\frac{E_H}{E_X} = \frac{T_H}{T_X}$$

- 8-13 For example, suppose a transformer has 2000 turns in the primary and 200 turns in the secondary. The primary is attached to a source supplying 240 V RMS. What is the potential difference across the secondary winding?
- 8-14 To answer this question, you start by writing the equation. Then you substitute all the values you know, and solve the equation for the unknown value, as shown below.

$$\text{Total} \quad \frac{E_H}{E_X} = \frac{T_H}{T_X}$$

$$\frac{240 \text{ V}}{E_X} = \frac{2000 \text{ turns}}{200}$$

$$E_X = 240 \text{ V} \times \frac{200 \text{ turns}}{2000 \text{ turns}} = 240 \text{ V} \times \frac{1}{10} = 24 \text{ Volts}$$

- 8-15 If the two windings have no resistance, the current in the primary lags the potential difference by  $90^\circ$ . Therefore, the potential difference in the secondary lags the potential difference in the primary by  $180^\circ$ . Figure 8.6 is a graph showing this relationship between the potential differences and the currents in the two windings.

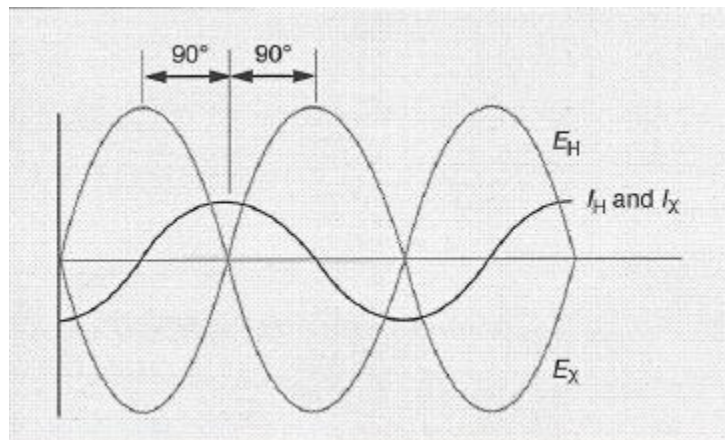


Figure 8.6: AC Values in Transformer Windings

## No-Load Operation (continued)

8-16 One of the basic laws of nature is that you never get something for nothing. A transformer cannot deliver power unless it takes in at least an equal amount of power. The power enters the transformer in the primary winding. The amount of power entering the primary is slightly greater than the amount of power delivered from the secondary. The difference equals the amount of power lost within the transformer. In modern transformers, the loss is quite small compared to the amount of power either received or delivered.

8-17 The product of the current in a transformer winding and the number of turns that make up the winding is the same for both windings.

$$I_H T_H = I_X T_X$$

8-18 This product is commonly called the number of *ampere-turns* in the winding. The equation expresses the fact that the number of ampere-turns in the primary equals the number of ampere-turns in the secondary. You can use this fact in calculating currents in the windings.

8-19 For example, suppose a transformer supplies a current of 50 A to a load at 480 V. The primary of the transformer has 2400 turns of wire and the secondary has 240 turns. What is the current in the primary winding and how much power does the transformer receive from the supply?

8-20 The number of ampere-turns in the secondary winding is 12,000 (50 A x 240 turns). Therefore, the primary winding must also have 12,000 ampere-turns. It has 2400 turns of wire, so the current must be 5 A.

8-21 The power delivered by the secondary is the product of the current and the potential difference which is 24,000 W or 24 kW. The power the transformer receives from the supply is exactly equal to the amount delivered, if there are no losses in the transformer. If you multiply the potential difference across the primary winding by the current in it, you will find that the power received by the primary is 24kW which is the proper amount according to the laws of nature.

8-22 In a real transformer, the power going in at the primary is slightly higher than the power delivered at the secondary. Therefore, the current in the primary of this transformer would have to be slightly more than 5 A. To calculate the current exactly, you would need to know the efficiency of the transformer.

8-23 The rated capacity of a transformer is the amount of power it can accept and deliver without overheating. This power is the RMS power which is the product of RMS potential difference and RMS current. The rated capacity of the transformer does not take into account the power factor of the load.

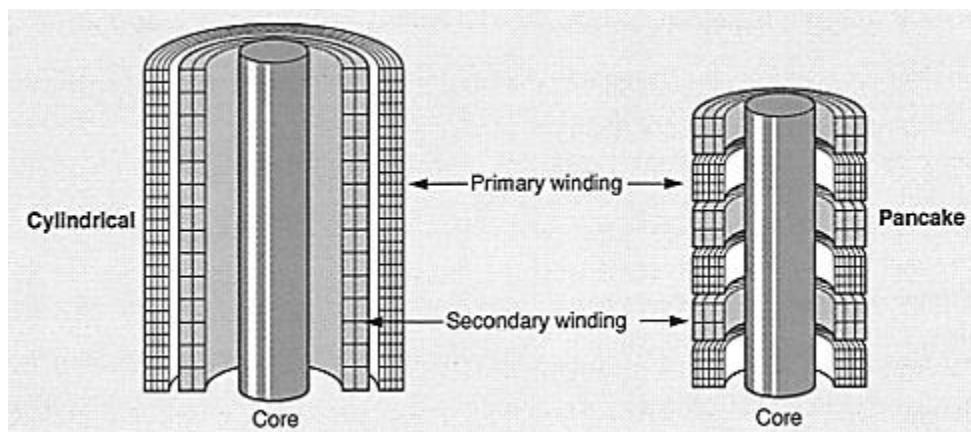


## Construction of Transformers

8-24 The windings of commercial transformers are not placed on separate "legs" of the core, as shown by the simplified diagram in Figure 8.5. The transformer can be made more efficient by placing both windings on the same leg, or by placing both windings on both legs. Placing the two windings together enables more of the magnetic field of the primary to induce current in the secondary.

8-25 There are two ways to combine the primary and secondary windings on a single leg of the core. Both ways are shown in Figure 8.7.

- The windings may be cylindrical and wound one over the other with insulation between them, as shown at the left in Figure 8.7.
- The windings may be shaped like pancakes and stacked alternately on the core, as shown at the right in Figure 8.7.



**Figure 8.7: Transformer Windings**

Notice the placement of the two windings. The low-voltage transformer winding is wound next to the core. The high-voltage winding is wound over the low-voltage winding.

8-26 The construction of transformers varies widely according to their size and use. One variation is the arrangement of the iron core and the windings. There are two basic construction arrangements— the core arrangement and the shell arrangement.

## Construction of Transformers (continued)

8-27 The *core-type transformer* has a core made in the shape of a hollow square. Half the windings are placed on each leg of the core. The arrangement of the windings is shown at the left in Figure 8.8.

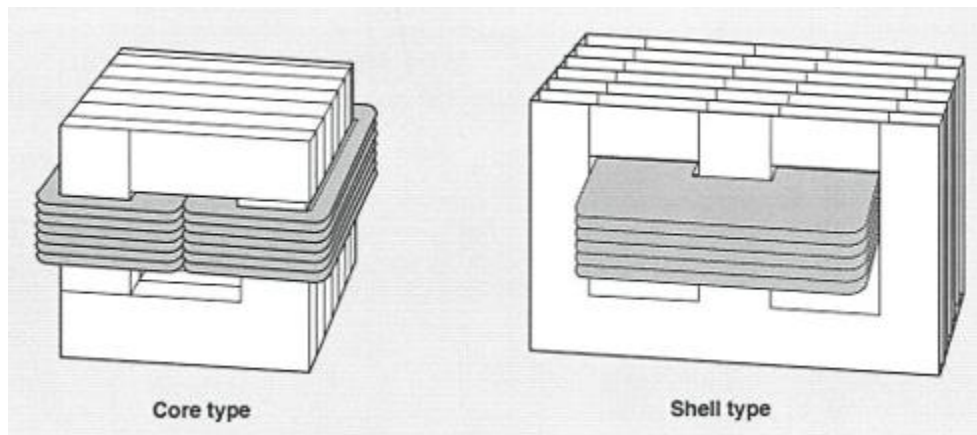


Figure 8.8: Types of Transformer Cores

8-28 Notice that the core of the core-type transformer passes through the center of the windings, but does not surround the windings. By contrast, the *shell-type transformer* has a core that surrounds the windings as well as passing through the center. This kind of core is shown at the right in Figure 8.8.

8-29 Typical transformer cores are made of thin steel sheets, called *laminations*. The laminations are coated with varnish or with some other insulating material and stacked together to form the core.

8-30 The number of laminations stacked together determines the thickness of the transformer core. The purpose of this laminated construction is to reduce the eddy currents that waste energy in a transformer.

8-31 Another kind of core is made of steel strip or C) ribbon wound in a spiral on a form. When this type of core is used, power losses are reduced, tighter construction of the transformer is possible, and the magnetic characteristics of the core are improved.

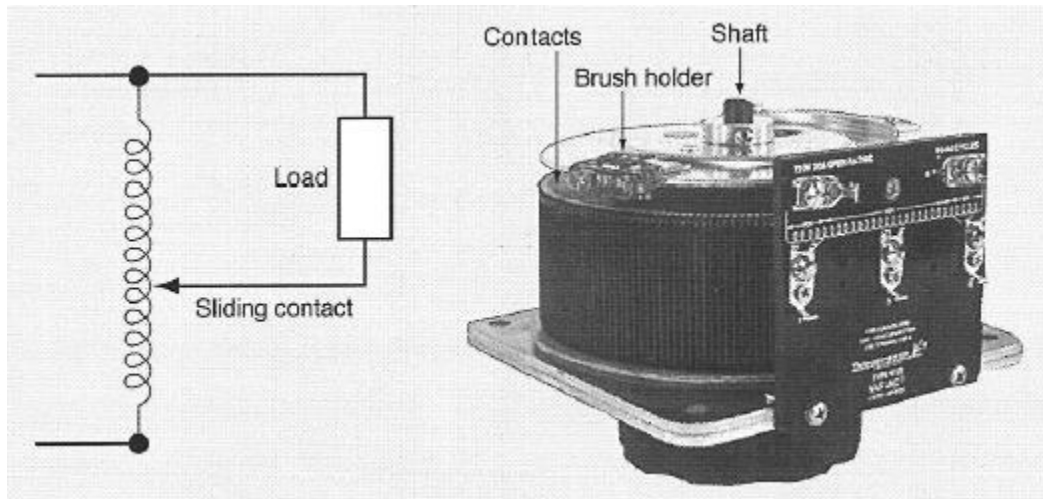
8-32 Transformer coils are usually made of copper because of its low resistance. They are designed to fit the required number of turns into a minimum amount of space. The cross-sectional area of the conductor must be large enough so that the conductor can carry the maximum required current without overheating. The coil must also be designed to leave enough space for insulation and for cooling ducts.

8-33 Round copper wire is used in transformer coils that carry low current. Round wire larger than number 10 is generally not used because of the large amount of wasted space between wires. Either square or rectangular wire ribbon is used instead.

8-34 The wire is insulated with cotton, enamel, paper, or a combination of materials. The insulation must have the proper dielectric strength for the potential difference between it and other parts of the transformer.

## Variable Transformers

- 8-35 A variable transformer has a movable-brush tap that rides on the transformer winding. An example is shown in Figure 8.9. Moving the brush makes small changes in the potential difference across the output terminals. The output can vary from zero up to the potential difference across the primary terminals. Some variable transformers can provide an output up to 20% higher than the potential difference across the input lines.



**Figure 8.9: Variable Transformer**

- 8-36 Variable transformers are available for single- and three-phase systems. They can be adjusted manually or by a servo motor. Many variable transformers operate on a primary input at 120 V, but units are also available that operate on 240 or 480 V.
- 8-37 Variable transformers have many applications, including the dimming of lights and adjusting of line voltage. For example, they are used as power sources for operating laboratory equipment that requires a specific potential difference.

## Transformer Losses and Efficiency

8-38 Transformers have high efficiencies, especially the larger sizes operating at 50 to 100% of full load. However, they are not perfect. Some losses occur in all transformers. These losses are divided into two types; copper losses and core losses.

8-39 *Copper loss* is the loss of power caused by the resistance of the copper windings. As current passes through the windings, it generates heat. The greater the current in the windings, the more power is lost in producing heat. The more current required by the load, the greater the copper loss. For this reason, copper losses are sometimes called *load losses*.

8-40 You can calculate the copper loss,  $P_L$ , for any given load current if you know the resistance of both windings. You calculate the current in the primary winding by multiplying the current in the secondary by either the ratio of turns or the ratio of potential differences. Then, you square each current, multiply it by the resistance of the winding and add the two values together.

$$P_L = I_H^2 R_H + I_X^2 R_X$$

8-41 Core loss occurs in two ways. One is the *eddy-current* loss, caused by the formation of eddy currents in the core material. The other is *hysteresis loss*, caused by the reversal in direction of the magnetic field in the core. Both losses produce heat in the transformer.

8-42 Eddy currents are reduced by laminating the core. Laminations break up the path of currents. The laminations are insulated from one another by oxidation on the surface of the plates, or by a thin coat of varnish.

8-43 The hysteresis loss is reduced by using a core of the proper material. The material must be one that can reverse its magnetic polarity easily.

8-44 Core losses are usually constant for all loads. You can measure the total loss by connecting wattmeter to the primary winding while the secondary winding is open-circuited. The power consumed by the primary winding equals the power lost in the transformer.

8-45 The efficiency of a transformer is defined in the same way as the efficiency of any other device.

$$\text{Efficiency} = \frac{\text{Work Output}}{\text{Work Input}}$$

8-46 The ratio of work output to work input equals the ratio of the power output to the power input, because work is the product of power and time.

$$\text{Efficiency} = \frac{\text{Work Output}}{\text{Work Input}} = \frac{(\text{Power Output}) \times \text{Time}}{(\text{Power Input}) \times \text{Time}} = \frac{\text{Power Output}}{\text{Power Input}}$$

## Autotransformers

8-47 The prefix *auto* means *self*. An autotransformer is a self-induced transformer. It has the primary and secondary windings electrically connected, as shown in Figure 8.10. When the transformer is used as a step-down transformer, the entire winding serves as the primary winding. The section XY is common to both the primary and secondary windings.

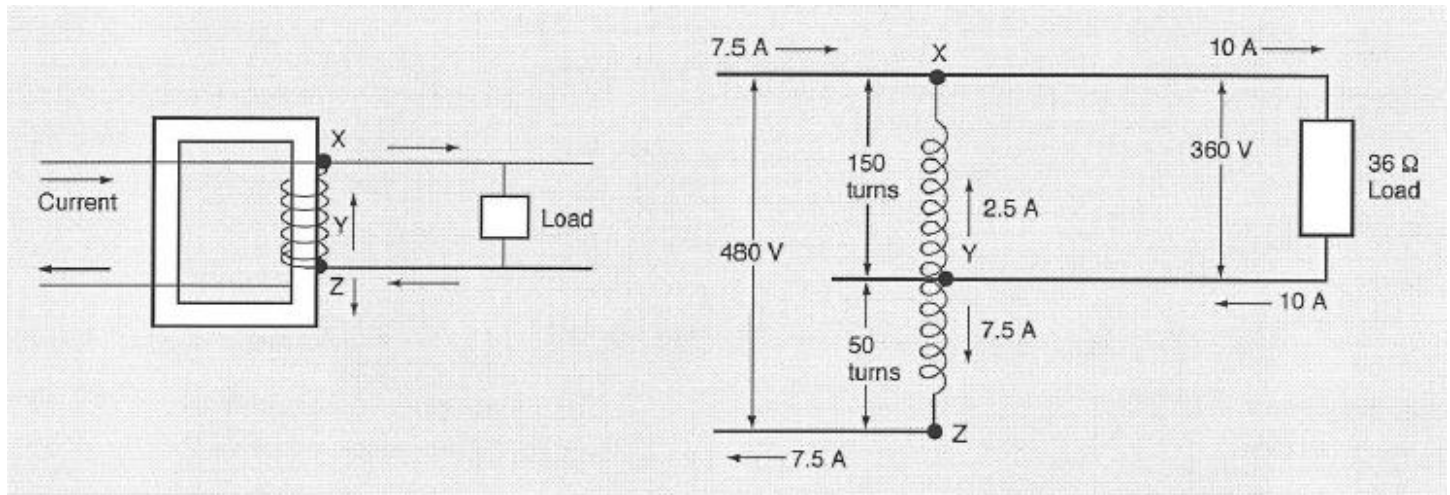


Figure 8.10: Autotransformer

8-48 As with the two-winding transformer, the ratio of potential differences equals the ratio of primary turns to secondary turns.

$$\frac{E_H}{E_X} = \frac{T_H}{T_X}$$

8-49 For example, the autotransformer in Fig. 8-10 has a total of 200 turns. Section XY has 150 turns, and section YZ has 50 turns. A potential difference of 480 V is applied across the transformer winding. The potential difference is therefore 360 V between X and Y, and 120 V between Y and Z.

$$\frac{E_H}{E_X} = \frac{T_H}{T_X} \quad \frac{360}{120} = \frac{150}{50}$$

8-50 An autotransformer is more efficient than a similar two-winding transformer, because the section common to the primary and secondary carries the difference between the primary and secondary current. This reduction in current makes the copper loss in an autotransformer much less than the copper loss in a two-winding transformer.

8-51 For example, suppose a resistive load of 36 Ω is connected to terminals X and Y. According to Ohm's law, the current in the load will be 10 A.

## Autotransformers (continued)

- 8-51 For example, suppose a resistive load of  $36 \Omega$  is connected to terminals X and Y. According to Ohm's law, the current in the load will be 10 A.

$$I = \frac{E}{R} = \frac{360 V}{36 \Omega} = 10 A$$

Therefore, the power output is 3600 W.

$$P_{out} = E \times I = 360 V \times 10 A = 3600 W$$

- 8-52 The power input equals the power output, so the primary current is 7.5 A.

$$P_{out} = E \times I = I = \frac{P_{out}}{E} = \frac{3600 W}{480 V} = 7.5 V$$

- 8-53 If you now apply Kirchhoff's point rule to point Y, you can see that the current in section XY of the winding is only 2.5 A. The diagram in Figure 8.10 shows the currents in each path connected to point Y.

- 8-54 Autotransformers are used in boosting the potential difference across a distribution line by a small fraction to compensate for voltage drop in the line. Another common use of the autotransformer is in starting large AC motors. The potential difference is reduced at starting, and held at that level until the motor reaches about 75% of its rated speed. Then, the motor is switched over to full potential difference across the line.

- 8-55 Autotransformers can be dangerous if used for reducing a high potential difference. If the winding that is common to both the primary and secondary should become open, the full potential difference across the primary terminals will occur across the secondary terminals.

## Instrument Transformers

- 8-56 Current- and voltage-measuring instruments are designed to operate at low current and low voltage. Safety is also a reason for not connecting test instruments to sources operating at high voltage. An instrument transformer reduces high voltages and currents to safe values.
- 8-57 An instrument transformer performs two functions.
- It serves as a ratio device so that low-voltage and low-current instruments can indicate accurate values for high-voltage and high-current equipment.
  - It serves as an isolating device, protecting the test equipment and operating personnel from high voltages.
- 8-58 There are two kinds of instrument transformers—potential transformers and current transformers. They are described in the following paragraphs.
- 8-59 *Potential transformers* establish a known ratio between the potential difference across the equipment and the potential difference across a volt-meter. For example, suppose a potential transformer establishes a ratio of 500 to 1. If a voltmeter connected across the secondary terminals reads 132 V, you know the potential difference across the primary terminals is 66,000 V.
- 8-60 Current transformers establish a known ratio between the current in the equipment and the current measured by an ammeter. These transformers provide a means of measuring currents beyond the normal range of most ammeters. In addition, the transformer isolates the equipment from the operator.
- 8-61 A current transformer increases the potential difference, but decreases the current to a measurable value. The secondary then contains more turns than the primary. The ratio of the primary to the secondary current is inversely proportional to the ratio of the primary to the secondary turns.
- 8-62 The primary winding in a current transformer may be nothing more than a solid copper busbar, as shown at the left in Figure 8.11. An iron core fits around the busbar, and the secondary winding is wound around the core. Another kind of current transformer consists of a doughnut-shaped secondary coil that you slip over a feeder cable. Another kind of current transformer consists of a doughnut-shaped secondary coil that you slip over a feeder cable.

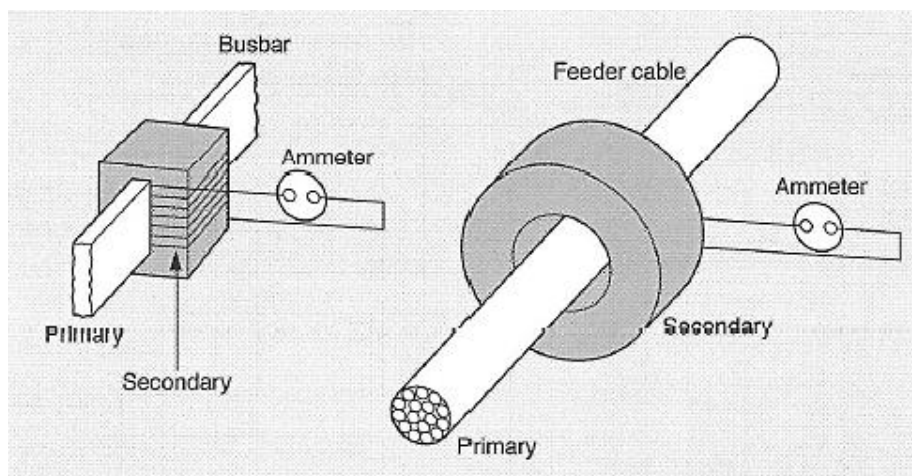


Figure 8.11: Current Transformers

## Instrument Transformers (continued)

- 8-63 To prevent damage to the equipment and injury to yourself and other people, the secondary winding of the current transformer must be short-circuited before removing the transformer from or connecting it to any equipment. Most current transformers have a shorting device that shorts the secondary winding automatically.
- 8-64 The diagram in Figure 8.12 shows how to measure the current, potential difference, and power in a circuit having a high current and high potential difference. Notice how the potential transformer and current transformer are connected.

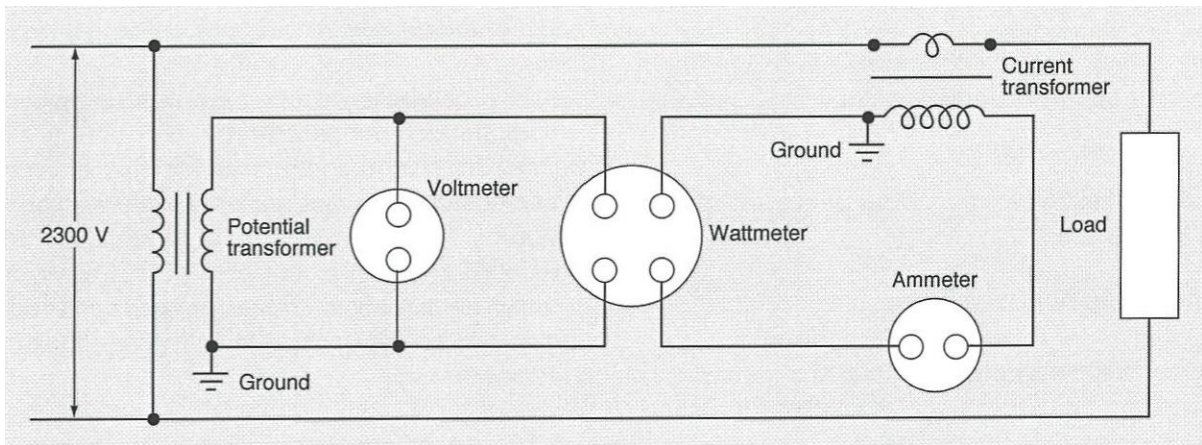


Figure 8.12: Using Potential and Current Transformers



## Chapter 8 Exercise

Circle the appropriate letter next to the correct answer.

1. The strength of a magnetic field at any point in space does not depend on \_\_\_\_\_.
  - a. How fast the charge moves
  - b. The amount of charge moving
  - c. The distance between the charge and the measuring point
  - d. The type of charge
  
2. Which of the following has the strongest magnetic field?
  - a. Straight length of wire
  - b. Wire coil with many loops
  - c. Wire coil with many loops around an iron core
  - d. Wire coil with one loop
  
3. The low-voltage winding is the primary winding in a(n) \_\_\_\_\_.
  - a. Alternating transformer
  - b. Autotransformer
  - c. Step-down transformers
  - d. Step-up transformer
  
4. A transformer has 3500 turns in the primary, and 350 turns in the secondary. What is the potential difference across the secondary if the primary is connected to a 120 V source?
  - a. 10 V
  - b. 12 V
  - c. 35 V
  - d. 120 V
  
5. What metal is usually used for the wire in transformer coil?
  - a. Aluminum
  - b. Babbit
  - c. Brass
  - d. Copper

## Chapter 8 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. Copper loss is a loss of power caused by \_\_\_\_\_.
- a. Counter EMF
  - b. Eddy currents
  - c. Magnetic field reversal
  - d. Resistance
7. Hysteresis loss is reduced by using the proper \_\_\_\_\_.
- a. Lamination thickness
  - b. Load
  - c. Material in the core
  - d. Number of coils
8. Which of the following reduces high voltages and currents to safe values for measurement?
- a. Autotransformer
  - b. Instrument transformer
  - c. Megohmmeter
  - d. Variable transformer
9. A potential transformer establishes a ratio of 300 to 1. A voltmeter between the secondary terminals reads 125 V. What is the potential difference between the primary terminals?
- a. 0.417 V
  - b. 125 V
  - c. 37,500 V
  - d. 41,700 V
10. How can you protect yourself and your measuring instruments when you remove or connect a current transformer?
- a. Ground the transformer and the instrument
  - b. Handle the transformer very carefully
  - c. Open-circuit the secondary winding
  - d. Short-circuit the secondary winding

## Summary

Transformers are used for changing electricity from one voltage to another. A transformer consists of two wound coils mounted in fixed positions relative to each other. The winding that receives current from the supply is called the primary winding. The winding connected to the load is called the secondary winding.

There are two basic arrangements of the transformer core and windings. One is the core arrangement, in which the core is in the shape of a hollow square. Half the windings are placed on each leg of the core. The other is the shell arrangement, in which the core surrounds the windings as well as passing through the center. These arrangements are used to make the transformer more efficient.

All transformers have copper losses or core losses. Copper loss is the loss of power caused by the resistance of the copper windings. Core losses are caused by either eddy currents or hysteresis. Eddy-current loss is caused by the formation of eddy currents in the core material. They are reduced by the use of laminations. Hysteresis loss is caused by the reversal in direction of the magnetic field of material that can reverse its magnetic polarity easily.

Before connecting any test instrument to a transformer, you should make sure the voltage and current are low enough not to cause damage or personal injury. An instrument transformer is used for reducing high voltages and currents to safe values.



# Chapter 9: Transformer Applications

## In this Chapter

Transformer Designation

Transformer insulation

Transformer Cooling

Transformer Polarity

Single-Phase Transformer Connections

Three-Phase Transformer Connections

Three-Phase Transformers

Installing Transformers

## Objectives

After completing this chapter, you should be able to:

- Name the general kinds of transformers.
- List the temperature limits for each class of transformer insulation.
- Explain how oil-immersed transformers are cooled.
- Name the common methods of connecting three single-phase transformers for three-phase operation.
- Explain how to select the correct location for a transformer.

## Terminology

**General-purpose transformer:** A dry transformer rated for an input of 600 V or less

**Load-center transformer:** A dry or liquid-filled transformer rated at 2400 V to 15,000 V at the input and 600 V or less at the output

**Distribution transformer:** An oil-filled transformer rated a 3 to 500 Kw at an input or 480 to 15,000 V

**Substation transformer:** A coolant-filled transformer rated for an input of 24000 to 67,000 V and an input of 600 to 15,000 V

**Power transformer:** A transformer rated above 500 kW at an input of over 67,000 V

Many different kinds of transformers are manufactured to serve various electrical requirements. In this chapter, you will study the characteristics of general-purpose, load-center, distribution, substation, and power transformers. You probably have seen several or all of these in or near your plant.

Insulation and cooling techniques are important to the efficiency of any transformer. You must make sure the transformer is insulated with a material that can withstand the ambient temperature, and that the cooling system is sufficient.

In this chapter, you will also study the basics of transformer handling and installation.

## Transformer Designation

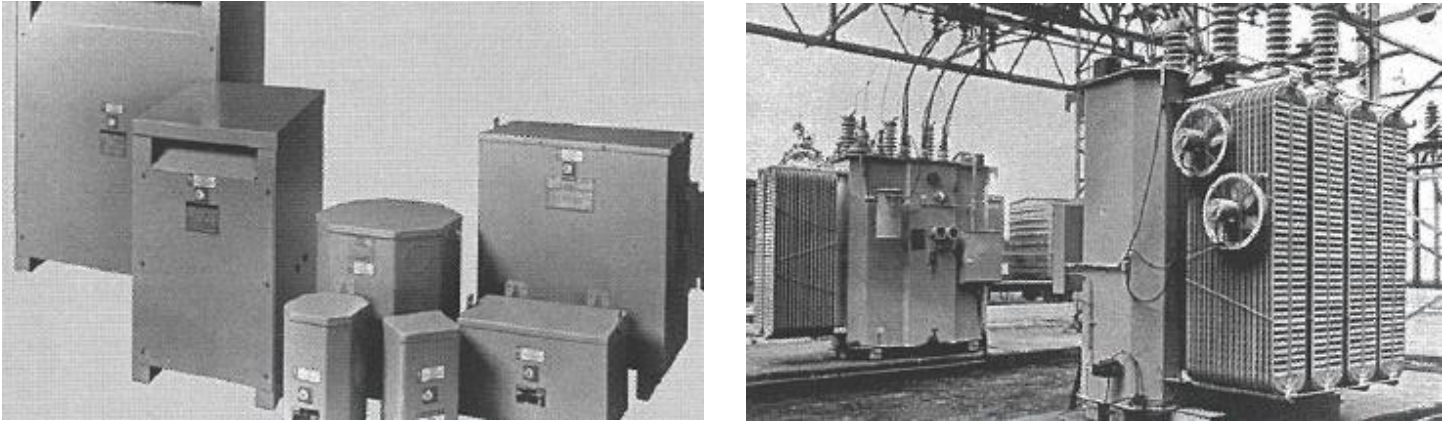
- 9-1 Many different kinds of transformers are manufactured. They are listed in the manufacturers' catalogs according to their ratings and construction features. Some of the most important general kinds of transformers are described in the following paragraphs.
- 9-2 *General-purpose transformers* are dry transformers. Most are rated for an input of 600 V or less. Their main use is for reducing potential differences to C) the values needed for general power and lighting. The general-purpose transformer may be mounted on the wall, suspended from the ceiling, or freestanding.
- 9-3 *Load-center transformers* can be either dry or liquid-filled. They are either base-mounted or freestanding, and may be located either indoors or outdoors. Most are rated for 2400 to 15,000 V at the input, and 600 V or less at the output. The load-center transformer is usually included as part of a packaged unit substation.
- 9-4 *Distribution transformers* have power ratings of 3 to 500 kW at an input of 480 to 15,000 V. They are mounted either on utility poles or on platforms. Transformers rated up to 167 kW can be mounted on poles. Larger transformers must be mounted on platforms.
- 9-5 Distribution transformers are supplied as both single-phase and three-phase units. They are filled with a non-conducting oil. The oil is either a natural or a synthetic material made especially for use in transformers.
- 9-6 *Substation transformers* are filled with liquid coolant. They are rated for an input of 2400 to 67,000 V and an output of 600 to 15,000 V. This kind of transformer is used in industrial substations and for utility distribution.
- 9-7 *Power transformers* are those rated above 500 kW. These large, outdoor transformers are used by utilities in transmission and distribution systems operating at more than 67,000 V. These units must be installed according to the specifications and standards of public utilities.

## Transformer Insulation

- 9-8 The kind of insulation used in a dry transformer determines the size and operating temperature of the unit. NEMA (the National Electrical Manufacturers Association) has defined four classes of insulation specifications and temperature limits. These are described in the following paragraphs.
- 9-9 **Class A.** Materials in this class are designed for use in an ambient temperature no higher than 104°F (40°C). The temperature rise in the transformer windings must not exceed 99°F or 55°C. That is, it must not go over 203°F (95°C). Transformers insulated with Class A material are used as control transformers or as distribution transformers where combustible materials may be present.
- 9-10 **Class B.** The insulation in this class can withstand temperatures up to 248°F (120°C). If the ambient temperature is 104°F (40°C), the temperature of the windings may rise by 144°F or 80°C. A transformer insulated with Class B material is smaller and weighs about half as much as one of the same electrical rating insulated with Class A material. Transformers insulated with Class B material are popular as distribution transformers.
- 9-11 **Class F.** This class of material can withstand temperatures as high as 311°F (155°C). If the ambient temperature is 104°F (40°C), the temperature of the windings can rise by 207°F or 115°C. Transformers insulated with Class F material are smaller than those insulated with Class B material. They are available at 25 kW or less in both single-phase and three-phase designs.
- 9-12 **Class H.** Materials in this class are made of glass and silicon. They can withstand temperatures as high as 374°F (190°C). For example, if the transformer is located where the ambient temperature is 104°F (40°C), the temperature of the windings can rise by 270°F or 150°C. transformers insulated with Class H materials are the most compact available. The core and coil are enclosed in a ventilated housing. These units are available at ratings of 30 kW and higher.

## Transformer Cooling

- 9-13 A transformer in operation develops heat as a result of the copper and core losses during operation. Heat is not produced rapidly in small transformers, but the rate is much higher in large transformers. The rate of heat production determines how high the operating temperature rises above the ambient temperature.
- 9-14 Getting rid of heat is a key element in keeping the temperature of a transformer as low as possible. The necessary rate of heat dissipation influences the size and construction of a transformer. Transformers are classified in two groups according to the method of cooling—*dry-type* and *oil-immersed*. Both classifications are described in the following paragraphs. Examples are shown in Figure 9.1.



**Figure 9.1: Dry-Type and Oil-immersed Transformers**

- 9-15 *Dry-type transformers* are cooled by air circulating over the outside housing. These transformers are usually rated no higher than 500 kW. Dry-type transformers are commonly wall-mounted, and used for lighting. Unlike oil-immersed transformers, they may be used indoors without a fireproof vault.
- 9-16 *Oil-immersed transformers* are suspended in tanks filled with oil. The oil absorbs heat from the transformer and delivers it to the environment outside the transformer.
- 9-17 Some transformers are cooled by convection. The oil expands as it becomes warm from contact with the transformer coils. It then rises to the top of the tank and releases the heat to the surrounding air. The cool oil sinks back to the bottom of the tank. This circulation continues as long as the transformer produces heat.
- 9-18 The tank of an oil-immersed transformer is designed to remove heat from the oil as rapidly as possible. The surface of the tank may have fins to expose more surface area to the surrounding air and increase the rate of cooling. If the transformer requires faster cooling, it can be equipped with fans to force air over the tank.
- 9-19 Some transformers are cooled by circulating water. A coil of pipe, usually made of copper, is placed inside the tank just below the surface of the oil. The ends of the pipe extend out through the tank wall and are connected to a pump that forces cool water through the pipe while the transformer is operating.

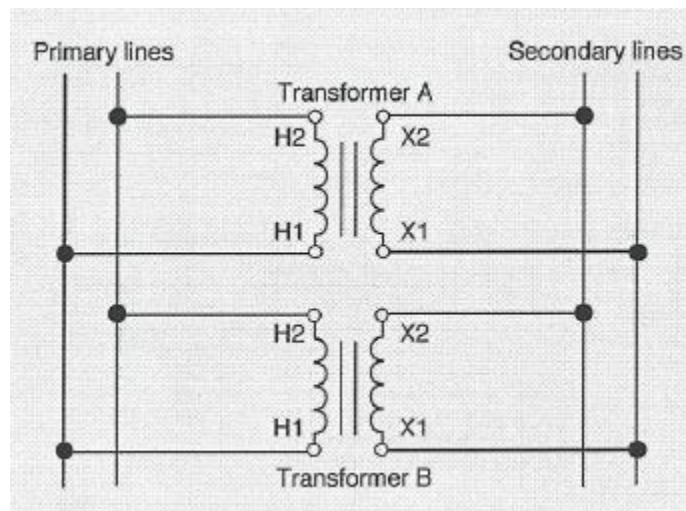


## Transformer Cooling (continued)

- 9-20 The oil can also be cooled by pumping it through a radiator exposed to the air. For faster cooling, fans may force air over the radiator.
- 9-21 An effective cooling system for the transformer can increase transformer capacity by 25 to C) 50%. For example, a 2000 kW transformer, if cooled efficiently, can operate at 3000 kW without damage.

## Transformer Polarity

- 9-22 Sometimes you may be called upon to connect one transformer in parallel with another. In order to connect two transformers for successful parallel operation, you must know the instantaneous polarities of the transformers. Two transformers with their primaries connected to the same supply and their secondaries connected to the same output lines are shown in Figure 9.2.



**Figure 9.2: Transformers Connected in Parallel**

- 9-23 Standard polarity markings enable you to connect transformers in parallel correctly. The transformers shown in Figure 9.2 are connected so that the H1 terminals are connected to one primary line and the 1--12 terminals are connected to the other primary line. Then, the X1 terminals are connected to one secondary line and the X2 terminals to the other secondary line.

## Transformer Polarity (continued)

9-24 If a transformer is not marked, you can determine its polarity very easily. Figure 9.3 shows the test connections. Viewing the transformer from potential the high-voltage side (the side indicated by the arrow), mark the left-hand terminal H1 and the right-hand terminal H2. Temporarily mark the low-voltage terminals XA and X B, as shown. Then, short terminals H1 and XA by connecting them with a jumper wire.

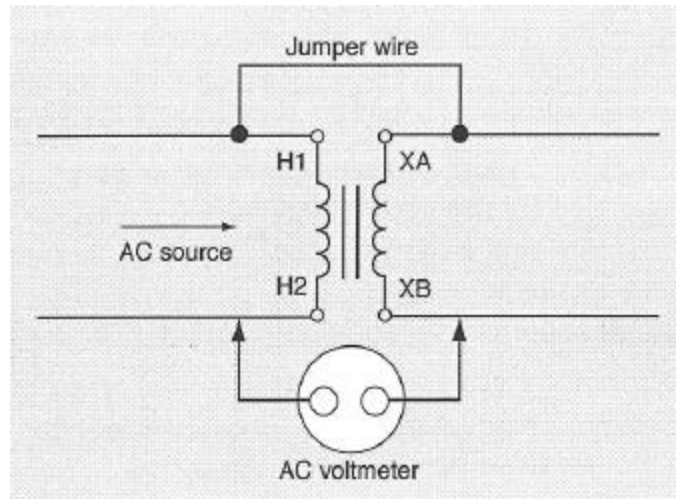


Figure 9.3: Phasing a Transformers

9-25 Connect an AC voltmeter across terminals 1-12 and XB. Connect H1 and H2 to a convenient ac source. An ordinary 120 V supply is good.

- If the voltmeter reading is less than the applied potential difference, the polarity is *subtractive*. Mark terminal XA as X1 and terminal XB as X2.
- If the voltmeter reads more than the applied difference, the polarity is *additive*. Terminal XA should be marked X2, and XB should be marked X 1.

9-26 To compensate for line drop, you may sometimes need to make small adjustments in the transformer ratio. The high-voltage windings of some transformers are equipped with a ratio-changing device. The winding is tapped at several points. Connections from these points are brought to a switch or terminal block inside the transformer tank. By operating the switch or changing the connections on the terminal block, you can select the winding ratio required to compensate for the line drop. For safety, disconnect the transformer from the power supply before making the adjustment.

## Single-Phase Transformer Connections

9-27 Distribution transformers are usually made with two secondary windings, as shown in Fig. 9-4. You have a choice in connecting the two windings. You can connect the two windings in series, as shown in the diagram at the left in Fig. 9-4, or in parallel, as shown at the right.

- The series connection gives you two outputs at different potential differences. The outputs are marked 120 V and 240 V in Fig. 9-4.
- The parallel connection gives you only one output, marked 120 V in Fig. 9-4. However, this connection enables the transformer to deliver more current than the series-connected transformer.

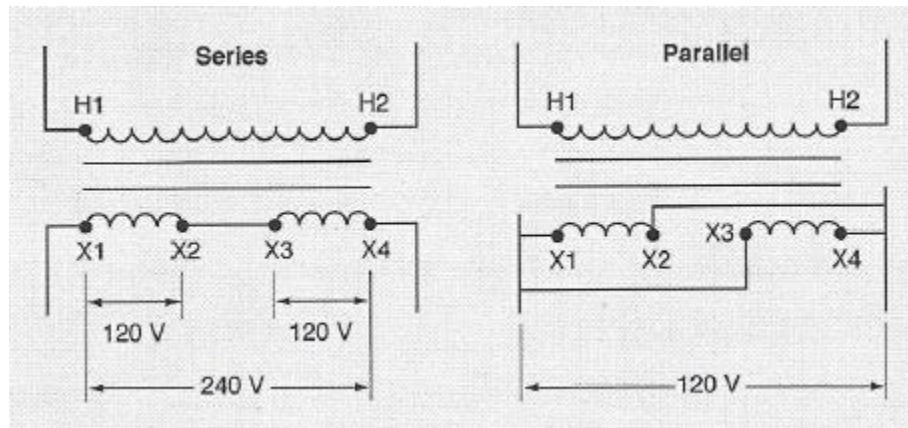


Figure 9.4: Connecting Transformer Secondary Windings

## Three-Phase Transformer Connections

9-28 Single-phase transformers can be connected to either increase or decrease the potential differences between the lines in a three-phase system. There are four common methods of connecting three single-phase transformers for three-phase operation:

- delta-delta
- delta-Y
- Y-delta
- Y-Y

All four methods are shown in figure 9.5 on the following page and are described in the following paragraphs.

### Three-Phase Transformer Connections (continued)

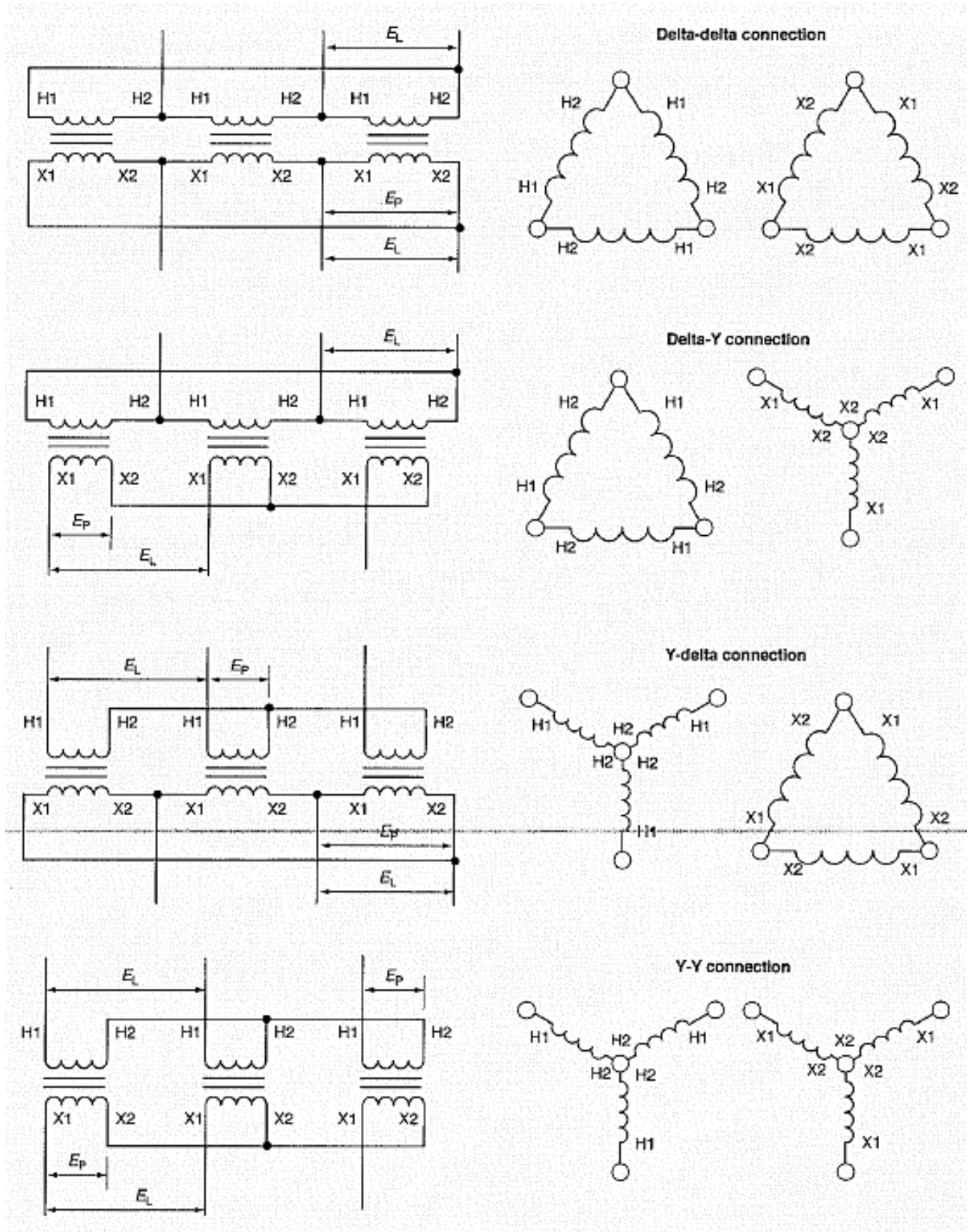


Figure 9.5: Single-Phase Transformers for Three-Phase Systems

## Three-Phase Transformer Connections (continued)

9-29 The *delta-delta connection* is quite common. One of its advantages is that, if one transformer is damaged or removed from service, the other two can be connected in an *open-delta* or *V-connection*, as shown in Figure 9.6. This type of connection gives you three-phase current and potential difference. However, the maximum load is only 57.7% (the reciprocal of the square root of 3) of a full delta-connected load.

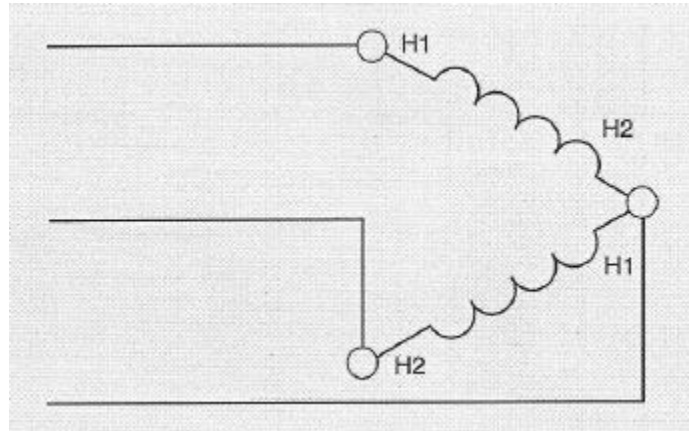


Figure 9.6: Open-Delta Connection

9-30 Power circuits for the operation of three-phase motors and other three-phase equipment are often supplied from 240 V delta-connected secondaries. To provide 120 V for lighting circuits, the midpoint of one transformer is brought out to form a four-wire delta system.

9-31 Figure 9.7 shows a three-wire, single-phase lighting circuit and a three-wire, three-phase circuit. The center-tapped transformer should have a higher capacity than the others.

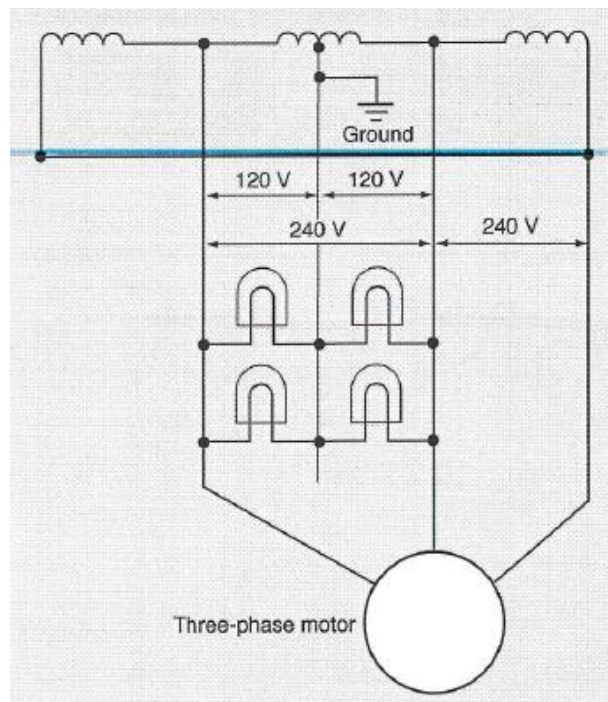


Figure 9.7: Three-wire Delta-Connection

## Three-Phase Transformer Connections (continued)

- 9-32 Both the delta-Y and the Y-delta connections can be used for either stepping up or stepping down the potential difference. With these connections, the ratio of the potential differences equals the transformer ratio multiplied by the square root of 3. Systems that require a grounded neutral conductor must have a Y connection as the secondary.
- 9-33 The Y-Y connection shown in Figure 9.5 provides only 57.7% of the line potential difference across each winding. But each winding carries the full line current. The Y-Y connection also disturbs communications equipment nearby. For these reasons, Y-Y connections are not often used.
- 9-34 To connect single-phase transformers for three-phase operation, the polarities must match.
- For a *Y-Y connection*, connect all the H2 terminals together and all the X2 terminals together.
  - For a *delta-delta connection*, H1 of each transformer must be connected to H2 of another transformer and X1 of each transformer to the X2 of another transformer.
  - The *delta-Y* and *Y-delta* connections are both combinations of these two connections.
- 9-35 When a large number of single-phase loads are to be served from a three-phase step-down transformer bank, the most desirable connection for the secondary winding is the Y-connection. The single-phase loads are easily balanced on all three phases.
- 9-36 Figure 9.8 shows the connection for a four-wire, Y-connected, three-phase system. The transformer bank supplies 120 V for lights and small appliances, and 208 V ( $208 = 120 \times \text{the square root of } 3$ ) for motors or other three-phase loads.

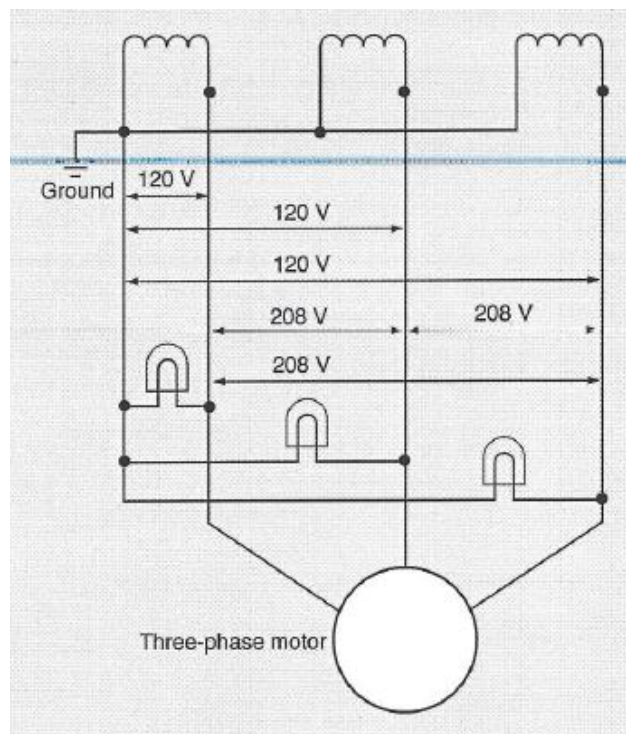


Figure 9.8: Four-Wire Y-Connection

## Three-Phase Transformers

9-37 Instead of using three single-phase transformers to make a three-phase transformer bank, the windings can be placed on one core as shown in Figure 9.9. The core of a three-phase transformer is made with three legs. Both the primary and secondary windings of one phase are put on one leg. It is possible to build the core with only three legs, because the magnetic fields produced by the three windings are 120 electrical degrees apart.

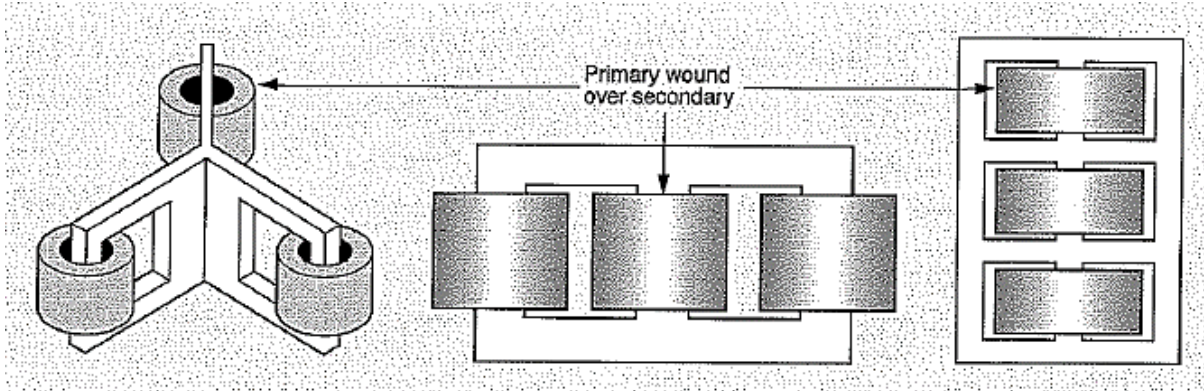


Figure 9.9: Three-Phase Transformer Connection

9-38 Because the three windings can be placed on one core, the three-phase transformer takes up less space than three single-phase transformers of the same total capacity. A disadvantage of a three-phase transformer is that the entire unit must be removed from service if one phase becomes defective.

9-39 The three-phase transformer windings are connected exactly like those in the three singlephase transformers. The connections between windings are made inside the enclosure. Only the necessary leads are brought out for terminal connections.

9-40 Standard transformers are sometimes used for boosting the potential difference along a long or overloaded line. Figure 9.10 shows an example of a connection for a distribution transformer of additive polarity.

- The high-voltage winding is connected across the line.
- The low-voltage winding is connected in series with the line, to add its voltage to the line-voltage.

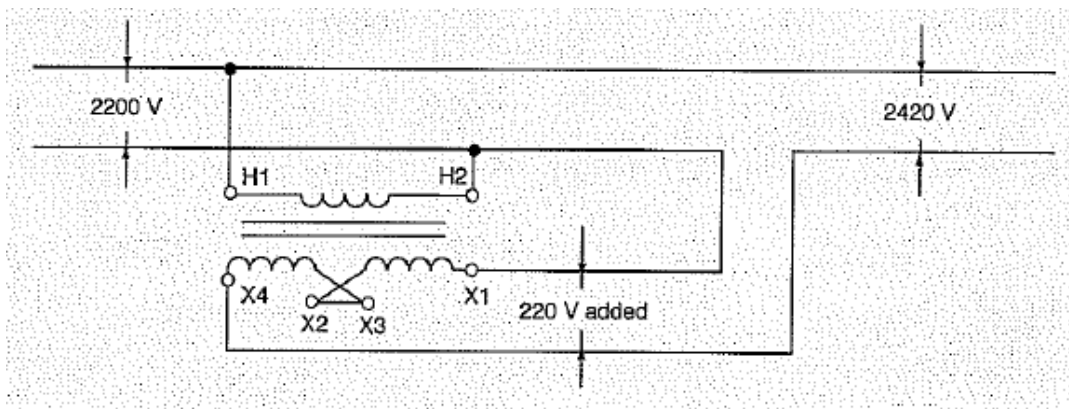


Figure 9.10: Booster Transformer in a Line

## Three-Phase Transformers (continued)

9-41 The proper size transformer must be used for this purpose. To find the correct capacity, multiply the rated potential difference across the transformer's secondary by the maximum current to be carried in the line.

9-42 For example, suppose you want to boost the voltage of a nominal 2400 V line by 10%, and the maximum current in the line is 100 A. You can use a standard 220/240 V transformer to get the 10% boost. The rated capacity of the transformer must be 24 kW.

$$240\text{ V} \times 100\text{ A} = 24\text{ kW}$$

9-43 Figure 9.11 shows a ratio autotransformer used as a balancer or *balun* (balancing unit) to provide a three-wire 120/240 V circuit. This circuit has been used for lighting circuits, but has been generally

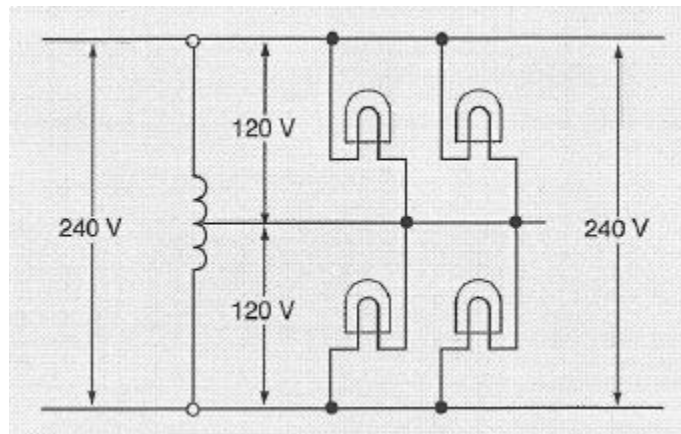


Figure 9.11: Autotransformer Balancing Unit

9-44 Figure 9.12 shows another use for the autotransformer in a three-phase motor compensating starter. The compensating starter reduces the potential difference to about half the line value.

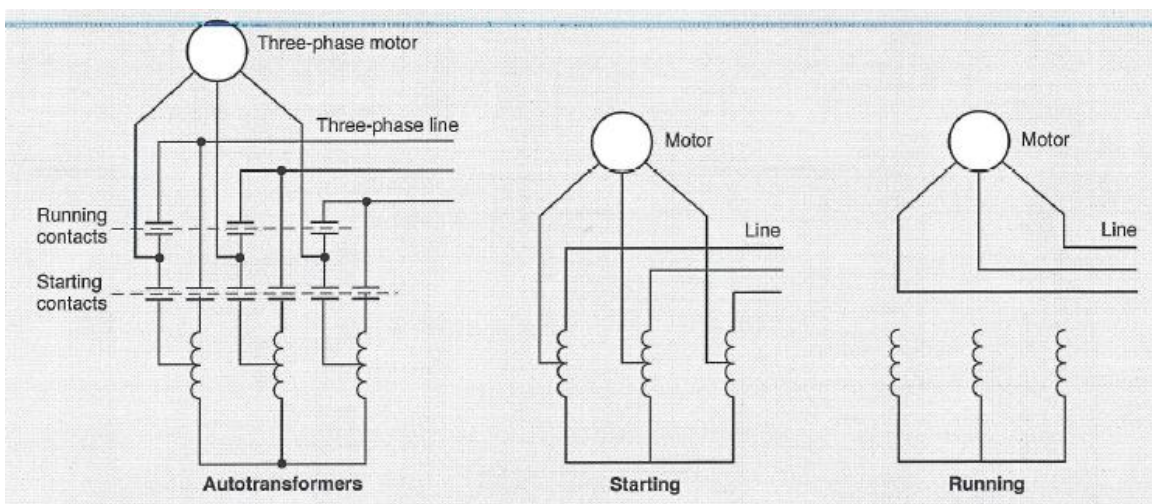


Figure 9.12: Autotransformers in a Compensating Motor Starter



## Three-Phase Transformers (continued)

- 9-45 After the motor reaches about 75% of its rated speed, the autotransformers are switched out of the circuit, and the motor is connected across the line. This is usually a three-phase application. It is used on large motors and on motors that must start under heavy loads.
- 9-46 The zigzag connection shown in Figure 9.13, on the following page, is used to provide a neutral line for three-phase, four-wire operations when a neutral is not available in the supply.

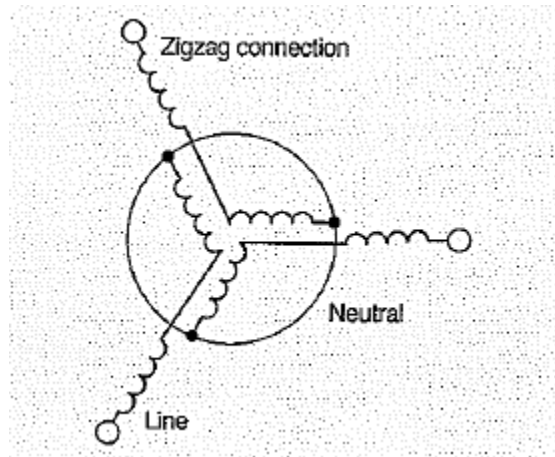


Figure 9.13: Establishment of a Neutral Line

## Installing Transformers

- 9-47 The following paragraphs describe the general precautions and mounting methods for dry transformers. These methods conform to the National Electrical Code (NEC). Make sure you follow the manufacturer's recommendations and instructions whenever you install or connect any transformer unit.
- 9-48 **Location:** Transformers must be accessible to qualified personnel for hookup and maintenance. The units must not be installed near combustible materials. Avoid installing transformers in areas where their noise would be greater than the noise of the surroundings.
- 9-49 Select a place where the air is clean and dry for the installation of open-ventilated transformers. Avoid places where dripping, splashing, or other wet conditions occur. If you cannot avoid wet conditions, protect the transformer against the moisture.
- 9-50 Avoid installing transformers in areas where the ambient temperature rises above 104°F (40°F). Otherwise, the transformers may need to be operated at less than their rated capacity to avoid excessive temperature rise.
- 9-51 Dry transformers require circulation of clean air, free of dust or corrosive materials. Air filters may be required in places where the air is dirty as in foundries, steel mills, and refineries. At least 100 cubic feet per minute (CFM) of air circulation is required for each kilowatt of transformer loss.

## Installing Transformers (continued)

9-52 **Safety:** The safety of personnel is always important, especially when a transformer is to operate with exposed live parts. The NEC regulates the installation of dry transformers indoors. Figure 9.14 shows some installations which conform to the NEC.

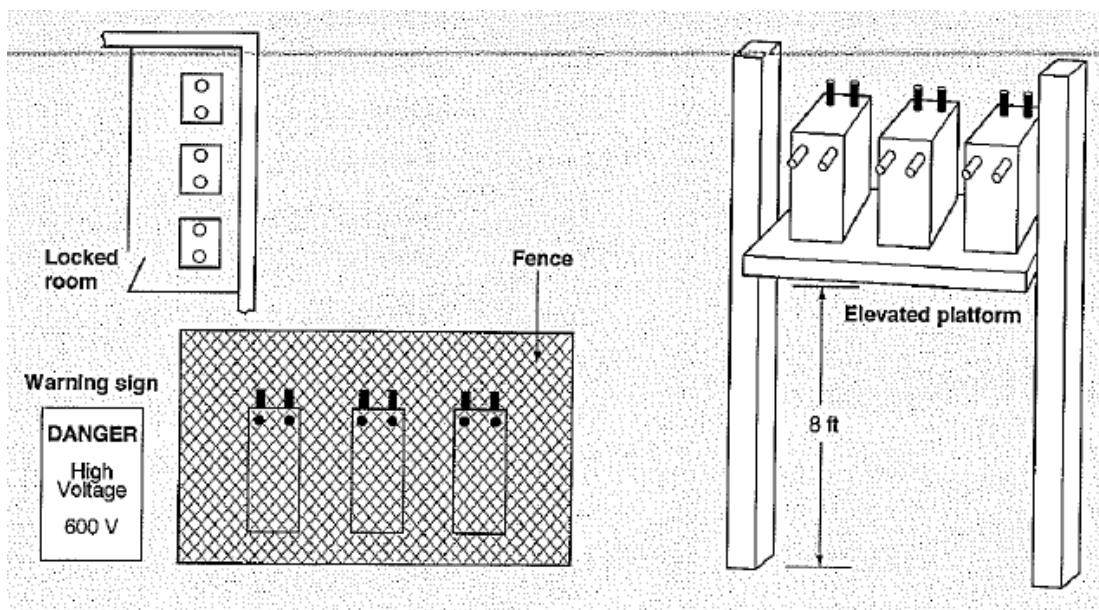


Figure 9.14: Guarding Exposed Live Parts

9-53 Protection must be provided against accidental contact with live parts.

- The best arrangement is to isolate the transformer in a room that can be entered only by qualified personnel.
- If such an arrangement is not possible, elevate the transformer so that it is at least 8 feet above floor level.
- An alternative is to install a guard rail around the equipment, if the transformer operates at 600 V or less.

Place signs on the equipment indicating the maximum potential difference between exposed parts.

9-54 Do not install transformers in areas where they can be damaged by normal traffic of personnel or moving equipment. Protect ventilation openings with small-mesh screen to prevent people from poking things into the windings. The screens will also prevent entry of small animals, insects, and other foreign objects.

9-55 **Handling:** To prevent damage to transformer assemblies and enclosures during lifting, use the lifting eyes or openings provided by the manufacturer. Make sure the cables used for lifting the transformer

9-56 Always move a transformer in its upright position. Pay attention to THIS END UP markings on the shipping crate or transformer enclosure.

9-57 If the transformer is heavy, do not drag it across the ground or floor. Use dollies or pry trucks. Use a forklift truck if one is available with enough lifting capacity. A forklift is a great help in moving the transformer and in placing it in position for installation. Also, use hand hoists, power hoists, or other tools to give you a mechanical advantage.

## Installing Transformers (continued)

- 9-58 When installing a transformer, be careful not to drop tools, nuts, bolts, or other parts onto the coils. These can damage the insulation on the coils and cause the transformer to fail.
- 9-59 **Mounting:** Transformers may be mounted on various kinds of surfaces and in different ways. Usually, the upright position is the best position for mounting. Check the manufacturer's instructions before you install a transformer in any position other than upright. Make sure the structure supporting the transformer is strong enough.
- 9-60 Figure 9.15 shows how a transformer rated at 112.5 kW may be installed. The transformer must be mounted at least 12 inches from combustible materials, unless a fire-resistant barrier is installed between the transformer and the material. The transformer must be rated at not more than 600 V and it must be totally enclosed except for ventilating holes.

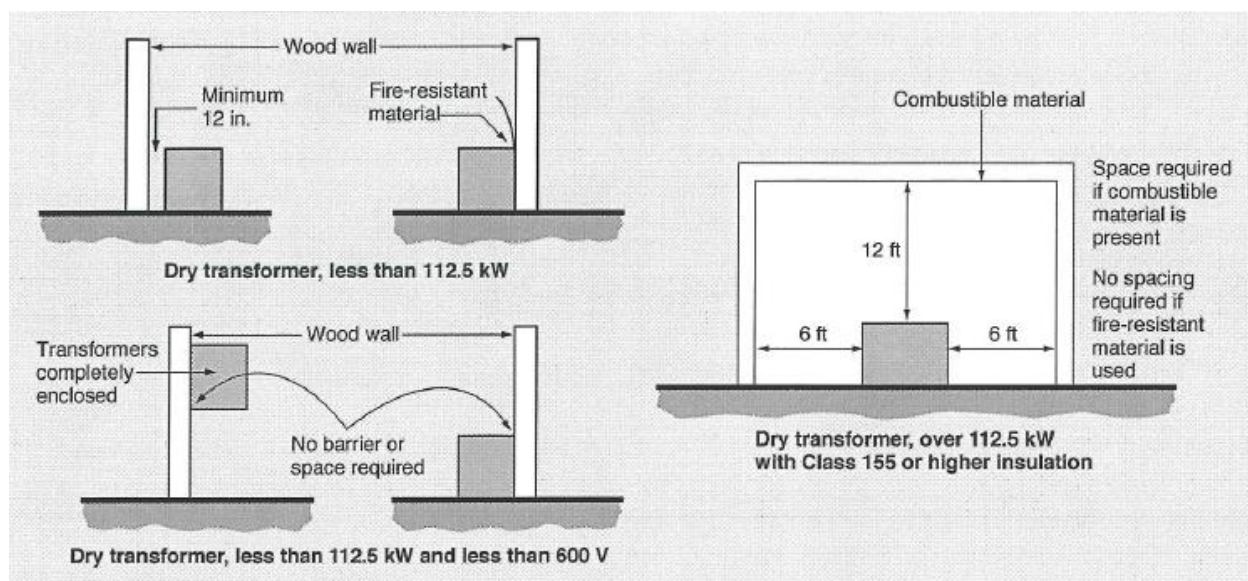


Figure 9.15: NEC Installation Requirements

- 9-61 Transformers rated at 112.5 kW or more must be installed in a separate room. The transformer must be separated from any combustible material by distances of 6 feet horizontally and 12 feet vertically. However, if the room is made of fire-resistant and heat-insulating materials, there is no space requirement. Transformers rated at 35,000 V or more must be installed in a vault conforming to NEC requirements.

## Chapter 9 Exercise

Circle the appropriate letter next to the correct answer.

1. Which of the following transformers is used for supplying general power and lighting?
  - a. Distribution
  - b. General purpose
  - c. Power
  - d. Substation
  
2. Which of the following transformers must be installed according to the specifications and standards of public utilities?
  - a. Distribution
  - b. Load-center
  - c. Power
  - d. Substation
  
3. Which class of insulation is used in transformers located near combustible materials?
  - a. Class A
  - b. Class B
  - c. Class F
  - d. Class H
  
4. A 2000 kW transformer, cooled efficiently, can operate at \_\_\_\_\_ kW without damage.
  - a. 2000
  - b. 3000
  - c. 4000
  - d. 5000
  
5. Before making a transformer ratio adjustment you should \_\_\_\_\_.
  - a. Clear the area of personnel
  - b. Disconnect it from the power supply
  - c. Ground the transformer
  - d. Short circuit the transformer

## Chapter 9 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. Which transformer connection is seldom used because of the disturbance it causes in communications equipment?
- a. Delta-delta
  - b. Delta-Y
  - c. Y-delta
  - d. Y-Y
7. Dry transformers require at least \_\_\_\_\_ cfm of air circulation for each kilowatt of transformer loss.
- a. 10
  - b. 100
  - c. 1000
  - d. 10,000
8. A transformer may be enclosed by a guard rail, but only if \_\_\_\_\_.
- a. The plant has fewer than 50 employees
  - b. The transformer has no live parts
  - c. The transformer operates at 600 V or less
  - d. There is no other alternative
9. When moving a transformer, you should move it only in \_\_\_\_\_.
- a. Its crate
  - b. Its upright position
  - c. Small steps
  - d. The most convenient position
10. Transformers rated at 112.5 kW or more must be installed in a(n) \_\_\_\_\_.
- a. Elevated area
  - b. Guarded area
  - c. Separate room
  - d. Vaulting

## **SUMMARY**

Among the kinds of transformers used are general-purpose, load-center, distribution, substation, and power transformers. Transformers are either dry-type or oil-immersed. The kind of insulation used in a transformer determines the size and operating temperature of the unit. There are four classes of insulation specifications and temperature limits:

- Class A
- Class B
- Class F
- Class H

To connect two transformers in parallel, you must know the instantaneous polarities of the transformers. Most have standard polarity markings. Single-phase transformers can be connected to either increase or decrease the potential difference between the lines in a three-phase system. The four common methods are called:

- Delta-delta
- Delta-Y
- Y-delta
- Y-Y

Transformers should never be installed near combustible materials or in areas where their noise would be greater than the noise of the surroundings. You should select a place where the air is clean and dry. Also, the ambient temperature should not rise above 104F (40C). Transformers should be isolated in a closed room, on an elevated structure at least 8 feet above floor level, or inside a guardrail. Always move a transformer its upright position and use the proper equipment to move it.

# Chapter 10: Maintaining Transformers

## In this Chapter

Preventive Maintenance Program

Inspection

Making Transformer Inspections

Transformer Liquid

Dielectric Test

Breakdown Test

General Testing

Transformer Failure

Electrical Test

Disassembly and Inspection

## Objectives

After completing this chapter, you should be able to:

- Explain what to look for during an inspection of sealed transformers.
- List the problems that are indicated by an increase in the transformer operating temperature.
- Demonstrate how to perform a breakdown test.
- Explain How to locate the exact point of a leak in a welded joint below the liquid level.
- List the steps in inspecting a transformer when a winding fails.

## Terminology

**Dielectric strength:** The potential difference between two electrodes placed a standard distance apart when a transformer oil breaks down and allows electricity to flow

**Thief:** A device for removing a sample of transformer oil from any level in a container

Transformers, like all electrical devices, require regular inspection and maintenance if they are to perform properly. A large part of transformer maintenance is good housekeeping. Dirt is a major cause of problems in transformers. Heat is another cause of trouble.

While transformer manufacturers can provide maintenance guidelines, it is your responsibility to decide which schedule works best in your plant.

In this lesson, you will study how to make inspections on various kinds of transformers, what to look for, and how to store, test, and use transformer liquids. Information on how to conduct breakdown and electrical tests is also included. Regular maintenance will improve the efficiency of the transformers in your plant and make your job easier.

## Preventive Maintenance Program

- 10-1 Transformers do not require much attention compared to most other electrical equipment. However, you cannot simply forget about a transformer after it is installed. A transformer that receives no attention may develop serious problems. Careful inspection and proper maintenance are essential.
- 10-2 A preventive maintenance program should be established for transformers, just as for other equipment in the plant. The frequency of inspection should be determined from the plant records and from experience. Such a program cannot be established overnight. It will take a year or two to establish an effective schedule.
- 10-3 Transformer manufacturers provide maintenance guidelines and suggested time intervals for certain types of inspections. At the beginning, you should follow these recommendations. As you develop experience with the equipment, you can decide whether to shorten or lengthen these intervals.
- 10-4 Keep complete and accurate records of all inspections. They will provide the basis for developing your own schedule. The schedule for each transformer will depend on its size, importance, location in the system, and operating conditions.
- 10-5 Distribution transformers and small power transformers need less attention than larger transformers. However, small transformers sometimes supply power in situations where continuity of service is of great importance. These transformers should be given frequent attention. Usually about once a month.
- 10-6 Before transformers are put into service, check the level of the liquid in all compartments of the transformer.
- Small transformers have a mark inside the tank to indicate the correct oil level at a temperature of 25°C.
  - Large transformers have an oil-level gauge showing the correct level at a temperature of 250C.
- 10-7 Improper liquid level can cause serious problems in a transformer.
- If the level is too low, the transformer may overheat and fail.
  - If the level is too high, the liquid may cause problems when it becomes hot and expands.



## Inspection

10-8 Different kinds of transformers require different kinds of inspections. The four major kinds require the following kinds of inspection.

- *Dry-type transformers* depend on the circulation of air to remove heat. Therefore, anything that interferes with the flow of air must be eliminated. Most transformers have ventilation paths to carry air through the transformer case, as shown in Figure 10.1. The air may flow naturally by convection, or it may be forced through the transformer by special fans. Inspect the transformer regularly for dust and dirt that can reduce the flow of air. Equipment or materials placed too near the transformer can block the air flow. To prevent blockage and overheating, install the transformer in an open space, keep it clean, and make sure the fans are working properly.



**Figure 10.1: Dry-Type Transformers**

## Inspection (continued)

- *Oil-filled transformers* are filled with a special mineral oil that absorbs the heat from the coils. The transformer case is sealed to prevent foreign matter from entering and oil from leaking out.

The space above the oil may be filled with nitrogen or with another inert gas. The pressure of this gas should be checked regularly, and adjusted if necessary. Figure 10-2 is a diagram of the nitrogen-filling system on a typical oil-filled transformer.

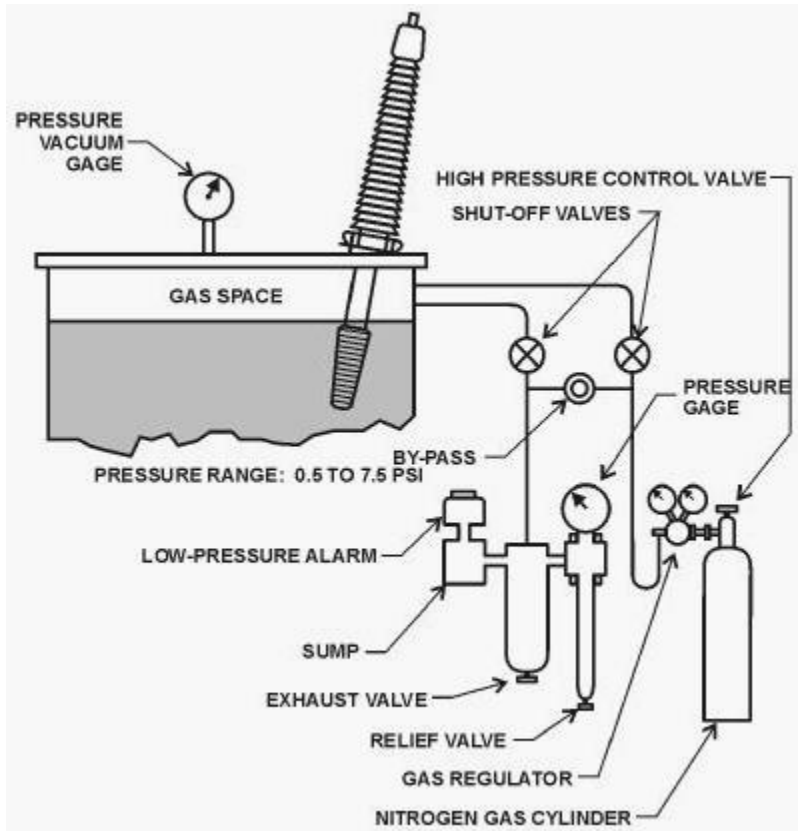


Figure 10.2: Nitrogen Filling System

## Inspection (continued)

The oil may circulate through radiator tubes for cooling. A typical radiator is shown on the oil-filled transformer in Figure 10.3. The pump must be inspected periodically for proper operation. Feel the radiator fins with your hand. A fin that feels cooler than the others indicates a blocked passageway inside. Any fans that force air through the radiator must be inspected for cleanliness and proper operation. You should also check the case and radiator for any signs of oil leaking from a flaw.



**Figure 10.3: Oil-Cooled Transformer**

- *High fire-point, liquid-cooled transformers* are filled with a silicon fluid or with a high molecular-weight liquid. The coolant should be tested on a regular schedule.
- *Vapor-cooled transformers* are filled with a refrigerant. This material cools the transformer by changing from a liquid to a gas. The transformer is sealed, and you should inspect the seals to make sure the refrigerant is not leaking out. Also measure the pressure of the refrigerant and compare it to the specifications for the indicated temperature of the transformer.

## Inspection (continued)

- 10-9 Some transformers are equipped with temperature alarms. Make sure the air-temperature alarm works when you move the pointer manually past the alarm temperature.
- 10-10 Inspect the cores, the coils, and the terminal boards for dust accumulation. How often you will need to make this inspection depends on the environment the equipment is located. If necessary, blow the accumulated dust off with dry compressed air at 25 to 50 psi. Also blow out all ventilating ducts.
- 10-11 When you reset a ratio adjuster, operate it several times through the new position. This action will help clean oxidation and corrosion off the contact surfaces, ensuring a good contact.
- 10-12 The following true story indicates the importance of regular transformer inspection. Three dry transformers, rated at 480/240/120 V and 300 kW each, provided power for lighting and electrical receptacles. The transformers were located in a part of the plant where metallic dust and flying metal chips were present. The transformers had been in operation for about 2 years. During this time, they were completely neglected by the maintenance department.
- 10-13 At about 3:00 one morning, a 400 A circuit breaker tripped and shut off power to a major section of the plant. Fortunately, the plant was not running at the time, so production was not interrupted.
- 10-14 Inspection of the transformers revealed the cause of the problem. For 2 years, metal chips and dust had been accumulating on the transformer terminal board. At first, the dust simply burned away when short circuits formed. It happened too fast to trip the circuit breaker.
- 10-15 These repeated burnings gradually charred the terminal board. In time, a sufficient carbon path was formed between two of the transformer terminals, causing a major arc that tripped the circuit breaker. A diagram of the terminal board and the charred areas is shown in Figure 10.4.

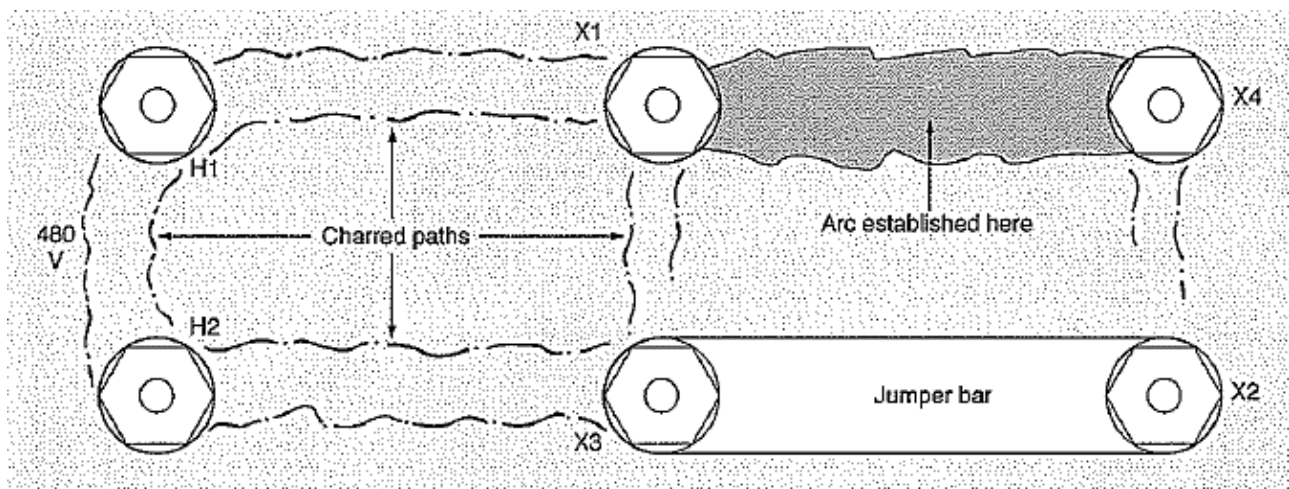


Figure 10.4: Charring on a Transformer Terminal Board

## Inspection (continued)

10-16 A new terminal board had to be made and installed before the transformers could be put into service again.

- If the breakdown had occurred during production hours, it would have idled about 100 employees until the fault was corrected.
- If the circuit breaker had not interrupted the current when it did, the transformers could have been ruined, causing greater expense and downtime.

Periodic inspection and simple preventive maintenance could have prevented this breakdown.

## Making Transformer Inspections

10-17 You cannot make an effective inspection unless you know what to look for. The following paragraphs describe the most important points you should check when you inspect various kinds of transformers.

10-18 **Sealed transformers:** On conservator transformers, check the pressure-relief diaphragm for cracks or breaks. If you find any cracks, replace the diaphragm at once. On other sealed transformers, you should check the pressure-vacuum gauge. If the pressure does not change as the oil temperature changes, the transformer may be leaking at a point somewhere above the surface of the oil.

10-19 **Oil-immersed, air-cooled transformers.** Check the oil temperature to find out whether the fans should be running. On a monthly basis, start the fans to test for proper operation. Inspect the automatic controls of the motors, including fuses or circuit breakers.

10-20 **Water-cooled transformers:** At least once a week, measure the temperature of the ingoing water and the outgoing water. Keep a record of temperatures to check the cooling efficiency.

10-21 The water pressure and flow rate should be recorded when each transformer is put into operation. When checking at later times, you can make other comparisons. If later inspections show an increase in temperature difference between outgoing and incoming water and there has been no corresponding increase in the transformer load, you should measure the flow rate in each section to check for possible clogging.

10-22 **Forced-oil-cooled transformers:** Keep records of the temperature of the oil going into the transformer tank and the temperature of the oil coming out. If your records show a sudden increase in the temperature difference, you should look for a problem. Inspect the screens to make sure they are not clogged.

10-23 A pressure gauge on each side of the oil strainer will indicate any pressure difference. If the pressure difference is large, it probably indicates that the strainer is clogged. You should remove the strainer, clean it, and replace it. Then check the pressure difference again.

## Making Transformer Inspections (continued)

- 10-24 **Air-blast transformers—indoor:** Keep records of the temperature of the ingoing air and of the outgoing air. Pay special attention to any increase in the temperature difference. The forced air should start flowing at the moment each transformer goes into operation, and it should continue for as long as the transformer is energized. Check the temperature alarm system to make sure it is working.
- 10-25 An air-blast transformer should be blown out with dry compressed air to remove any accumulated dirt. Dirt is a conductor and can cause electrical leakage across the coils or to the ground. The kind of environment will determine the frequency of cleaning.
- 10-26 You can probably see from these paragraphs that dirt and heat are the main problems in transformers. You should always record the temperature when you check a transformer. A thermometer installed on the equipment will show the temperature of the transformer at a glance. A recording thermometer should also be used. This device produces a continuous record that can be checked at any time to determine past temperatures.
- 10-27 If you watch for changes in temperature or in temperature differences, you can get advance warning of coming trouble. You can then take immediate action to find the problem and solve it before it causes downtime or serious damage.
- 10-28 An increase in operating temperature may indicate any one of the problems listed below, or it may indicate a combination of these problems:
- Improper ventilation
  - Poor circulation
  - Faulty fan operation
  - Dirt accumulation
  - Circuit overloading
- 10-29 In general, equipment will serve you well if you keep it clean. The amount and kind of dirt in the area around the equipment will determine how often you should clean it. It is better to clean too often than to let too much dirt accumulate. Once you have established an effective timetable for cleaning the equipment, you should make a real effort to stick to the schedule.

## Transformer Liquids

- 10-30 Three kinds of cooling liquids are used in transformers today—*mineral oil*, *silicone liquids*, and *hydrocarbon liquids*. All are electrically non-conducting and do not burn easily.
- 10-31 If you need to add liquid or replace it, make sure the liquid is the same temperature as the surrounding air. Open all air vents on the transformer tank. Fill the transformer through a filter press, using metal or Neoprene hose. **Do not use rubber hose.** The sulfur in rubber corrodes the insulation on the transformer windings.
- 10-32 Figure 10.5 is a diagram of a transformer being filled through a filter press. Figure 10-6, on the following page, shows the filter plate and filter paper. Figure 10.6 also shows how the oil flows through the press.

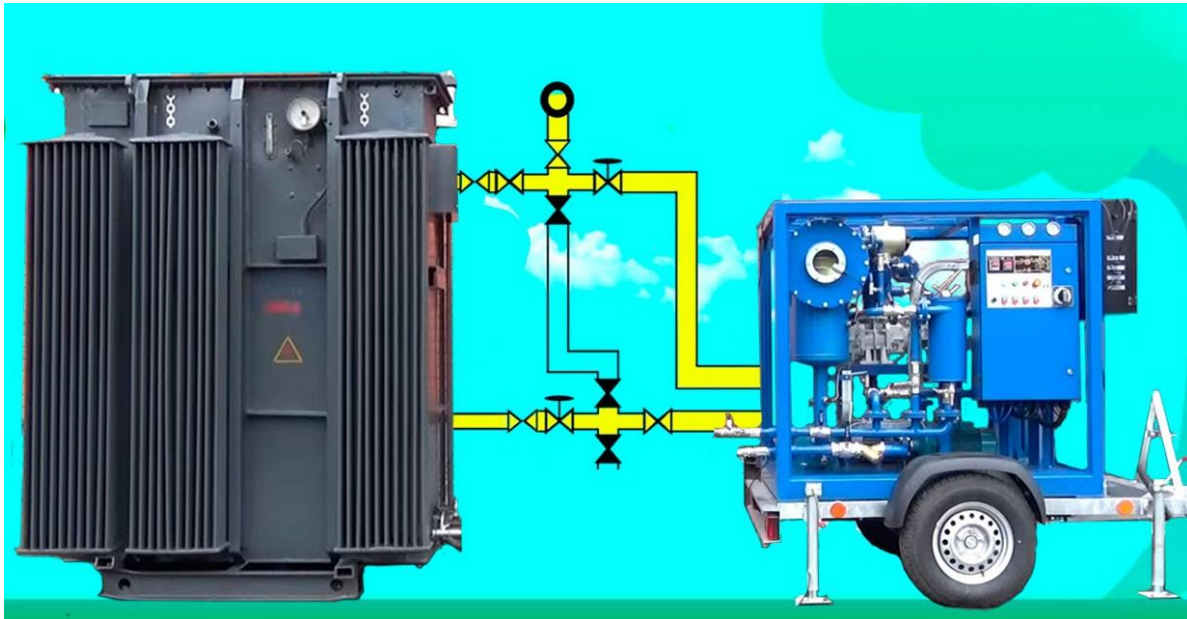


Figure 10.5: Portable Filtering System

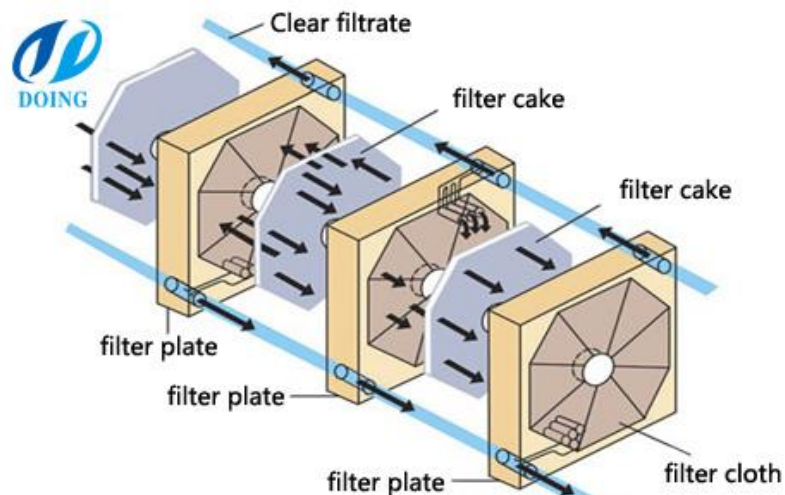


Figure 10.6: Filter Plate for Transformer Liquid

## **Transformer Liquids (continued)**

- 10-33 Fill the transformer through the bottom drain valve to prevent air from mixing with the oil. In a conservator transformer, reduce the rate of oil flow when the transformer is almost full. The reduction helps keep the pressure from building up and rupturing the relief diaphragm.
- 10-34 If you do not have a filter press, also shown in Figure 10.5, filter the liquid through two or more thicknesses of muslin as you pour it into the tank. Adjust the level after the liquid has settled for at least 12 hours.

## **Dielectric Test**

- 10-35 Accurate measurement of the dielectric strength of a transformer liquid depends on keeping the sampling and test equipment clean. Clean equipment will produce accurate results and eliminate unnecessary filtering of the liquid.
- 10-36 Always use clear glass bottles for taking samples of the transformer liquid. You can inspect clear bottles easily. Pint or quart Mason jars with two-piece lids make excellent sample bottles.
- 10-37 Before using the bottles, wash them with strong detergent. Rinse the bottles thoroughly with clean, hot water, and dry them in an oven at 230°F (110°C) for several hours.
- 10-38 Store the clean bottles, preferably open, in a dust-free cabinet. The cabinet should be heated and kept at about 100°F (40°C). A 60 W bulb kept burning in the cabinet should maintain this temperature.
- 10-39 A "thief" is a glass tube used for removing transformer liquid samples from upright drums. It should be cleaned and stored in the same way as the sample bottles.
- 10-40 When you take a sample of transformer liquid from outdoor equipment, do it on a clear day. Take precautions to guard against dust entering the sample.
- 10-41 Before you take the sample, open the drain valve on the transformer and let the liquid run out for a few seconds to clean the drain valve. Then rinse the sample bottle several times with liquid from the transformer. Thoroughly drain the bottle before taking the sample. Do not fill the bottle to the top. Allow some space for expansion. Label the sample to identify the equipment, and date it.



## Breakdown Test

10-42 The testing equipment shown in Figure 10.7 is used for measuring the breakdown voltage of transformer liquids. The test cell has two electrodes, each measuring 1 inch in diameter. Adjust the space between the electrodes to 0.1 inches, using the spacing tool provided. Wipe the cell and the electrodes clean with lint-free paper and thoroughly rinse the cell with the liquid to be tested.



**Figure 10.7: Liquid Dielectric Tester**

- 10-43 The transformer liquid should be at room temperature for the breakdown test. Agitate the sample gently each time before filling the test cell. Agitation prevents settling, which causes variations in the results. Rock the test cell and allow it to stand for 3 minutes before starting the test. This procedure allows any air bubbles to rise and escape from the liquid.
- 10-44 For the test, increase the potential difference between the electrodes steadily at the rate of 3 kV per second. Record the potential difference between the electrodes when the liquid breaks down. Avoid inhaling any vapors released during the test.
- 10-45 Make only five breakdowns per cell of liquid, allowing 1 minute between breakdowns. Repeat the test for three cell fillings which is a total of 15 breakdowns. Use the average of all the breakdown values as the dielectric strength of the sample.

## Breakdown Test (continued)

10-46 A liquid with a dielectric strength of less than 20 kV should be filtered until the value is 25 kV or higher. If your plant has a transformer oil filter press, follow the manufacturer's instructions for its use.

- The apparatus must be clean.
- The filter paper must be fresh, clean, and dry.

If you do not have a filter press, your local electrical contract or manufacturer's service shop may be able to filter the transformer liquid for you.

## General Testing

- 10-47 Periodically, you should inspect the winding insulation, bushings, and other parts of a transformer. In addition, you should make a test for combustible gases (abbreviated TCG) on the air above the liquid in the transformer tank.
- 10-48 Your electric utility is interested in keeping the transformers connected to its distribution lines in good condition. The TCG is an important test of this condition. The test should show less than 1% combustible gases. A higher percentage of combustible gases is cause for concern. The gases might explode, blowing the tank apart and disrupting electric service in your plant.
- 10-49 A leaking tank loses its liquid, which can lead to overheating and failure of the transformer. If inspection shows the liquid level in the tank is decreasing and oil appears on the outside of the tank, you need to take prompt action to find and correct the leak.
- 10-50 To locate the exact point of a leak in a welded joint below the liquid level, first clean the surface with gasoline or alcohol. Then, when the surface is dry, dust the area with dry lime or with cement dust. A dark spot will appear around the leak.
- 10-51 If the leak is above the liquid level, add nitrogen gas inside the transformer housing to increase the pressure and make the leak easier to find. Increase the pressure to one of the following values.
- 10 psi in a gas-seal or gas-oil-seal transformer
  - 5 psi in a sealed transformer
- 10-52 Apply a solution made of equal parts of liquid soap and water to the welded joints, the screw threads, the pipe threads, and the gaskets. Use an oil can to apply a fine stream of solution. Any leaks will show up as white spots where escaping gas forms bubbles.
- 10-53 Leaks around threaded joints can be eliminated by rethreading. Before reassembling the joint, apply a joint compound that will not dissolve in the liquid. Leaks at gaskets can often be eliminated simply by tightening the bolts. If not, you must disassemble the joint and replace the gasket.
- 10-54 Small leaks in welds can sometimes be sealed by *peening* with a ball-peen hammer, as shown in Figure 10.8. Cracks or spongy areas in a weld should be repaired by re-welding or by brazing. However, welding or brazing must be done with care, because the transformer liquid may be flammable.

## Transformer Failure

- 10-55 When a transformer winding fails, you may see smoke or liquid coming from the tank, and the transformer may make noise. Disconnect the transformer from the power source. Do not reconnect the transformer. Doing so may cause further damage. The damaged transformer is also a fire hazard.
- 10-56 After disconnecting the transformer from both the source and load, make a careful inspection and perform a few tests. If you do not have the facilities for testing, contact your local electrical utility or a transformer service shop. Before you call the shop, make the inspections listed below so that you will know as much as possible about the transformer's condition.
- Look for any external damage (mechanical or electrical) to bushings, leads, potheads, and other parts of the transformer
  - Measure the temperature of the liquid
  - Look for leaks
  - Look for evidence on both the primary and the secondary windings of the transformer for the cause of failure

## Electrical Tests

- 10-57 Use a megohmmeter to measure the resistance between the primary and secondary windings and between each winding and electrical ground. The measurements may indicate a failure of the insulation. But even if they do not, you should not assume the insulation is undamaged. A fault may have occurred which has been sealed by the insulating liquid.
- 10-58 Remove samples of the liquid from the top and bottom of each compartment in the transformer. Measure the dielectric strength of each sample. The liquid should not break down at a potential difference of less than 20 kV.

## Disassembly and Inspection

- 10-59 If you are sure the fault is inside the transformer, make an internal inspection. Remove the liquid from all compartments. Store the liquid taken from each compartment separately. You should use a clean container labeled for identification.
- 10-60 Inspect the inside of the transformer. Make note of any damage or unusual condition. Disconnect the leads and equipment, and remove the top cover of the transformer housing.
- 10-61 Remove the core and coils from the tank. Be careful not to bump or damage the assembly. Inspect the coils, the insulation, and the core for electrical damage. You can usually see evidence where a failure has occurred. Look for burned or damaged spots on the core insulation. If necessary, have the coil assembly crated and shipped to the transformer manufacturer or to a service shop for a complete overhaul and repair.

## Chapter 10 Exercise

Circle the appropriate letter next to the correct answer.

1. Which kind of transformer is cooled by circulating air?
  - a. Dry-type transformer
  - b. High fire-point transformer
  - c. Oil-filled transformer
  - d. Vapor-cooled transformer
  
2. The simplest way to test the temperature alarm on a transformer is to \_\_\_\_\_.
  - a. Measure the ingoing and outgoing temperatures
  - b. Move the pointer manually
  - c. Raise the ambient temperature
  - d. Use compressed air
  
3. You should suspect a leak in a sealed transformer if the \_\_\_\_\_.
  - a. Pressure increases
  - b. Temperature rises
  - c. Temperature rises and the pressure does not
  - d. Pressure and temperature never change
  
4. Which of the following causes most of the problems in transformer?
  - a. Constant use
  - b. Dirt alone
  - c. Dirt and heat
  - d. Heat alone
  
5. Which of the following liquids is *not* used as coolant in transformers?
  - a. Hydrocarbon liquids
  - b. Mineral oil
  - c. Silicone liquids
  - d. Water

## Chapter 10 Exercise (continued)

Circle the appropriate letter next to the correct answer.

6. Which of the following should *not* be used for filling a transformer?
- a. Filter press
  - b. Metal hose
  - c. Neoprene hose
  - d. Rubber hose
7. A transformer liquid with a dielectric strength of less than 20 kV should be \_\_\_\_\_.
- a. Discarded
  - b. Filtered
  - c. Retested
  - d. Used
8. The air above the liquid in a transformer should contain less than \_\_\_\_\_ % combustible gases.
- a. 1
  - b. 2
  - c. 3
  - d. 4
9. All of the following are signs of a failed transformer winding, *except* \_\_\_\_\_.
- a. Dirt
  - b. Leaking liquid
  - c. Noise
  - d. Smoke
10. If a megohmmeter shows high resistance between a transformer winding and the transformer case, the insulation on the winding \_\_\_\_\_.
- a. Is damaged
  - b. Is undamaged
  - c. May be damaged
  - d. must be replaced

## **Summary**

**Transformers require regular inspection and maintenance in order to perform efficiently. However, they are often neglected to the point of breakdown because their maintenance schedule is less demanding than that of other electrical devices. The best transformer maintenance program is probably one structured around the manufacturer's guidelines and your own experience with the transformers.**

**Transformer parts that should be inspected regularly include the fans in dry transformers, the pump and the radiator fins on oil-filled transformers, and the seals in a vapor-cooled transformer.**

**Water, oil, and air temperatures should be monitored and compared regularly. Any increase in transformer operating temperature may indicate improper ventilation, poor circulation, faulty fan operation, dirt accumulation, circuit overloads, or a combination of these problems.**

**Mineral oil, silicone liquids, and hydrocarbon liquids are used as transformer coolants. Proper storage of these liquids is important. You should measure the dielectric strength of the coolant before filling the transformer. Keep your sampling and test equipment clean to get accurate test results.**

## Answers to Chapter 1 Exercise

1. d. Time (Paragraph 1-9)
2. c. Zero to maximum (Paragraph 1-17)
3. a.  $90^\circ$  (Paragraph 1-25)
4. c. Half (Paragraph 1-27)
5. c. 100 Hz (Paragraph 1-28 to 1-31)
6. a. All individual values (Paragraph 1-47)
7. a. Amplitude (Paragraph 1-48)
8. b. Coil (Paragraph 1-53)
9. a. Current in the resistor (Paragraph 1-56)
10. d. Resistance (Paragraph 1-61)

## Answers to Chapter 2 Exercise

1. d. Two lines meet (Paragraph 2-4)
2. b.  $60^\circ$  (Paragraph 2-9)
3. b. Right triangle (Paragraph 2-10)
4. b. Horizontal; toward the right (Paragraph 2-19)
5. b. Impedance (Paragraph 2-20)
6. d. Right (Paragraph 2-32)
7. d. Leads (Paragraph 2-39)
8. c. Phase angle (Paragraph 2-54)
9. b. Peak value (Paragraph 2-56)
10. a. Divided by 0.707 (Paragraph 2-57)

## Answers to Chapter 3 Exercise

1. d. Resistance (Paragraph 3-2)
2. b. Length of the coil increases (Paragraph 3-18)
3. a. AC circuit (Paragraph 3-25)
4. c. Radian (Paragraph 3-32)
5. d. 377 (Paragraph 3-33)
6. b. Delays the rise and fall of current (Paragraph 3-39)
7. d. Resistance (Paragraph 3-53)
8. b. Add vectors (Paragraph 3-58)
9. d. Sum of all values (Paragraph 3-68)
10. a. Decreases it (Paragraph 3-74)



## Answers to Chapter 4 Exercise

1. d. Retains (Paragraph 4-4)
2. b. DC (Paragraph 4-8)
3. a. Ambient temperature (Paragraph 4-14)
4. a. Air (Paragraph 4-26)
5. b. Across the AC line (Paragraph 4-35)
6. b. 500 (Paragraph 4-37)
7. c. Resistor (Paragraph 4-40)
8. d. Lower than the lowest capacitance (Paragraph 4-43)
9. d. Size of the plates (Paragraph 4-48)
10. c. Frequency and capacitance (Paragraph 4-62)

## Answers to Chapter 5 Exercise

1. c. Resistors (Paragraph 5-1)
2. c.  $X_L$  (Paragraph 5-2)
3. d. Vector sum of the two reactances (Paragraph 5-3, 5-4)
4. a. 2000  $\Omega$  (Paragraph 5-7)
5. c. Lags (Paragraph 5-12)
6. d. Total reactance (Paragraph 5-15)
7. c.  $X_L$  and  $X_C$  are equal (Paragraph 5-21)
8. b. Current (Paragraph 5-28)
9. b. Horizontally (Paragraph 5-32)
10. a. Capacitor (Paragraph 5-37)

## Answers to Chapter 6 Exercise

1. d. 3600 lb-ft (Paragraph 6-2)
2. b. Power (Paragraph 6-14)
3. a. Negative power value (Paragraph 6-22)
4. d. Reactance (Paragraph 6-24)
5. d. Resistor (Paragraph 6-36)
6. b. Phase angle will decrease (Paragraph 6-46)
7. a. Add capacitors to the circuits (Paragraph 6-51)
8. a. Across any two lines (Paragraph 6-65)
9. c. Proper installation (Paragraph 6-67)
10. c. 165 to 250 (Paragraph 6-71)

## Answers to Chapter 7 Exercise

1. b. 120° (Paragraph 7-2)
2. c. Any pair of hot terminals (Paragraph 7-9)
3. a. A single coil (Paragraph 7-20)
4. a. A high current in the coils (Paragraph 7-22)
5. d. Three times the amount developed in one coil (Paragraph 7-29)
6. b. 277 V (Problem 1)
7. c. 240 V RMS (Problem 2)
8. d. 16,600 W (Problem 5)
9. c. All three lines together (Paragraph 7-40)
10. b. 50% (Paragraph 7-43)

## Answers to Chapter 8 Exercise

1. d. The type of charge (Paragraph 8-1)
2. c. Wire coil with many loops around an iron core (Paragraph 8-4)
3. d. Step-up transformer (Paragraph 8-9)
4. b. 12 V (Paragraphs 8-13, 8-14)
5. d. Copper (Paragraph 8-32)
6. d. Resistance (Paragraph 8-39)
7. c. Material in the core (Paragraph 8-43)
8. b. Instrument transformer (Paragraph 8-56)
9. c. 37,500 V (Paragraph 8-59)
10. d. Short circuit the secondary winding (Paragraph 8-63)

## Answers to Chapter 9 Exercise

1. b. The type of charge (Paragraph 9-2)
2. c. Wire coil with many loops around an iron core (Paragraph 9-7)
3. a. Step-up transformer (Paragraph 9-9)
4. b. 12 V (Paragraph 9-21)
5. b. Copper (Paragraph 9-26)
6. d. Resistance (Paragraph 9-33)
7. b. Material in the core (Paragraph 9-51)
8. c. Instrument transformer (Paragraph 9-53)
9. b. 37,500 V (Paragraph 9-56)
10. c. Short circuit the secondary winding (Paragraph 9-61)

## Answers to Chapter 10 Exercise

1. a. Dry-type transformer (Paragraph 10-8)
2. b. Move the pointer manually (Paragraph 10-9)
3. c. Temperature rises and the pressure does not (Paragraph 10-18)
4. c. dirt and heat (Paragraph 10-26)
5. d. Water (Paragraph 10-30)
6. d. Rubber hose (Paragraph 10-31)
7. d. Filtered (Paragraph 10-46)
8. a. 1 (Paragraph 10-48)
9. a. Dirt (Paragraph 10-55)
10. c. May be damaged (Paragraph 10-57)