Three-Phase Systems in Power Applications

21

Chapter Outline

Chapter Objectives

- Discuss the advantages of three-phase generators in power applications
- Analyze three-phase generator connections
- Analyze three-phase generators with three-phase loads
- Discuss power measurements in three-phase systems

Key Terms

- Balanced load
- Phase voltage (V_θ)
- Phase current (I_θ)
- Line current (I_L)
- Line voltage (V_L)

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Introduction

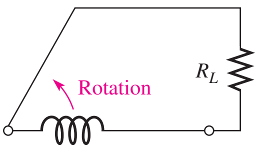
In Chapter 11, the basic concepts of three-phase ac generators were introduced. In this chapter, the basic generation of three-phase sinusoidal waveforms is examined further. The advantages of three-phase systems in power applications are covered, and various types of three-phase connections and power measurement are introduced.

21–1 Generators in Power Applications

Three-phase generators (alternators) were introduced in Chapter 11. The advantages of using three-phase generators to deliver power to a load over using a single-phase machine are discussed in this section.

After completing this section, you should be able to

- **Discuss the advantages of three-phase generators in power applications**
  - Explain the copper advantage
  - Compare single-phase and three-phase systems in terms of the copper advantage
  - Explain the advantage of constant power
  - Explain the advantage of a constant rotating magnetic field



▲ FIGURE 21–1

Simplified representation of a single-phase generator connected to a resistive load.

The size of the copper wire required to carry current from a generator to a load can be reduced when a three-phase rather than a single-phase generator is used. The total copper cross section, which is a quantity representing the number of conductors and the load carried by each conductor, is also less with three-phase systems. Think of the copper cross section as measuring the total amount of copper required to deliver a certain amount of power.

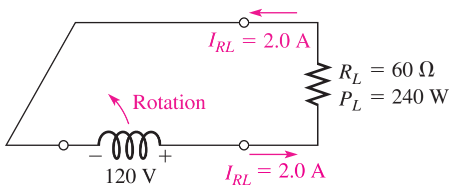
Figure 21–1 is a simplified representation of a single-phase generator connected to a resistive load. The coil symbol represents the generator winding.

For example, a single-phase sinusoidal voltage is induced in the winding and applied to a 60 Ω load, as indicated in Figure 21–2. The resulting load current is

$$\mathbf{I}_{RL} = \frac{120\angle 0^\circ\ \text{V}}{60\angle 0^\circ\ \Omega} = 2.0\angle 0^\circ\ \text{A}$$

► FIGURE 21–2

Single-phase example.



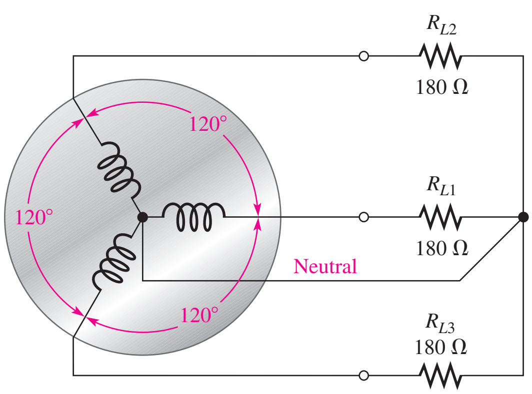
The total current that must be delivered by the generator to the load is 2.0∠0° A. This means that each of the two conductors carrying current to and from the load must each be capable of handling 2.0 A; thus, the total copper cross section is 4.0 A. The total load power is

$$P_{L(tot)} = I_{RL}^2 R_L = 240\ \text{W}$$

Figure 21–3 shows a simplified representation of a three-phase generator connected to three 180 Ω resistive loads. An equivalent single-phase system would be required to

► FIGURE 21–3

A simplified representation of a three-phase generator with each phase connected to a 180 Ω load.



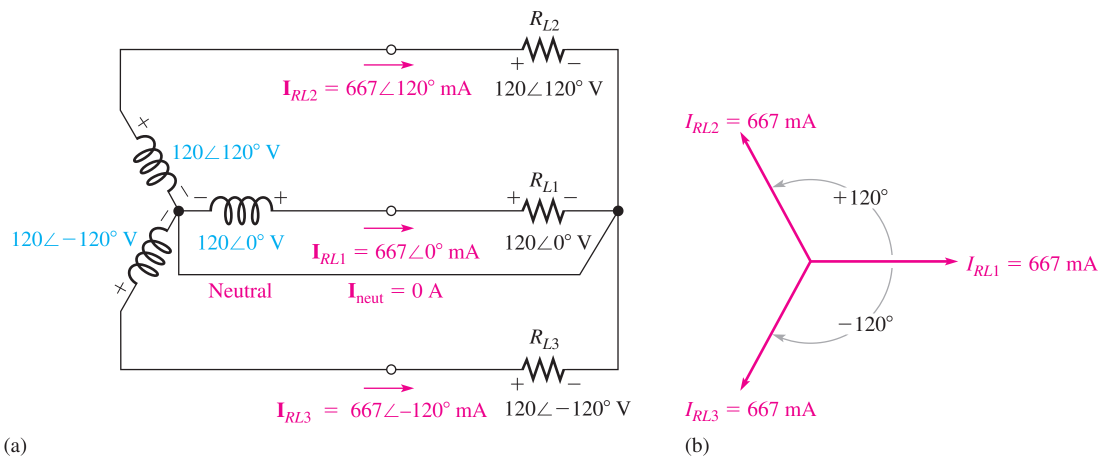
feed three 180 Ω resistors in parallel, thus creating an effective load resistance of 60 Ω. The coils represent the generator windings separated by 120°.

The voltage across R_{L1} is $120\angle 0°$ V, the voltage across R_{L2} is $120\angle 120°$ V, and the voltage across R_{L3} is $120\angle -120°$ V, as indicated in Figure 21–4(a). The current from each winding to its respective load is as follows:

$$\mathbf{I}_{RL1} = \frac{120\angle 0° \text{ V}}{180\angle 0° \ \Omega} = 667\angle 0° \text{ mA}$$

$$\mathbf{I}_{RL2} = \frac{120\angle 120° \text{ V}}{180\angle 0° \ \Omega} = 667\angle 120° \text{ mA}$$

$$\mathbf{I}_{RL3} = \frac{120\angle -120° \text{ V}}{180\angle 0° \ \Omega} = 667\angle -120° \text{ mA}$$



▲ **FIGURE 21–4**

Three-phase example.

The total load power is

$$P_{L(tot)} = I^2_{RL1}R_{L1} + I^2_{RL2}R_{L2} + I^2_{RL3}R_{L3} = 240 \text{ W}$$

This is the same total load power as delivered by the single-phase system previously discussed.

Notice that four conductors, including the neutral, are required to carry the currents to and from the loads. The current in each of the three conductors is 667 mA, as indicated in Figure 21–4(a). The current in the neutral conductor is the phasor sum of the three load currents and is equal to zero, as shown in the following equation, with reference to the phasor diagram in Figure 21–4(b).

$$\begin{aligned}
\mathbf{I}_{RL1} + \mathbf{I}_{RL2} + \mathbf{I}_{RL3} &= 667\angle 0° \text{ mA} + 667\angle 120° \text{ mA} + 667\angle -120° \text{ mA} \\
&= 667 \text{ mA} - 333 \text{ mA} + j577 \text{ mA} - 333 \text{ mA} - j577 \text{ mA} \\
&= 667 \text{ mA} - 667 \text{ mA} = 0 \text{ A}
\end{aligned}$$

This condition, where all load currents are equal and the neutral current is zero, is called a **balanced load** condition.

The total copper cross section must handle 667 mA + 667 mA + 667 mA + 0 mA = 2 A. This result shows that considerably less copper is required to deliver the same load power with a three-phase system than is required for the single-phase system. The amount of copper is an important consideration in power distribution systems.

EXAMPLE 21–1

Compare the total copper cross sections in terms of current-carrying capacity for single-phase and three-phase 120 V systems with effective load resistances of 12 Ω.

Solution Single-phase system: The load current is

$$I_{RL} = \frac{120\text{ V}}{12\ \Omega} = 10\text{ A}$$

The conductor to the load must carry 10 A, and the return conductor from the load must also carry 10 A.

The total copper cross section, therefore, is 2 × 10 A = **20 A**.

Three-phase system: For an effective load resistance of 12 Ω, the three-phase generator feeds three load resistors of 36 Ω each. The current in each load resistor is

$$I_{RL} = \frac{120\text{ V}}{36\ \Omega} = 3.33\text{ A}$$

Each of the three conductors feeding the balanced load must carry 3.33 A, and the neutral current is zero.

Therefore, the total copper cross section is 3 × 3.33 A ≅ **10 A**. This is half the copper cross section of the single-phase system with an equivalent load.

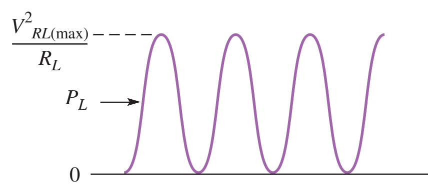
*Related Problem** Compare the total copper cross sections in terms of current-carrying capacity for single-phase and three-phase 240 V systems with effective load resistances of 100 Ω.

*Answers are at the end of the chapter.

A second advantage of three-phase systems over a single-phase system is that three-phase systems produce a constant amount of power in the load. As shown in Figure 21–5, the load power fluctuates as the square of the sinusoidal voltage divided by the resistance. It changes from a maximum of $V^2_{RL(\max)}/R_L$ to a minimum of zero at a frequency equal to twice that of the voltage.

▶ **FIGURE 21–5**

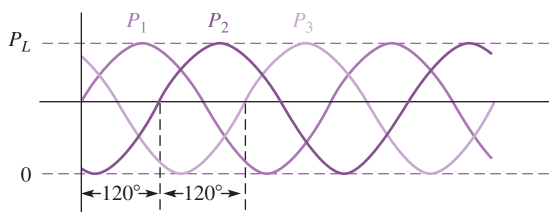
Single-phase load power ($\sin^2$ curve).



The power waveform across one of the load resistors in a three-phase system is 120° out of phase with the power waveforms across the other loads, as shown in Figure 21–6. Examination of the power waveforms shows that when three instantaneous values are added, the sum is always constant and equal to $V^2_{RL(\max)}/R_L$. A constant load power

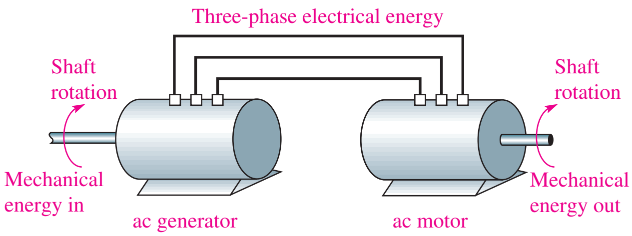
▶ **FIGURE 21–6**

Three-phase power $(P_L = V^2_{RL(\max)}/R_L)$.



means a uniform conversion of mechanical to electrical energy, which is an important consideration in many power applications.

In many applications, ac generators are used to drive ac motors for conversion of electrical energy to mechanical energy in the form of shaft rotation in the motor. The original energy for operation of the generator can come from any of several sources, such as hydroelectric and steam. Figure 21–7 illustrates the basic concept.



◄ FIGURE 21–7

Simple example of mechanical-to-electrical-to-mechanical energy conversion.

When a three-phase generator is connected to the motor windings, a magnetic field is created within the motor that has a constant flux density and that rotates at the frequency of the three-phase sine wave. The motor's rotor is pulled around at a constant rotational velocity by the rotating magnetic field, producing a constant shaft rotation, which is an advantage of three-phase systems. The rotating field simplifies the design of motors.

A single-phase system is unsuitable for many applications because it produces a magnetic field that fluctuates in flux density and reverses direction during each cycle without providing the advantage of constant rotation. Single-phase motors require some means to start the motor, whereas three-phase motors do not.

SECTION 21–1 CHECKUP
Answers are at the end of the chapter.

1. List three advantages of three-phase systems over single-phase systems.
2. Which advantage is most important in mechanical-to-electrical energy conversions?
3. Which advantage is most important in electrical-to-mechanical energy conversions?

21–2 TYPES OF THREE-PHASE GENERATORS

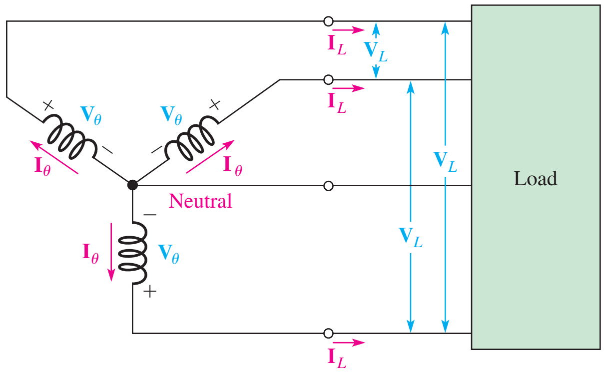
In the previous sections, the Y-connection was used for illustration. In this section, the Y-connection is examined further and a second type, the Δ-connection, is introduced.

After completing this section, you should be able to

- **Analyze three-phase generator connections**
  - Analyze the Y-connected generator
  - Analyze the Δ-connected generator

The Y-Connected Generator

A Y-connected system can be either a three-wire or, when the neutral is used, a four-wire system, as shown in Figure 21–8, connected to a generalized load, which is indicated by the green block. Recall that when the loads are perfectly balanced, the neutral current is zero; therefore, the neutral conductor is unnecessary. However, in cases where the loads are not equal (unbalanced), a neutral wire is essential to provide a return current path because the neutral current has a nonzero value.



▶ FIGURE 21–8

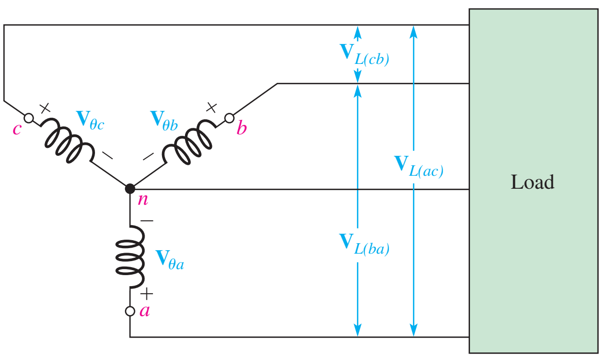
Y-connected generator.

The voltages across the generator windings are called **phase voltages (V_θ)**, and the currents through the windings are called **phase currents (I_θ)**. Also, the currents in the lines connecting the generator windings to the load are called **line currents (I_L)**, and the voltages across the lines are called the **line voltages (V_L)**. Note that the magnitude of each line current is equal to the corresponding phase current in the Y-connected circuit because there is no other path for current.

Equation 21–1

$$I_L = I_\theta$$

In Figure 21–9, the line terminations of the windings are designated a, b, and c, and the neutral point is designated n. These letters are added as subscripts to the phase and line currents to indicate the phase with which each is associated. The phase voltages are also designated in the same manner. Notice that the phase voltages are always positive at the terminal end of the winding and are negative at the neutral point. The line voltages are from one winding terminal to another, as indicated by the double-letter subscripts. For example, $\mathbf{V}_{L(ba)}$ is the line voltage from b to a.



▶ FIGURE 21–9

Phase voltages and line voltages in a Y-connected system.

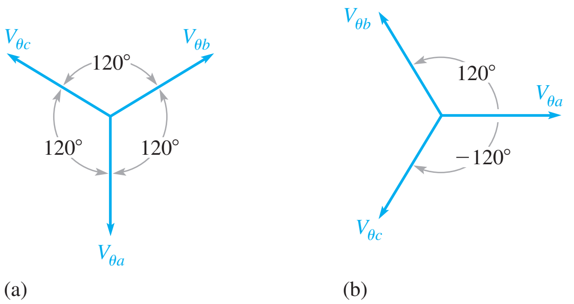
Figure 21–10(a) shows a phasor diagram for the phase voltages. By rotation of the phasors, as shown in part (b), $V_{\theta a}$ is given a reference angle of zero, and the polar expressions for the phasor voltages are as follows:

$$\mathbf{V}_{\theta a} = V_{\theta a}\angle 0^\circ$$
$$\mathbf{V}_{\theta b} = V_{\theta b}\angle 120^\circ$$
$$\mathbf{V}_{\theta c} = V_{\theta c}\angle -120^\circ$$

There are three line voltages: one between a and b, one between a and c, and another between b and c. It can be shown that the magnitude of each line voltage is equal to $\sqrt{3}$ times the magnitude of the phase voltage and that there is a phase angle of 30° between each line voltage and the nearest phase voltage.

Equation 21–2

$$V_L = \sqrt{3}V_\theta$$



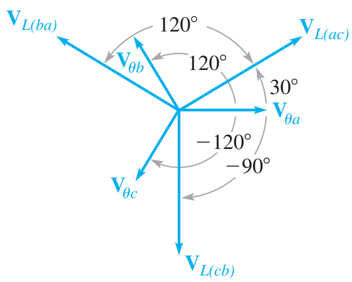
◀ **FIGURE 21–10**

Phase voltage diagram.

Since all phase voltages are equal in magnitude,

$$\mathbf{V}_{L(ba)} = \sqrt{3}V_\theta\angle 150°$$
$$\mathbf{V}_{L(ac)} = \sqrt{3}V_\theta\angle 30°$$
$$\mathbf{V}_{L(cb)} = \sqrt{3}V_\theta\angle -90°$$

The line voltage phasor diagram is shown in Figure 21–11 superimposed on the phasor diagram for the phase voltages. Notice that there is a phase angle of 30° between each line voltage and the nearest phase voltage and that the line voltages are 120° apart.



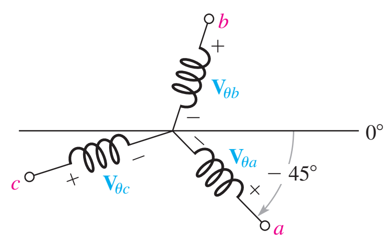
▲ **FIGURE 21–11**

Phase diagram for the phase voltages and line voltages in a Y-connected, three-phase system.

EXAMPLE 21–2

The instantaneous position of a certain Y-connected ac generator is shown in Figure 21–12. If each phase voltage has a magnitude of 120 V rms, determine the magnitude of each line voltage, and draw the phasor diagram.

▶ **FIGURE 21–12**

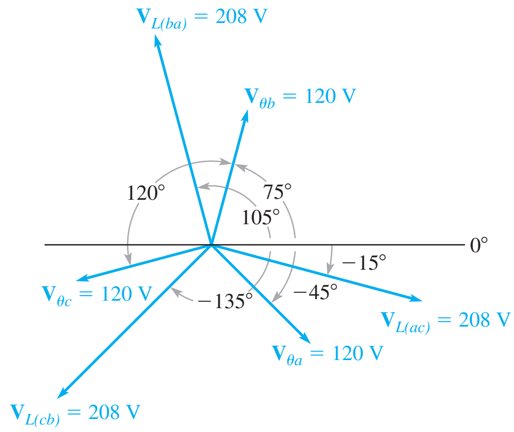


Solution The magnitude of each line voltage is

$$V_L = \sqrt{3}V_\theta = \sqrt{3}(120\text{ V}) = \mathbf{208\text{ V}}$$

The phasor diagram for the given instantaneous generator position is shown in Figure 21–13.

▶ FIGURE 21–13



Related Problem Determine the line voltage magnitude if the generator position indicated in Figure 21–13 is rotated another 45° clockwise.

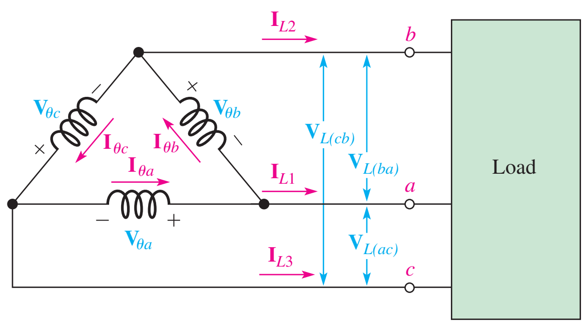
The Δ-Connected Generator

In the Y-connected generator, two voltage magnitudes are available at the terminals in the four-wire system: the phase voltage and the line voltage. Also, in the Y-connected generator, the line current is equal to the phase current. Keep these characteristics in mind as you examine the Δ-connected generator.

The windings of a three-phase generator can be rearranged to form a Δ-connected generator, as shown in Figure 21–14. By examination of this diagram, you can see that the magnitudes of the line voltages and phase voltages are equal because they are measured across the same two points, but the line currents do not equal the phase currents.

▶ FIGURE 21–14

Δ-connected generator.



Since this is a three-wire system, only a single voltage magnitude is available, expressed as

Equation 21–3

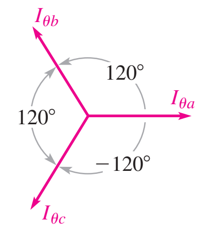
$$V_L = V_\theta$$

All of the phase voltages are equal in magnitude; thus, the line voltages are expressed in polar form as follows:

$$\mathbf{V}_{L(ac)} = V_\theta\angle 0^\circ$$
$$\mathbf{V}_{L(ba)} = V_\theta\angle 120^\circ$$
$$\mathbf{V}_{L(cb)} = V_\theta\angle -120^\circ$$

The phasor diagram for the phase currents is shown in Figure 21–15, and the polar expressions for each current are as follows:

$$\mathbf{I}_{\theta a} = I_{\theta a}\angle 0^\circ$$
$$\mathbf{I}_{\theta b} = I_{\theta b}\angle 120^\circ$$
$$\mathbf{I}_{\theta c} = I_{\theta c}\angle -120^\circ$$



▲ FIGURE 21–15

Phase current diagram for the Δ-connected system.

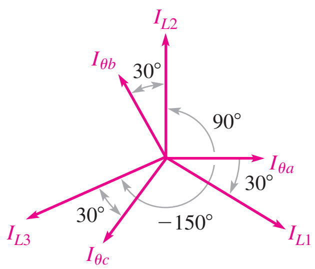
It can be shown that the magnitude of each line current is equal to $\sqrt{3}$ times the magnitude of the phase current and that there is a phase angle of 30° between each line current and the nearest phase current.

$$I_L = \sqrt{3}I_\theta \qquad \text{Equation 21–4}$$

Since all phase currents are equal in magnitude,

$$\mathbf{I}_{L1} = \sqrt{3}I_\theta\angle -30^\circ$$
$$\mathbf{I}_{L2} = \sqrt{3}I_\theta\angle 90^\circ$$
$$\mathbf{I}_{L3} = \sqrt{3}I_\theta\angle -150^\circ$$

The current phasor diagram is shown in Figure 21–16.



◀ FIGURE 21–16

Phasor diagram of phase currents and line currents.

EXAMPLE 21–3

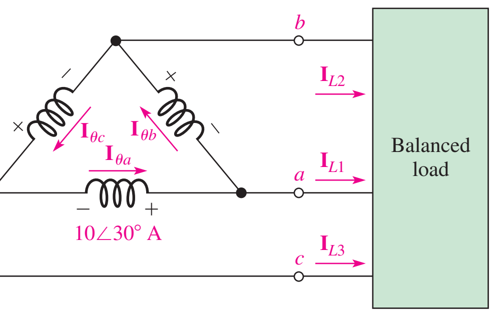
The three-phase Δ-connected generator represented in Figure 21–17 is driving a balanced load such that each phase current is 10 A in magnitude. When $\mathbf{I}_{\theta a} = 10\angle 30^\circ$ A, determine the following:

(a) The polar expressions for the other phase currents

(b) The polar expressions for each of the line currents

(c) The complete current phasor diagram

▶ FIGURE 21–17



Solution (a) The phase currents are separated by 120°; therefore,

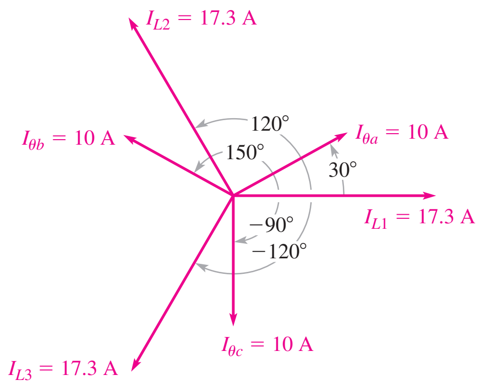
$$\mathbf{I}_{\theta b} = 10\angle(30^\circ + 120^\circ) = \mathbf{10\angle 150^\circ\ A}$$
$$\mathbf{I}_{\theta c} = 10\angle(30^\circ - 120^\circ) = \mathbf{10\angle -90^\circ\ A}$$

(b) The line currents are separated from the nearest phase current by 30°; therefore,

$$\mathbf{I}_{L1} = \sqrt{3}I_{\theta a}\angle(30° - 30°) = \mathbf{17.3\angle 0°\ A}$$
$$\mathbf{I}_{L2} = \sqrt{3}I_{\theta b}\angle(150° - 30°) = \mathbf{17.3\angle 120°\ A}$$
$$\mathbf{I}_{L3} = \sqrt{3}I_{\theta c}\angle(-90° - 30°) = \mathbf{17.3\angle -120°\ A}$$

(c) The phasor diagram is shown in Figure 21–18.

▶ FIGURE 21–18



Related Problem Repeat parts (a) and (b) of the example if $\mathbf{I}_{\theta a} = 8.0\angle 60°$ A.

SECTION 21–2 CHECKUP

1. In a certain three-wire, Y-connected generator, the phase voltages are 1.0 kV. Determine the magnitude of the line voltages.
2. In the Y-connected generator mentioned in Question 1, all the phase currents are 5.0 A. What are the line current magnitudes?
3. In a Δ-connected generator, the phase voltages are 240 V. What are the line voltages?
4. In a Δ-connected generator, a phase current is 2.0 A. Determine the magnitude of the line current.

21–3 Three-Phase Source/Load Analysis

In this section, we look at four basic types of source/load configurations. As with the generator connections, a load can be either a Y or a Δ configuration.

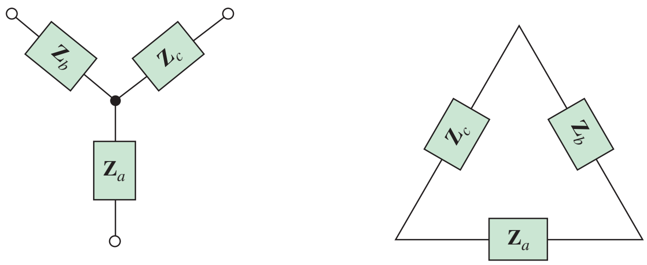
After completing this section, you should be able to

- **Analyze three-phase generators with three-phase loads**
  - Analyze the Y-Y source/load configuration
  - Analyze the Y-Δ source/load configuration
  - Analyze the Δ-Y source/load configuration
  - Analyze the Δ-Δ source/load configuration

A Y-connected load is shown in Figure 21–19(a), and a Δ-connected load is shown in part (b). The blocks $\mathbf{Z}_a$, $\mathbf{Z}_b$, and $\mathbf{Z}_c$ represent the load impedances, which can be resistive, reactive, or both.

The four source/load configurations are:

1. Y-connected source driving a Y-connected load (Y-Y system)
2. Y-connected source driving a Δ-connected load (Y-Δ system)
3. Δ-connected source driving a Y-connected load (Δ-Y system)
4. Δ-connected source driving a Δ-connected load (Δ-Δ system)



(a) Y-connected load

(b) Δ-connected load

FIGURE 21–19 Three-phase loads.

The Y-Y System

Figure 21–20 shows a Y-connected source driving a Y-connected load. The load can be a balanced load, such as a three-phase motor where $\mathbf{Z}_a = \mathbf{Z}_b = \mathbf{Z}_c$, or it can be three independent single-phase loads where, for example, $\mathbf{Z}_a$ is a lighting circuit, $\mathbf{Z}_b$ is a heater, and $\mathbf{Z}_c$ is an air-conditioning compressor.

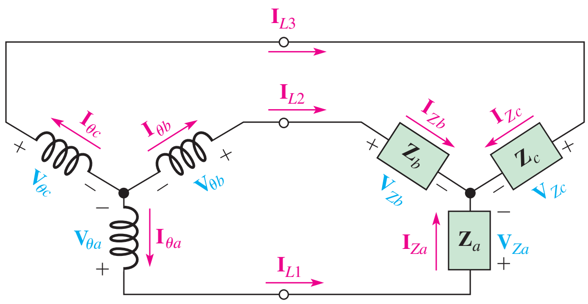


FIGURE 21–20 A Y-connected source driving a Y-connected load.

An important feature of a Y-connected source is that two different values of three-phase voltage are available: the phase voltage and the line voltage. For example, in the standard power distribution system, a three-phase transformer can be considered a source of three-phase voltage supplying 120 V and 208 V. In order to utilize a phase voltage of 120 V, the loads are connected in the Y configuration. A Δ-connected load is used for the 208 V line voltages.

Notice in the Y-Y system in Figure 21–20 that the phase current, the line current, and the load current are all equal in each phase. Also, each load voltage equals the corresponding phase voltage. These relationships are expressed as follows and are true for either a balanced or an unbalanced load.

$$I_\theta = I_L = I_Z \quad \textbf{Equation 21–5}$$

$$V_\theta = V_Z \quad \textbf{Equation 21–6}$$

where V_Z and I_Z are the load voltage and current, respectively.

TECH TIP

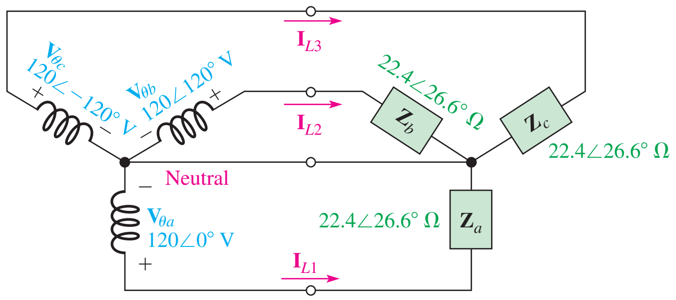
For industrial plants with three-phase motors and other loads, there will normally be a regular scheduled preventive maintenance (PM) program with a record kept of all maintenance performed. The purpose of preventive maintenance is to avoid failures that cost downtime on equipment. This is particularly important in high moisture, high temperature, or dusty environments that have cooling fans, lubrication requirements, air filters, etc. Electrical equipment should be inspected regularly; this often includes a thermographic inspection to identify hot components before they fail. Some industries constantly monitor and record certain parameters such as node voltages of electrical assemblies so that maintenance outside of the normal schedule can be assessed and addressed.

For a balanced load, all the phase currents are equal, and the neutral current is zero. For an unbalanced load, each phase current is different, and the neutral current is, therefore, nonzero. Although a small imbalance in loads is common, a large imbalance sacrifices the advantages of a three-phase system.

EXAMPLE 21–4

In the Y-Y system of Figure 21–21, determine the following:

(a) Each load current **(b)** Each line current **(c)** Each phase current
(d) Neutral current **(e)** Each load voltage



▲ FIGURE 21–21

Solution This system has a balanced load. $\mathbf{Z}_a = \mathbf{Z}_b = \mathbf{Z}_c = 22.4\angle 26.6°\ \Omega$.

(a) The load currents are

$$\mathbf{I}_{Za} = \frac{\mathbf{V}_{\theta a}}{\mathbf{Z}_a} = \frac{120\angle 0°\ \text{V}}{22.4\angle 26.6°\ \Omega} = \mathbf{5.36\angle -26.6°\ A}$$

$$\mathbf{I}_{Zb} = \frac{\mathbf{V}_{\theta b}}{\mathbf{Z}_b} = \frac{120\angle 120°\ \text{V}}{22.4\angle 26.6°\ \Omega} = \mathbf{5.36\angle 93.4°\ A}$$

$$\mathbf{I}_{Zc} = \frac{\mathbf{V}_{\theta c}}{\mathbf{Z}_c} = \frac{120\angle -120°\ \text{V}}{22.4\angle 26.6°\ \Omega} = \mathbf{5.36\angle -147°\ A}$$

(b) The line currents are

$$\mathbf{I}_{L1} = \mathbf{5.36\angle -26.6°\ A}$$
$$\mathbf{I}_{L2} = \mathbf{5.36\angle 93.4°\ A}$$
$$\mathbf{I}_{L3} = \mathbf{5.36\angle -147°\ A}$$

(c) The phase currents are

$$\mathbf{I}_{\theta a} = \mathbf{5.36\angle -26.6°\ A}$$
$$\mathbf{I}_{\theta b} = \mathbf{5.36\angle 93.4°\ A}$$
$$\mathbf{I}_{\theta c} = \mathbf{5.36\angle -147°\ A}$$

(d)
$$\begin{aligned}\mathbf{I}_{\text{neut}} &= \mathbf{I}_{Za} + \mathbf{I}_{Zb} + \mathbf{I}_{Zc}\\ &= 5.36\angle -26.6°\ \text{A} + 5.36\angle 93.4°\ \text{A} + 5.36\angle -147°\ \text{A}\\ &= (4.80\ \text{A} - j2.40\ \text{A}) + (-0.33\ \text{A} + j5.35\ \text{A}) + (-4.47\ \text{A} - j2.95\ \text{A}) = \mathbf{0\ A}\end{aligned}$$

If the load impedances were not equal (unbalanced load), the neutral current would have a nonzero value.

(e) The load voltages are equal to the corresponding source phase voltages.

$$\mathbf{V}_{Za} = 120\angle 0^\circ \text{ V}$$
$$\mathbf{V}_{Zb} = 120\angle 120^\circ \text{ V}$$
$$\mathbf{V}_{Zc} = 120\angle -120^\circ \text{ V}$$

Related Problem Determine the neutral current if $\mathbf{Z}_a$ and $\mathbf{Z}_b$ are the same as in Figure 21–21, but $\mathbf{Z}_c = 50\angle 26.6^\circ\ \Omega$.

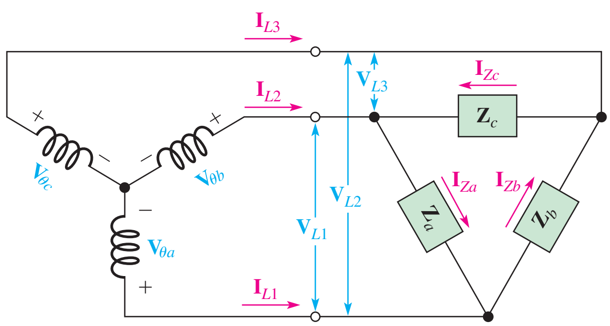
The Y-Δ System

Figure 21–22 shows a Y-connected source driving a Δ-connected load. An important feature of this configuration is that each phase of the load has the full line voltage across it.

$$V_Z = V_L \qquad \text{Equation 21–7}$$

The line currents equal the corresponding phase currents, and each line current divides into two load currents, as indicated. For a balanced load ($\mathbf{Z}_a = \mathbf{Z}_b = \mathbf{Z}_c$), the expression for the current in each load is

$$I_L = \sqrt{3}I_Z \qquad \text{Equation 21–8}$$



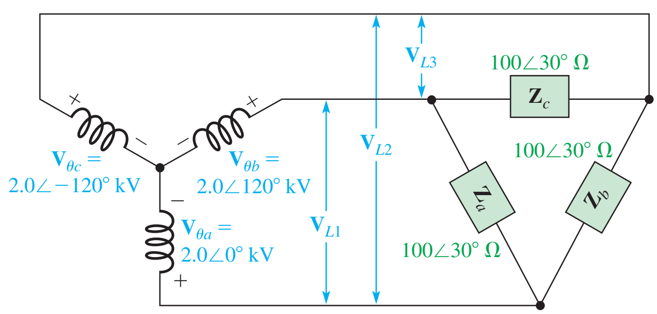
◀ FIGURE 21–22

A Y-connected source driving a Δ-connected load.

You might wonder about the $\sqrt{3}$ in Equation 21–8. It occurs with a balanced load as a consequence of applying Kirchhoff's Current Law to any of the three junctions on the delta.

EXAMPLE 21–5

Determine the load voltages and load currents in Figure 21–23, and show their relationship in a phasor diagram.



▲ FIGURE 21–23

Solution Using $V_L = \sqrt{3}V_\theta$ (Equation 21–2) and the fact that there is 30° between each line voltage and the nearest phase voltage, the load voltages are

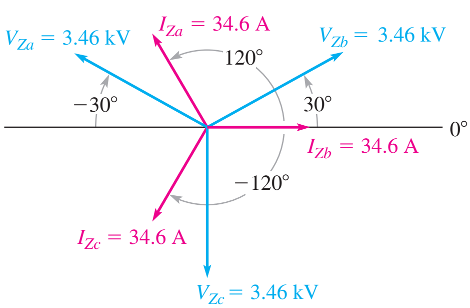
$$\mathbf{V}_{Za} = \mathbf{V}_{L1} = 2.0\sqrt{3}\angle 150^\circ \text{ kV} = \mathbf{3.46\angle 150^\circ \text{ kV}}$$
$$\mathbf{V}_{Zb} = \mathbf{V}_{L2} = 2.0\sqrt{3}\angle 30^\circ \text{ kV} = \mathbf{3.46\angle 30^\circ \text{ kV}}$$
$$\mathbf{V}_{Zc} = \mathbf{V}_{L3} = 2.0\sqrt{3}\angle -90^\circ \text{ kV} = \mathbf{3.46\angle -90^\circ \text{ kV}}$$

The load currents are

$$\mathbf{I}_{Za} = \frac{\mathbf{V}_{Za}}{\mathbf{Z}_a} = \frac{3.46\angle 150^\circ \text{ kV}}{100\angle 30^\circ\ \Omega} = \mathbf{34.6\angle 120^\circ \text{ A}}$$
$$\mathbf{I}_{Zb} = \frac{\mathbf{V}_{Zb}}{\mathbf{Z}_b} = \frac{3.46\angle 30^\circ \text{ kV}}{100\angle 30^\circ\ \Omega} = \mathbf{34.6\angle 0^\circ \text{ A}}$$
$$\mathbf{I}_{Zc} = \frac{\mathbf{V}_{Zc}}{\mathbf{Z}_c} = \frac{3.46\angle -90^\circ \text{ kV}}{100\angle 30^\circ\ \Omega} = \mathbf{34.6\angle -120^\circ \text{ A}}$$

The phasor diagram is shown in Figure 21–24.

► FIGURE 21–24



Related Problem Determine the load currents in Figure 21–23 if the phase voltages have a magnitude of 240 V.

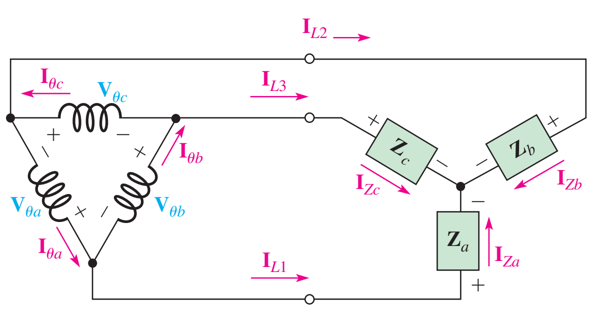
The Δ-Y System

Figure 21–25 shows a Δ-connected source driving a Y-connected balanced load. By examination of the figure, you can see that the line voltages are equal to the corresponding phase voltages of the source. Also, each phase voltage equals the difference of the corresponding load voltages, as you can see by the polarities.

Each load current equals the corresponding line current. The sum of the load currents is zero because the load is balanced; thus, there is no need for a neutral return.

► FIGURE 21–25

A Δ-connected source driving a Y-connected load.



The relationship between the load voltages and the corresponding phase voltages (and line voltages) is

$$V_\theta = \sqrt{3}V_Z \quad \text{Equation 21–9}$$

The line currents and corresponding load currents are equal, and for a balanced load, the sum of the load currents is zero.

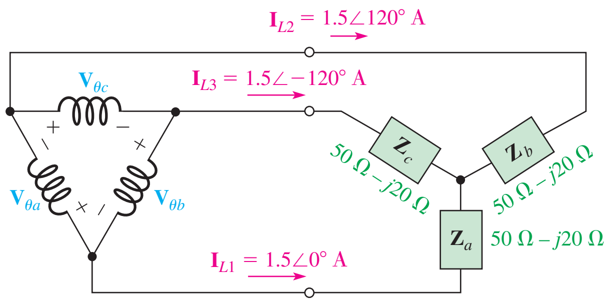
$$\mathbf{I}_L = \mathbf{I}_Z \quad \text{Equation 21–10}$$

As you can see in Figure 21–25, each line current is the difference of two phase currents.

$$\mathbf{I}_{L1} = \mathbf{I}_{\theta a} - \mathbf{I}_{\theta b}$$
$$\mathbf{I}_{L2} = \mathbf{I}_{\theta c} - \mathbf{I}_{\theta a}$$
$$\mathbf{I}_{L3} = \mathbf{I}_{\theta b} - \mathbf{I}_{\theta c}$$

EXAMPLE 21–6

Determine the currents and voltages in the balanced load and the magnitude of the line voltages in Figure 21–26.



▲ FIGURE 21–26

Solution The load currents equal the specified line currents.

$$\mathbf{I}_{Za} = \mathbf{I}_{L1} = \mathbf{1.5\angle 0^\circ\ A}$$
$$\mathbf{I}_{Zb} = \mathbf{I}_{L2} = \mathbf{1.5\angle 120^\circ\ A}$$
$$\mathbf{I}_{Zc} = \mathbf{I}_{L3} = \mathbf{1.5\angle -120^\circ\ A}$$

The load voltages are

$$\mathbf{V}_{Za} = \mathbf{I}_{Za}\mathbf{Z}_a$$
$$= (1.5\angle 0^\circ\ \text{A})(50\ \Omega - j20\ \Omega)$$
$$= (1.5\angle 0^\circ\ \text{A})(53.9\angle -21.8^\circ\ \Omega) = \mathbf{80.9\angle -21.8^\circ\ V}$$
$$\mathbf{V}_{Zb} = \mathbf{I}_{Zb}\mathbf{Z}_b$$
$$= (1.5\angle 120^\circ\ \text{A})(53.9\angle -21.8^\circ\ \Omega) = \mathbf{80.9\angle 98.2^\circ\ V}$$
$$\mathbf{V}_{Zc} = \mathbf{I}_{Zc}\mathbf{Z}_c$$
$$= (1.5\angle -120^\circ\ \text{A})(53.9\angle -21.8^\circ\ \Omega) = \mathbf{80.9\angle -142^\circ\ V}$$

The magnitude of the line voltages is

$$V_L = V_\theta = \sqrt{3}V_Z = \sqrt{3}(80.9\ \text{V}) = \mathbf{140\ V}$$

Related Problem If the magnitudes of the line currents are 1.0 A, what are the load currents?

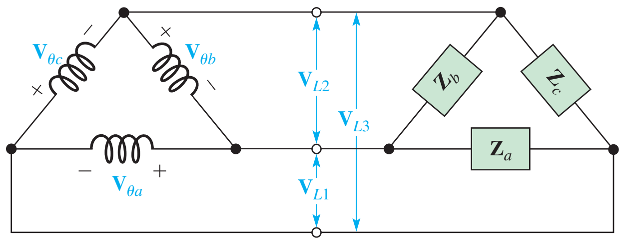
The Δ-Δ System

Figure 21–27 shows a Δ-connected source driving a Δ-connected load. Notice that the load voltage, line voltage, and source phase voltage are all equal for a given phase.

$$V_{\theta a} = V_{L1} = V_{Za}$$
$$V_{\theta b} = V_{L2} = V_{Zb}$$
$$V_{\theta c} = V_{L3} = V_{Zc}$$

FIGURE 21–27

A Δ-connected source driving a Δ-connected load.



Of course, when the load is balanced, all the voltages are equal, and a general expression can be written

Equation 21–11
$$V_\theta = V_L = V_Z$$

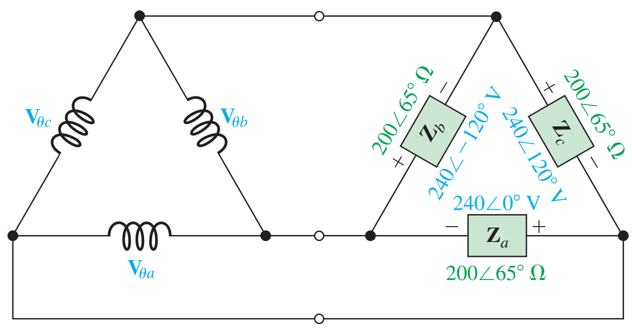
For a balanced load and equal source phase voltages, it can be shown that

Equation 21–12
$$I_L = \sqrt{3}I_Z$$

EXAMPLE 21–7

Determine the magnitude of the load currents and the line currents in Figure 21–28.

FIGURE 21–28



Solution

$$V_{Za} = V_{Zb} = V_{Zc} = 240\text{ V}$$

The magnitude of the load currents is

$$I_{Za} = I_{Zb} = I_{Zc} = \frac{V_{Za}}{Z_a} = \frac{240\text{ V}}{200\ \Omega} = \mathbf{1.20\ A}$$

The magnitude of the line currents is

$$I_L = \sqrt{3}I_Z = \sqrt{3}(1.20\text{ A}) = \mathbf{2.08\ A}$$

Related Problem Determine the magnitude of the load and line currents in Figure 21–28 if the magnitude of the load voltages is 120 V and the impedances are 600 Ω.

SECTION 21–3 CHECKUP

1. List the four types of three-phase source/load configurations.
2. In a certain Y-Y system, the source phase currents each have a magnitude of 3.5 A. What is the magnitude of each load current for a balanced load condition?
3. In a given Y-Δ system, $V_L = 220\text{ V}$. Determine V_Z.
4. Determine the line voltages in a balanced Δ-Y system when the magnitude of the source phase voltages is 60 V.
5. Determine the magnitude of the load currents in a balanced Δ-Δ system having a line current magnitude of 3.2 A.

21–4 Three-Phase Power

In this section, power in three-phase systems is studied and methods of power measurement are introduced.

After completing this section, you should be able to

- **Discuss power measurements in three-phase systems**
  - Describe the three-wattmeter method
  - Describe the two-wattmeter method

Each phase of a balanced three-phase load has an equal amount of power. Therefore, the total true load power is three times the power in each phase of the load.

$$P_{L(tot)} = 3V_ZI_Z\cos\theta \qquad \textbf{Equation 21–13}$$

where V_Z and I_Z are the voltage and current associated with each phase of the load, and $\cos\theta$ is the power factor.

Recall that in a balanced Y-connected system, the line voltage and line current were

$$V_L = \sqrt{3}V_Z \qquad \text{and} \qquad I_L = I_Z$$

and in a balanced Δ-connected system, the line voltage and line current were

$$V_L = V_Z \qquad \text{and} \qquad I_L = \sqrt{3}I_Z$$

When either of these relationships is substituted into Equation 21–13, the total true power for both Y- and Δ-connected systems is

$$P_{L(tot)} = \frac{3}{\sqrt{3}}V_LI_L\cos\theta = \sqrt{3}V_LI_L\cos\theta \qquad \textbf{Equation 21–14}$$

EXAMPLE 21–8

In a certain Δ-connected balanced load, the line voltages are 250 V and the impedances are $50\angle 30^\circ\ \Omega$. Determine the total load power.

Solution In a Δ-connected system, $V_Z = V_L$ and $I_L = \sqrt{3}I_Z$. The load current magnitudes are

$$I_Z = \frac{V_Z}{Z} = \frac{250\text{ V}}{50\ \Omega} = 5.0\text{ A}$$

and

$$I_L = \sqrt{3}I_Z = \sqrt{3}(5.0\text{ A}) = 8.66\text{ A}$$

The power factor is

$$\cos\theta = \cos 30° = 0.866$$

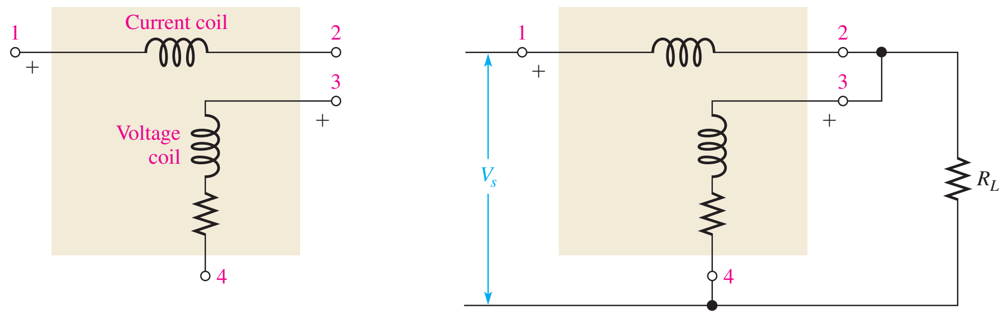
The total load power is

$$P_{L(tot)} = \sqrt{3}V_L I_L \cos\theta = \sqrt{3}(250\text{ V})(8.66\text{ A})(0.866) = \mathbf{3.25\ kW}$$

Related Problem Determine the total load power if $V_L = 120$ V and $\mathbf{Z} = 100\angle 30°\ \Omega$.

Power Measurement

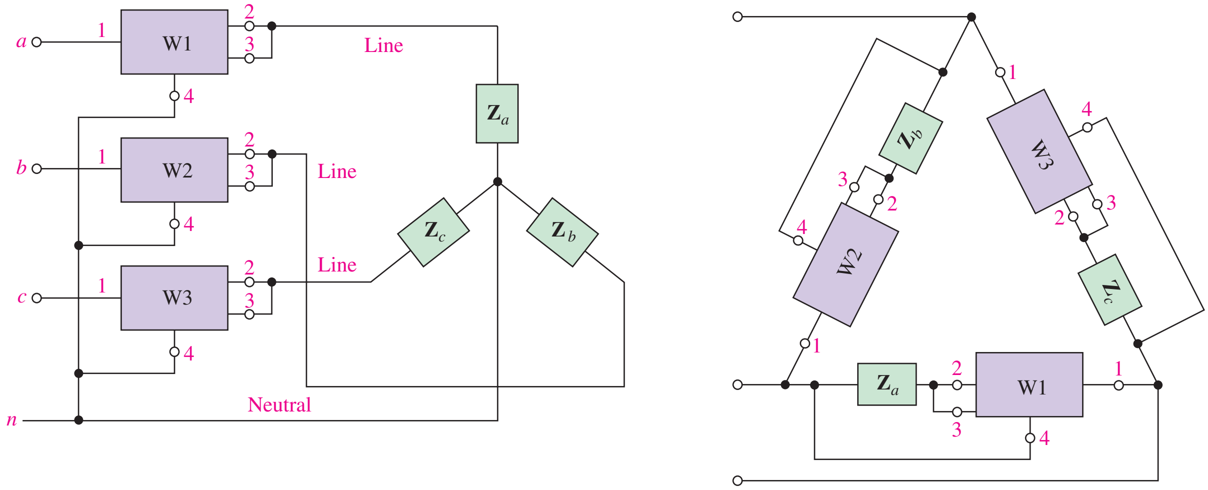
Power is measured in three-phase systems using wattmeters. The wattmeter uses a basic electrodynamometer-type movement consisting of two coils. One coil is used to measure the current, and the other is used to measure the voltage. Figure 21–29 shows a basic wattmeter schematic and the connections for measuring power in a load. The resistor in series with the voltage coil limits the current through the coil to a small amount proportional to the voltage across the coil.



(a) Wattmeter schematic (b) Wattmeter connected to measure load power

▲ FIGURE 21–29

Three-Wattmeter Method Power can be measured easily in a balanced or unbalanced three-phase load of either the Y or the Δ type by using three wattmeters connected as shown in Figure 21–30. This is sometimes known as the *three-wattmeter method.*



(a) Y-connected load (b) Δ-connected load

▲ FIGURE 21–30

Three-wattmeter method of power measurement.

The total power is determined by summing the three wattmeter readings.

$$P_{tot} = P_1 + P_2 + P_3 \qquad \text{Equation 21–15}$$

If the load is balanced, the total power is simply three times the reading on any one wattmeter.

In many three-phase loads, particularly the Δ configuration, it is difficult to connect a wattmeter such that the voltage coil is across the load or such that the current coil is in series with the load because of inaccessibility of points within the load.

Two-Wattmeter Method Another method of three-phase power measurement uses only two wattmeters. The connections for this two-wattmeter method are shown in Figure 21–31. Notice that the voltage coil of each wattmeter is connected across a line voltage and that the current coil has a line current through it. It can be shown that the algebraic sum of the two wattmeter readings equals the total power in the Y- or Δ-connected load.

$$P_{tot} = P_1 \pm P_2 \qquad \text{Equation 21–16}$$

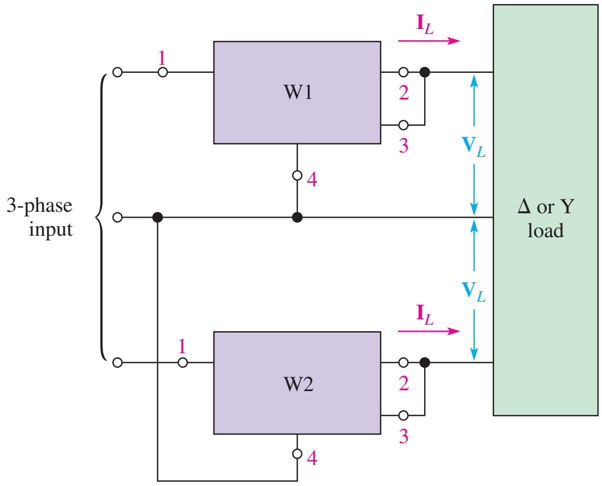


FIGURE 21–31

Two-wattmeter method.

SECTION 21–4 CHECKUP

1. $V_L = 30$ V, $I_L = 1.2$ A, and the power factor is 0.257. What is the total power in a balanced Y-connected load? In a balanced Δ-connected load?
2. Three wattmeters connected to measure the power in a certain balanced load indicate a total of 2,678 W. How much power does each meter measure?

SUMMARY

- A simple three-phase generator consists of three conductive loops separated by 120°.
- Three advantages of three-phase systems over single-phase systems are a smaller copper cross section for the same power delivered to the load, constant power delivered to the load, and a constant, rotating magnetic field.
- In a Y-connected generator, $I_L = I_\theta$ and $V_L = \sqrt{3}V_\theta$.
- In a Y-connected generator, there is a 30° difference between each line voltage and the nearest phase voltage.
- In a Δ-connected generator, $V_L = V_\theta$ and $I_L = \sqrt{3}I_\theta$.
- In a Δ-connected generator, there is a 30° difference between each line current and the nearest phase current.
- A balanced load is one in which all the impedances are equal.
- Power is measured in a three-phase load using either the three-wattmeter method or the two-wattmeter method.

KEY TERMS

Key terms and other bold terms in the chapter are defined in the end-of-book glossary.

Balanced load A condition in a three-phase system where all the load currents are equal and the neutral current is zero.

Line current (I_L) The current through a line feeding a load.

Line voltage (V_L) The voltage between lines feeding a load.

Phase current (I_θ) The current through a generator winding.

Phase voltage (V_θ) The voltage across a generator winding.

FORMULAS

Y Generator

21–1 $I_L = I_\theta$

21–2 $V_L = \sqrt{3}V_\theta$

Δ Generator

21–3 $V_L = V_\theta$

21–4 $I_L = \sqrt{3}I_\theta$

Y-Y System

21–5 $I_\theta = I_L = I_Z$

21–6 $V_\theta = V_Z$

Y-Δ System

21–7 $V_Z = V_L$

21–8 $I_L = \sqrt{3}I_Z$

Δ-to-Y System

21–9 $V_\theta = \sqrt{3}V_Z$

21–10 $I_L = I_Z$

Δ-Δ System

21–11 $V_\theta = V_L = V_Z$

21–12 $I_L = \sqrt{3}I_Z$

Three-Phase Power

21–13 $P_{L(tot)} = 3V_Z I_Z \cos\theta$

21–14 $P_{L(tot)} = \sqrt{3}V_L I_L \cos\theta$

Three-Wattmeter Method

21–15 $P_{tot} = P_1 + P_2 + P_3$

Two-Wattmeter Method

21–16 $P_{tot} = P_1 \pm P_2$

TRUE/FALSE QUIZ

Answers are at the end of the chapter.

1. The copper cross section in a three-phase system can be smaller than in a single-phase system for the same total power delivered.
2. A balanced load condition occurs when all load currents and the neutral current are equal.
3. A three-phase system produces a constant amount of power to the load.

4. A Y-connected system can have either three or four wires.
5. Voltages across the generator windings are called line voltages.
6. In a Δ-connected generator the line currents and the phase currents are equal.
7. Source-load connections can be Y-Y, Δ-Y, Y-Δ, or Δ-Δ.
8. The three-wattmeter method and the two-wattmeter method are two ways of measuring three-phase power.
9. A wattmeter uses a basic electrodynamometer-type movement consisting of three coils.
10. If a three-phase load is balanced, the total power is indicated by any one of the three meters.

SELF-TEST

Answers are at the end of the chapter.

1. In a three-phase system, the voltages are separated by
   (a) 90° **(b)** 30° **(c)** 180° **(d)** 120°
2. Two major parts of an ac generator are
   (a) rotor and stator **(b)** rotor and stabilizer
   (c) regulator and slip-ring **(d)** magnets and brushes
3. Advantages of a three-phase system over a single-phase system are
   (a) smaller cross-sectional area for the copper conductors
   (b) slower rotor speed
   (c) constant power
   (d) smaller chance of overheating
   (e) both (a) and (c)
   (f) both (b) and (c)
4. The phase current produced by a certain 240 V, Y-connected generator is 12 A. The corresponding line current is
   (a) 36 A **(b)** 4.0 A **(c)** 12 A **(d)** 6.0 A
5. A certain Δ-connected generator produces phase voltages of 30 V. The magnitude of the line voltages are
   (a) 10 V **(b)** 30 V **(c)** 90 V **(d)** none of these
6. A certain Δ-Δ system produces phase currents of 5 A. The line currents are
   (a) 5.0 A **(b)** 15 A **(c)** 8.66 A **(d)** 2.87 A
7. A certain Y-Y system produces phase currents of 15 A. Each line and load current is
   (a) 26 A **(b)** 8.66 A **(c)** 5.0 A **(d)** 15 A
8. If the source phase voltages of a Δ-Y system are 220 V, the magnitude of the load voltages is
   (a) 220 V **(b)** 381 V **(c)** 127 V **(d)** 73.3 V

PROBLEMS

More difficult problems are indicated by an asterisk (*).
Answers to odd-numbered problems are at the end of the book.

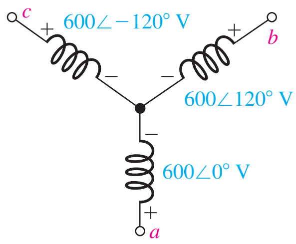
SECTION 21–1 Generators in Power Applications

1. A single-phase generator drives a load consisting of a 200 Ω resistor and a capacitor with a reactance of 175 Ω. The generator produces a voltage of 100 V. Determine the magnitude of the load current.
2. Determine the phase of the load current with respect to the generator voltage in Problem 1.
3. A certain three-phase unbalanced load in a four-wire system has currents of $2.0\angle 20°$ A, $3.0\angle 140°$ A, and $1.5\angle -100°$ A. Determine the current in the neutral line.

SECTION 21–2 Types of Three-Phase Generators

4. Determine the line voltages in Figure 21–32.

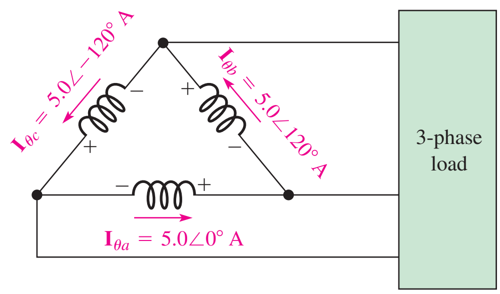
► FIGURE 21–32



5. Determine the line currents in Figure 21–33.

6. Develop a complete current phasor diagram for Figure 21–33.

► FIGURE 21–33

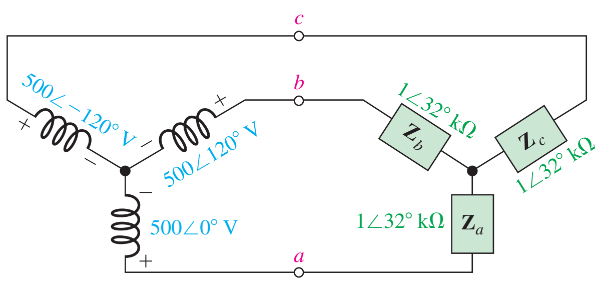


SECTION 21–3 Three-Phase Source/Load Analysis

7. Determine the following quantities for the Y-Y system in Figure 21–34:

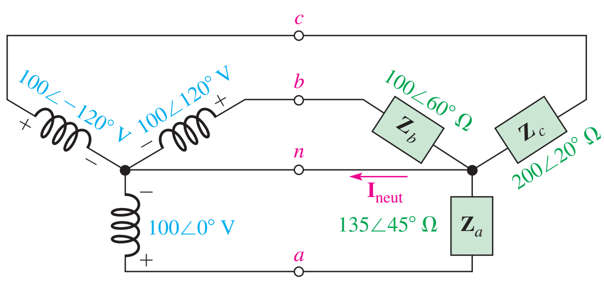
(a) Line voltages **(b)** Phase currents **(c)** Line currents

(d) Load currents **(e)** Load voltages



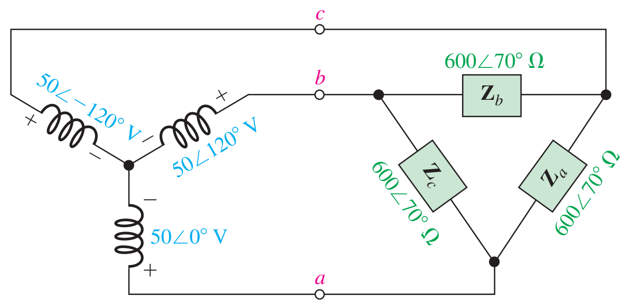
▲ FIGURE 21–34

8. Repeat Problem 7 for the system in Figure 21–35, and also find the neutral current.



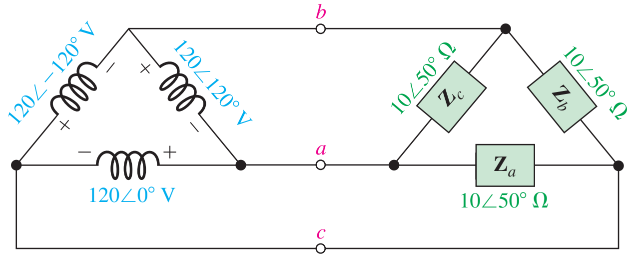
▲ FIGURE 21–35

9. Repeat Problem 7 for the system in Figure 21–36.



▲ **FIGURE 21–36**

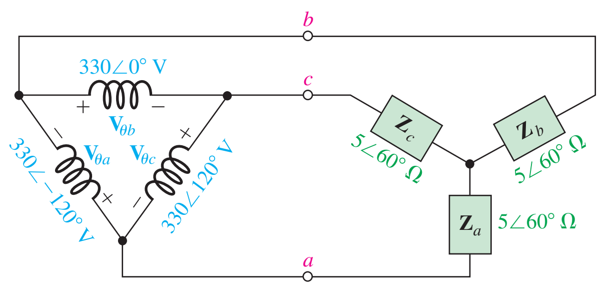
10. Repeat Problem 7 for the system in Figure 21–37.



▲ **FIGURE 21–37**

11. Determine the line voltages and load currents for the system in Figure 21–38.

▶ **FIGURE 21–38**



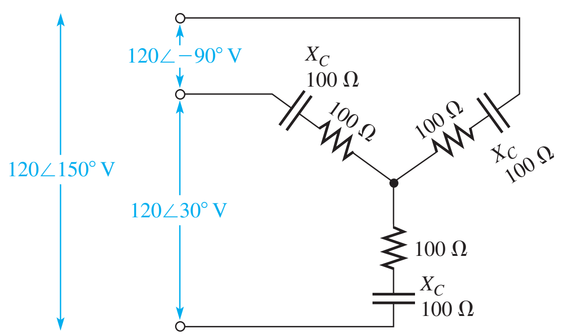
SECTION 21–4 **Three-Phase Power**

12. The power in each phase of a balanced three-phase system is 1,200 W. What is the total power?

13. Determine the load power in Figures 21–34 through 21–38.

14. Find the total load power in Figure 21–39.

▶ **FIGURE 21–39**



***15.** Using the three-wattmeter method for the system in Figure 21–39, how much power does each wattmeter indicate?

***16.** Repeat Problem 15 using the two-wattmeter method.

ANSWERS

SECTION CHECKUPS

SECTION 21–1 Generators in Power Applications

1. The advantages of polyphase systems are less copper cross section to conduct current; constant power to load; and constant, rotating magnetic field.
2. Constant power
3. Constant, rotating magnetic field

SECTION 21–2 Types of Three-Phase Generators

1. $V_L = 1.73$ kV
2. $I_L = 5.0$ A
3. $V_L = 240$ V
4. $I_L = 3.46$ A

SECTION 21–3 Three-Phase Source/Load Analysis

1. The source/load configurations are Y-Y, Y-Δ, Δ-Y, and Δ-Δ.
2. $I_L = 3.5$ A
3. $V_Z = 220$ V
4. $V_L = 60$ V
5. $I_Z = 1.85$ A

SECTION 21–4 Three-Phase Power

1. $P_Y = 16.0$ W; $P_\Delta = 16.0$ W
2. $P = 893$ W

RELATED PROBLEMS FOR EXAMPLES

21–1 4.8 A total for single phase; 2.4 A total for three-phase

21–2 208 V

21–3 **(a)** $\mathbf{I}_{\theta b} = 8.0\angle 180°$ A, $\mathbf{I}_{\theta c} = 8.0\angle -60°$ A
(b) $\mathbf{I}_{L1} = 13.9\angle 30°$ A, $\mathbf{I}_{L2} = 13.9\angle 150°$ A, $\mathbf{I}_{L3} = 13.9\angle -90°$ A

21–4 $2.96\angle 33.4°$ A

21–5 $\mathbf{I}_{Za} = 4.16\angle 120°$ A, $\mathbf{I}_{Zb} = 4.16\angle 0°$, $\mathbf{I}_{Zc} = 4.16\angle -120°$ A

21–6 $\mathbf{I}_{L1} = \mathbf{I}_{Za} = 1.0\angle 0°$ A, $\mathbf{I}_{L2} = \mathbf{I}_{Zb} = 1.0\angle 120°$ A, $\mathbf{I}_{L3} = \mathbf{I}_{Zc} = 1.0\angle -120°$ A

21–7 $I_Z = 200$ mA, $I_L = 346$ mA

21–8 374 W

TRUE/FALSE QUIZ

1. T **2.** F **3.** T **4.** T **5.** F **6.** F **7.** T **8.** T **9.** F **10.** F

SELF-TEST

1. (d) **2.** (a) **3.** (e) **4.** (c) **5.** (b) **6.** (c) **7.** (d) **8.** (c)

Table of Standard Resistor Values

Appendix A

Resistance Tolerance (±%)

0.1% 0.25% 0.5%	1%	2% 5%	10%	0.1% 0.25% 0.5%	1%	2% 5%	10%	0.1% 0.25% 0.5%	1%	2% 5%	10%	0.1% 0.25% 0.5%	1%	2% 5%	10%	0.1% 0.25% 0.5%	1%	2% 5%	10%	0.1% 0.25% 0.5%	1%	2% 5%	10%
10.0	10.0	10	10	14.7	14.7	—	—	21.5	21.5	—	—	31.6	31.6	—	—	46.4	46.4	—	—	68.1	68.1	68	68
10.1	—	—	—	14.9	—	—	—	21.8	—	—	—	32.0	—	—	—	47.0	—	47	47	69.0	—	—	—
10.2	10.2	—	—	15.0	15.0	15	15	22.1	22.1	22	22	32.4	32.4	—	—	47.5	47.5	—	—	69.8	69.8	—	—
10.4	—	—	—	15.2	—	—	—	22.3	—	—	—	32.8	—	—	—	48.1	—	—	—	70.6	—	—	—
10.5	10.5	—	—	15.4	15.4	—	—	22.6	22.6	—	—	33.2	33.2	33	33	48.7	48.7	—	—	71.5	71.5	—	—
10.6	—	—	—	15.6	—	—	—	22.9	—	—	—	33.6	—	—	—	49.3	—	—	—	72.3	—	—	—
10.7	10.7	—	—	15.8	15.8	—	—	23.2	23.2	—	—	34.0	34.0	—	—	49.9	49.9	—	—	73.2	73.2	—	—
10.9	—	—	—	16.0	—	16	—	23.4	—	—	—	34.4	—	—	—	50.5	—	—	—	74.1	—	—	—
11.0	11.0	11	—	16.2	16.2	—	—	23.7	23.7	—	—	34.8	34.8	—	—	51.1	51.1	51	—	75.0	75.0	75	—
11.1	—	—	—	16.4	—	—	—	24.0	—	24	—	35.2	—	—	—	51.7	—	—	—	75.9	—	—	—
11.3	11.3	—	—	16.5	16.5	—	—	24.3	24.3	—	—	35.7	35.7	—	—	52.3	52.3	—	—	76.8	76.8	—	—
11.4	—	—	—	16.7	—	—	—	24.6	—	—	—	36.1	—	36	—	53.0	—	—	—	77.7	—	—	—
11.5	11.5	—	—	16.9	16.9	—	—	24.9	24.9	—	—	36.5	36.5	—	—	53.6	53.6	—	—	78.7	78.7	—	—
11.7	—	—	—	17.2	—	—	—	25.2	—	—	—	37.0	—	—	—	54.2	—	—	—	79.6	—	—	—
11.8	11.8	—	—	17.4	17.4	—	—	25.5	25.5	—	—	37.4	37.4	—	—	54.9	54.9	—	—	80.6	80.6	—	—
12.0	—	12	12	17.6	—	—	—	25.8	—	—	—	37.9	—	—	—	56.2	—	—	—	81.6	—	—	—
12.1	12.1	—	—	17.8	17.8	—	—	26.1	26.1	—	—	38.3	38.3	—	—	56.6	56.6	56	56	82.5	82.5	82	82
12.3	—	—	—	18.0	—	18	18	26.4	—	—	—	38.8	—	—	—	56.9	—	—	—	83.5	—	—	—
12.4	12.4	—	—	18.2	18.2	—	—	26.7	26.7	—	—	39.2	39.2	39	39	57.6	57.6	—	—	84.5	84.5	—	—
12.6	—	—	—	18.4	—	—	—	27.1	—	27	27	39.7	—	—	—	58.3	—	—	—	85.6	—	—	—
12.7	12.7	—	—	18.7	18.7	—	—	27.4	27.4	—	—	40.2	40.2	—	—	59.0	59.0	—	—	86.6	86.6	—	—
12.9	—	—	—	18.9	—	—	—	27.7	—	—	—	40.7	—	—	—	59.7	—	—	—	87.6	—	—	—
13.0	13.0	13	—	19.1	19.1	—	—	28.0	28.0	—	—	41.2	41.2	—	—	60.4	60.4	—	—	88.7	88.7	—	—
13.2	—	—	—	19.3	—	—	—	28.4	—	—	—	41.7	—	—	—	61.2	—	—	—	89.8	—	—	—
13.3	13.3	—	—	19.6	19.6	—	—	28.7	28.7	—	—	42.2	42.2	—	—	61.9	61.9	62	—	90.9	90.9	91	—
13.5	—	—	—	19.8	—	—	—	29.1	—	—	—	42.7	—	—	—	62.6	—	—	—	92.0	—	—	—
13.7	13.7	—	—	20.0	20.0	20	—	29.4	29.4	—	—	43.2	43.2	43	—	63.4	63.4	—	—	93.1	93.1	—	—
13.8	—	—	—	20.3	—	—	—	29.8	—	—	—	43.7	—	—	—	64.2	—	—	—	94.2	—	—	—
14.0	14.0	—	—	20.5	20.5	—	—	30.1	30.1	30	—	44.2	44.2	—	—	64.9	64.9	—	—	95.3	95.3	—	—
14.2	—	—	—	20.8	—	—	—	30.5	—	—	—	44.8	—	—	—	65.7	—	—	—	96.5	—	—	—
14.3	14.3	—	—	21.0	21.0	—	—	30.9	30.9	—	—	45.3	45.3	—	—	66.5	66.5	—	—	97.6	97.6	—	—
14.5	—	—	—	21.3	—	—	—	31.2	—	—	—	45.9	—	—	—	67.3	—	—	—	98.8	—	—	—

NOTE: These values are generally available in multiples of 0.1, 1, 10, 100, 1 k, 10 k, and 100 k (depending on the type of resistor).

Appendix

B DERIVATIONS

Equation 7–3 Output Voltage of Temperature Measuring Bridge

At balance $V_{\text{OUT}} = 0$ and all resistances have the value R. For a small imbalance:

$$V_B = \frac{V_S}{2} \text{ and } V_A = \left(\frac{R}{2R + \Delta R_{\text{THERM}}}\right)V_S$$

$$\Delta V_{\text{OUT}} = V_B - V_A = \frac{V_S}{2} - \left(\frac{R}{2R + \Delta R_{\text{THERM}}}\right)V_S$$

$$= \left(\frac{1}{2} - \frac{R}{2R + \Delta R_{\text{THERM}}}\right)V_S$$

$$= \left(\frac{2R + \Delta R_{\text{THERM}} - 2R}{2(2R + \Delta R_{\text{THERM}})}\right)V_S$$

$$= \left(\frac{\Delta R_{\text{THERM}}}{4R + 2\Delta R_{\text{THERM}}}\right)V_S$$

Assume $2\Delta R_{\text{THERM}} << 4R$, then

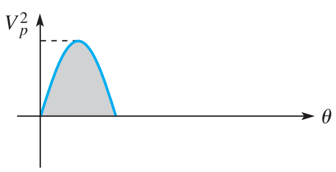
$$\Delta V_{\text{OUT}} \cong \left(\frac{\Delta R_{\text{THERM}}}{4R}\right)V_S = \Delta R_{\text{THERM}}\left(\frac{V_S}{4R}\right)$$

Equation 11–5 RMS (Effective) Value of a Sine Wave

The abbreviation "rms" stands for the root mean square process by which this value is derived. In the process, we first square the equation of a sinusoidal voltage wave.

$$v^2 = V_p^2 \sin^2\theta$$

Next, we obtain the mean or average value of v^2 by dividing the area under a half-cycle of the curve by π (see Figure B–1). The area is found by integration and trigonometric identities.



▲ FIGURE B–1

Area under the half-cycle squared of a sinusoidal voltage wave.

$$V_{\text{avg}}^2 = \frac{\text{area}}{\pi} = \frac{1}{\pi}\int_0^{\pi} V_p^2 \sin^2\theta\, d\theta$$

$$= \frac{V_p^2}{2\pi}\int_0^{\pi}(1 - \cos 2\theta)d\theta = \frac{V_p^2}{2\pi}\int_0^{\pi} 1\, d\theta - \frac{V_p^2}{2\pi}\int_0^{\pi}(-\cos 2\theta)\, d\theta$$

$$= \frac{V_p^2}{2\pi}\left(\theta - \tfrac{1}{2}\sin 2\theta\right)_0^{\pi} = \frac{V_p^2}{2\pi}(\pi - 0) = \frac{V_p^2}{2}$$

Finally, the square root of V_{avg}^2 is V_{rms}.

$$V_{\text{rms}} = \sqrt{V_{\text{avg}}^2} = \sqrt{V_p^2/2} = \frac{V_p}{\sqrt{2}} = 0.707V_p$$

Equation 11–11 Average Value of a Half-Cycle Sine Wave

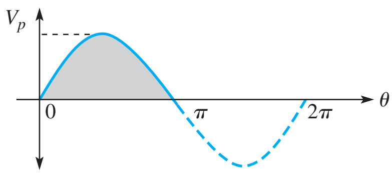
The average value of a sine wave is determined for a half-cycle because the average over a full cycle is zero.

The equation for a sine wave is

$$v = V_p \sin\theta$$

The average value of the half-cycle is the area under the curve divided by the distance of the curve along the horizontal axis (see Figure B–2).

$$V_{avg} = \frac{\text{area}}{\pi}$$



▲ FIGURE B–2

Area under the half-cycle of a sinusoidal voltage wave.

To find the area, we use integral calculus.

$$\begin{aligned} V_{avg} &= \frac{1}{\pi}\int_0^{\pi} V_p \sin\theta\, d\theta = \frac{V_p}{\pi}(-\cos\theta)\Big|_0^{\pi} \\ &= \frac{V_p}{\pi}[-\cos\pi - (-\cos 0)] = \frac{V_p}{\pi}[-(-1) - (-1)] \\ &= \frac{V_p}{\pi}(2) = \frac{2}{\pi}V_p = 0.637V_p \end{aligned}$$

Equations 12–25 and 13–12 Reactance Derivations

Derivation of Capacitive Reactance

$$\theta = 2\pi f t = \omega t$$

$$i = C\frac{dv}{dt} = C\frac{d(V_p \sin\theta)}{dt} = C\frac{d(V_p \sin\omega t)}{dt} = \omega C(V_p \cos\omega t)$$

$$I_{rms} = \omega C V_{rms}$$

$$X_C = \frac{V_{rms}}{I_{rms}} = \frac{V_{rms}}{\omega C V_{rms}} = \frac{1}{\omega C} = \frac{1}{2\pi f C}$$

Derivation of Inductive Reactance

$$v = L\frac{di}{dt} = L\frac{d(I_p \sin\omega t)}{dt} = \omega L(I_p \cos\omega t)$$

$$V_{rms} = \omega L I_{rms}$$

$$X_L = \frac{V_{rms}}{I_{rms}} = \frac{\omega L I_{rms}}{I_{rms}} = \omega L = 2\pi f L$$

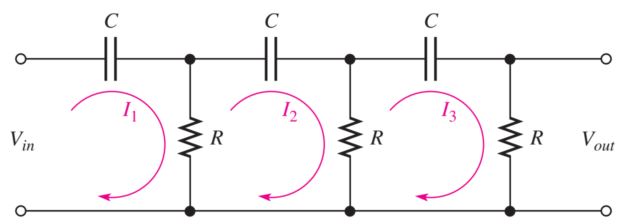
Equation 15–33

The feedback circuit in the phase-shift oscillator consists of three RC stages, as shown in Figure B–3. An expression for the attenuation is derived using the loop analysis method for the loop assignment shown. All Rs are equal in value, and all Cs are equal in value.

$$(R - j1/2\pi fC)I_1 - RI_2 + 0I_3 = V_{in}$$

$$-RI_1 + (2R - j1/2\pi fC)I_2 - RI_3 = 0$$

$$0I_1 - RI_2 + (2R - j1/2\pi fC)I_3 = 0$$



▲ FIGURE B–3

Feedback circuit for a phase-shift oscillator.

In order to get V_{out}, we must solve for I_3 using determinants:

$$I_3 = \frac{\begin{vmatrix} (R - j1/2\pi fC) & -R & V_{in} \\ -R & (2R - j1/2\pi fC) & 0 \\ 0 & -R & 0 \end{vmatrix}}{\begin{vmatrix} (R - j1/2\pi fC) & -R & 0 \\ -R & (2R - j1/2\pi fC) & -R \\ 0 & -R & (2R - j1/2\pi fC) \end{vmatrix}}$$

$$I_3 = \frac{R^2 V_{in}}{(R - j1/2\pi fC)(2R - j1/2\pi fC)^2 - R^2(2R - j1/2\pi fC) - R^2(R - 1/2\pi fC)}$$

$$\frac{V_{out}}{V_{in}} = \frac{RI_3}{V_{in}}$$

$$= \frac{R^3}{(R - j1/2\pi fC)(2R - j1/2\pi fC)^2 - R^3(2 - j1/2\pi fRC) - R^3(1 - 1/2\pi fRC)}$$

$$= \frac{R^3}{R^3(1 - j1/2\pi fRC)(2 - j1/2\pi fRC)^2 - R^3[(2 - j1/2\pi fRC) - (1 - j1/2\pi fRC)]}$$

$$= \frac{R^3}{R^3(1 - j1/2\pi fRC)(2 - j1/2\pi fRC)^2 - R^3(3 - j1/2\pi fRC)}$$

$$\frac{V_{out}}{V_{in}} = \frac{1}{(1 - j1/2\pi fRC)(2 - j1/2\pi fRC)^2 - (3 - j1/2\pi fRC)}$$

Expanding and combining the real terms and the j terms separately,

$$\frac{V_{out}}{V_{in}} = \frac{1}{\left(1 - \frac{5}{4\pi^2 f^2 R^2 C^2}\right) - j\left(\frac{6}{2\pi fRC} - \frac{1}{(2\pi f)^3 R^3 C^3}\right)}$$

For oscillation in the phase-shift amplifier, the phase shift through the RC circuit must equal 180°. For this condition to exist, the j term must be 0 at the frequency of oscillation f_r.

$$\frac{6}{2\pi f_r RC} - \frac{1}{(2\pi f_r)^3 R^3 C^3} = 0$$

$$\frac{6(2\pi)^2 f_r^2 R^2 C^2 - 1}{(2\pi)^3 f_r^3 R^3 C^3} = 0$$

$$6(2\pi)^2 f_r^2 R^2 C^2 - 1 = 0$$

$$f_r^2 = \frac{1}{6(2\pi)^2 R^2 C^2}$$

$$f_r = \frac{1}{2\pi\sqrt{6}RC}$$

Equation 17–13 Resonant Frequency for a Nonideal Parallel Resonant Circuit

$$\frac{1}{\mathbf{Z}} = \frac{1}{-jX_C} + \frac{1}{R_W + jX_L}$$

$$= j\left(\frac{1}{X_C}\right) + \frac{R_W - jX_L}{(R_W + jX_L)(R_W - jX_L)} = j\left(\frac{1}{X_C}\right) + \frac{R_W - jX_L}{R_W^2 + X_L^2}$$

The first term plus splitting the numerator of the second term yields

$$\frac{1}{\mathbf{Z}} = j\left(\frac{1}{X_C}\right) - j\left(\frac{X_L}{R_W^2 + X_L^2}\right) + \frac{R_W}{R_W^2 + X_L^2}$$

The j terms are equal.

$$\frac{1}{X_C} = \frac{X_L}{R_W^2 + X_L^2}$$

Thus,

$$R_W^2 = X_L^2 = X_L X_C$$

$$R_W^2 + (2\pi f_r L)^2 = \frac{2\pi f_r L}{2\pi f_r C}$$

$$R_W^2 + 4\pi^2 f_r^2 L^2 = \frac{L}{C}$$

$$4\pi^2 f_r^2 L^2 = \frac{L}{C} - R_W^2$$

Solving for f_r^2,

$$f_r^2 = \frac{\left(\frac{L}{C}\right) - R_W^2}{4\pi^2 L^2}$$

Multiplying both numerator and denominator by C,

$$f_r^2 = \frac{L - R_W^2 C}{4\pi^2 L^2 C} = \frac{L - R_W^2 C}{L(4\pi^2 LC)}$$

Factoring an L out of the numerator and canceling gives

$$f_r^2 = \frac{1 - (R_W^2 C/L)}{4\pi^2 LC}$$

Taking the square root of both sides yields

$$f_r = \frac{\sqrt{1 - (R_W^2 C/L)}}{2\pi\sqrt{LC}}$$

Equation 17–16 Impedance of Nonideal Tank Circuit at Resonance

Begin with the following expression for $1/\mathbf{Z}$ that was developed in the derivation for Equation 17–13.

$$\frac{1}{\mathbf{Z}} = j\left(\frac{1}{X_C}\right) - j\left(\frac{X_L}{R_W^2 + X_L^2}\right) + \frac{R_W}{R_W^2 + X_L^2}$$

At resonance, $\mathbf{Z}$ is purely resistive; so it has no j part (the j terms in the last expression cancel). Thus, only the real part is left, as stated in the following equation for Z at resonance:

$$Z_r = \frac{R_W^2 + X_L^2}{R_W}$$

Splitting the denominator, we get

$$Z_r = \frac{R_W^2}{R_W} + \frac{X_L^2}{R_W} = R_W + \frac{X_L^2}{R_W}$$

Factoring out R_W gives

$$Z_r = R_W\left(1 + \frac{X_L^2}{R_W^2}\right)$$

Since $X_L^2/R_W^2 = Q^2$, then

$$Z_R = R_W(Q^2 + 1)$$

CAPACITOR LABEL CODING

Appendix **C**

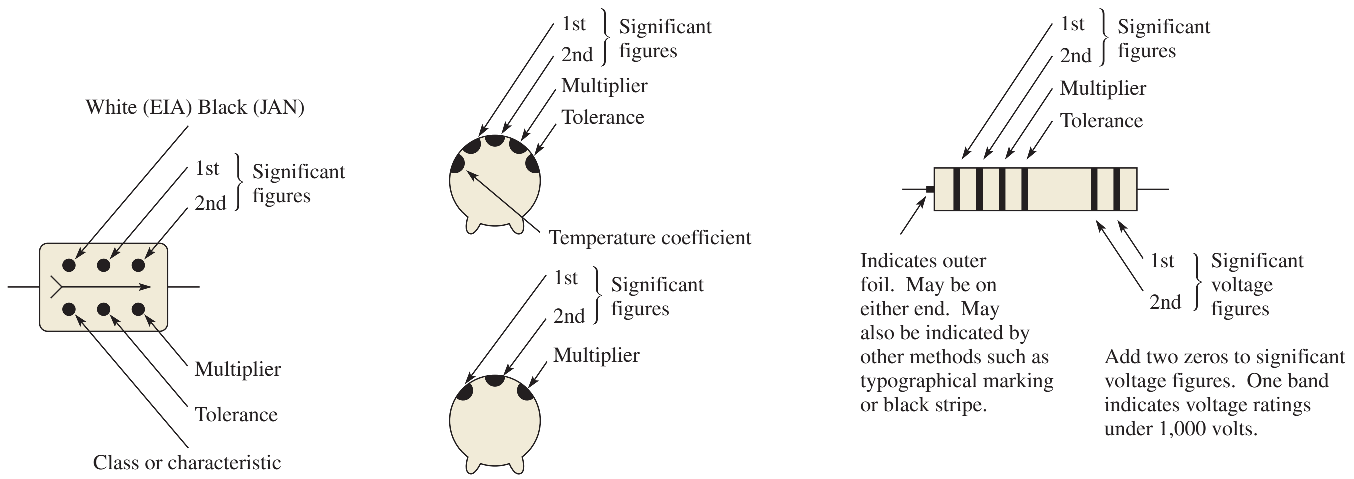
Some capacitors have color-coded designations. The color code used for capacitors is basically the same as that used for resistors. Some variations occur in tolerance designation. The basic color codes are shown in Table C–1, and some typical color-coded capacitors are illustrated in Figure C–1.

COLOR	DIGIT	MULTIPLIER	TOLERANCE
Black	0	1	20%
Brown	1	10	1%
Red	2	100	2%
Orange	3	1,000	3%
Yellow	4	10,000	
Green	5	100,000	5% (EIA)
Blue	6	1,000,000	
Violet	7		
Gray	8		
White	9		
Gold		0.1	5% (JAN)
Silver		0.01	10%

NOTE: EIA stands for Electronic Industries Association, and JAN stands for Joint Army-Navy, a military standard.

TABLE C–1

Typical composite color codes for capacitors (picofarads).



(a) Molded mica (b) Disk ceramic (c) Molded tubular

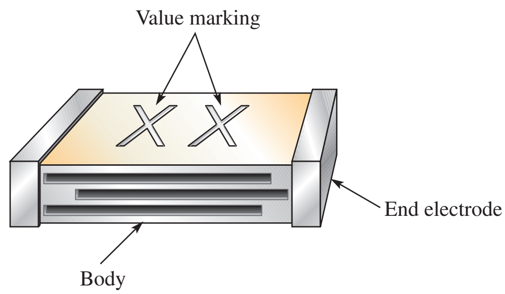
FIGURE C–1

Typical color-coded capacitors.

Marking Systems

A capacitor, as shown in Figure C–2, has certain identifying features.

- Body of one solid color (off-white, beige, gray, tan, or brown).
- End electrodes completely enclose ends of part.
- Many different sizes:
  1. Type 1206: 0.125 inch long by 0.063 inch wide (3.2 mm × 1.6 mm) with variable thickness and color.
  2. Type 0805: 0.080 inch long by 0.050 inch wide (2.0 mm × 1.25 mm) with variable thickness and color.
  3. Variably sized with a single color (usually translucent tan or brown). Sizes range from 0.059 inch (1.5 mm) to 0.220 inch (5.6 mm) in length and in width from 0.032 inch (0.8 mm) to 0.197 inch (5.0 mm).
- Three different marking systems:
  1. Two places (letter and number only).
  2. Two places (letter and number or two numbers).
  3. One place (letter of varying color).

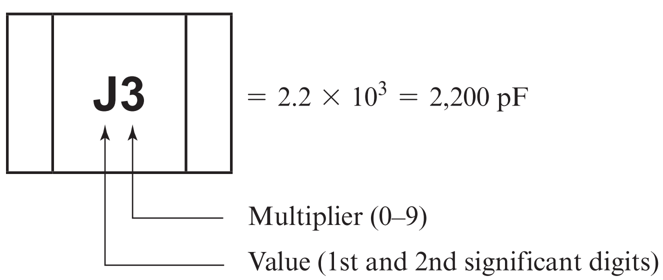


▲ FIGURE C–2

Capacitor marking.

Standard Two-Place Code

Refer to Table C–2.



Examples: S2 = 4.7 × 100 = 470 pF
b0 = 3.5 × 1.0 = 3.5 pF

VALUE*						MULTIPLIER
A	1.0	L	2.7	T	5.1	0 = ×1.0
B	1.1	M	3.0	U	5.6	1 = ×10
C	1.2	N	3.3	m	6.0	2 = ×100
D	1.3	b	3.5	V	6.2	3 = ×1,000
E	1.5	P	3.6	W	6.8	4 = ×10,000
F	1.6	Q	3.9	n	7.0	5 = ×100,000
G	1.8	d	4.0	X	7.5	etc.
H	2.0	R	4.3	t	8.0	
J	2.2	e	4.5	Y	8.2	
K	2.4	S	4.7	y	9.0	
a	2.5	f	5.0	Z	9.1	

*Note uppercase and lowercase letters.

TABLE C–2
Standard two-place code for capacitors.

Alternate Two-Place Code

Refer to Table C–3.

- Values below 100 pF—Value read directly

$\boxed{05}$ = 5 pF $\boxed{82}$ = 82 pF

- Values 100 pF and above—Letter/Number code

$\boxed{A1}$ $= 10 \times 10 = 100$ pF $\boxed{N3}$ $= 33 \times 1{,}000 = 33{,}000$ pF $= .033\ \mu$F

Multiplier (1–9)
Value (1st and 2nd significant digits)

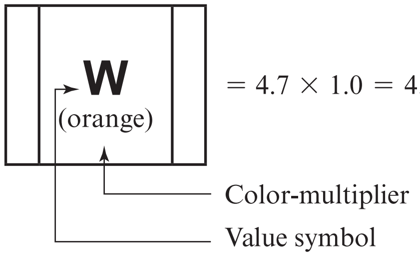
VALUE*						MULTIPLIER
A	10	J	22	S	47	1 = ×10
B	11	K	24	T	51	2 = ×100
C	12	L	27	U	56	3 = ×1,000
D	13	M	30	V	62	4 = ×10,000
E	15	N	33	W	68	5 = ×100,000
F	16	P	36	X	75	etc.
G	18	Q	39	Y	82	
H	20	R	43	Z	91	

*Note uppercase letters only.

TABLE C–3
Alternate two-place code for capacitors.

Standard Single-Place Code

Refer to Table C–4.



$= 4.7 \times 1.0 = 4.7$ pF

Examples: R (Green) $= 3.3 \times 100 = 330$ pF
7 (Blue) $= 8.2 \times 1{,}000 = 8{,}200$ pF

▶ **TABLE C–4**

Standard single-place code for capacitors.

VALUE						MULTIPLIER (COLOR)
A	1.0	K	2.2	W	4.7	Orange $= \times 1.0$
B	1.1	L	2.4	X	5.1	Black $= \times 10$
C	1.2	N	2.7	Y	5.6	Green $= \times 100$
D	1.3	O	3.0	Z	6.2	Blue $= \times 1{,}000$
E	1.5	R	3.3	3	6.8	Violet $= \times 10{,}000$
H	1.6	S	3.6	4	7.5	Red $= \times 100{,}000$
I	1.8	T	3.9	7	8.2	
J	2.0	V	4.3	9	9.1	

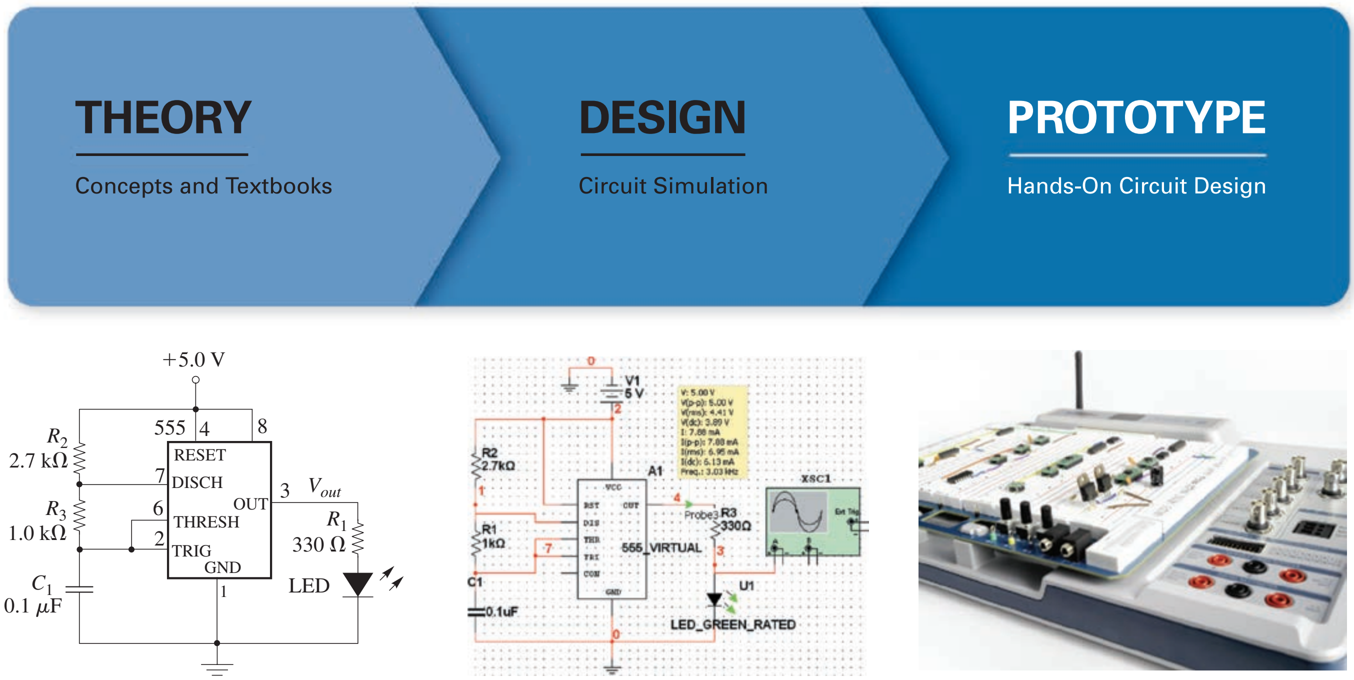
NI Multisim for Circuit Simulation

Appendix D

Simulate, Prototype, and Test Circuits

Theory, Design, and Prototype

As electronic circuits and systems become more advanced, circuit designers rely on computers in the design process. It is essential for engineers and technicians to systematically design, simulate, prototype, and lay out the circuit. Students can also use the engineering and design process to reinforce concepts and theory in the classroom. The three stages of the student design process are illustrated in Figure D–1.



▲ FIGURE D–1

Three steps of the student design process for a practical circuit.

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Notice: Information in this Appendix may differ from your version of Multisim.

The National Instruments Electronics Education Platform is an end-to-end tool-chain designed to meet student and educator needs. The platform consists of NI Multisim simulation software, the NI Educational Laboratory Virtual Instrumentation Suite (NI ELVIS) prototyping workstation, and the NI LabVIEW graphical programming environment. NI Multisim provides intuitive schematic capture, SPICE simulation, and integration with the NI ELVIS to help students explore circuit theory and design circuits to investigate behavior. NI ELVIS is a prototyping platform that allows students to quickly and easily create their circuits. With NI LabVIEW, students can measure real-world signals and compare simulation results.

1. Investigate Theory Learn the fundamental theory of circuit design through the *Principles of Electric Circuits* textbook and course lectures. Reinforce important concepts in the easy-to-use Multisim environment by downloading the Multisim circuit files for the textbook. The Multisim circuit files help build the foundation for an in-depth understanding of circuit behavior. Using the prebuilt circuit files, simulate and analyze the circuit behavior of examples and problems in each chapter.

2. Design and Simulate Circuit simulation provides an interactive view into a circuit. Build a circuit from scratch and learn about the design performance using built-in circuit instruments and probes in an ideal pre-laboratory environment. With the 3D breadboard in Multisim, take the leap from circuit diagram to real-world physical implementation.

3. Prototype, Measure, and Compare Hands-on experience building physical circuitry is essential. Move from the 3D breadboard in Multisim to a real-world breadboard on NI ELVIS to seamlessly complete the entire design process by prototyping the circuit. Within the LabVIEW environment, compare real-world measurements to the simulation values to reinforce theory, fully understand circuit behavior, and build the foundations of professional engineering analysis.

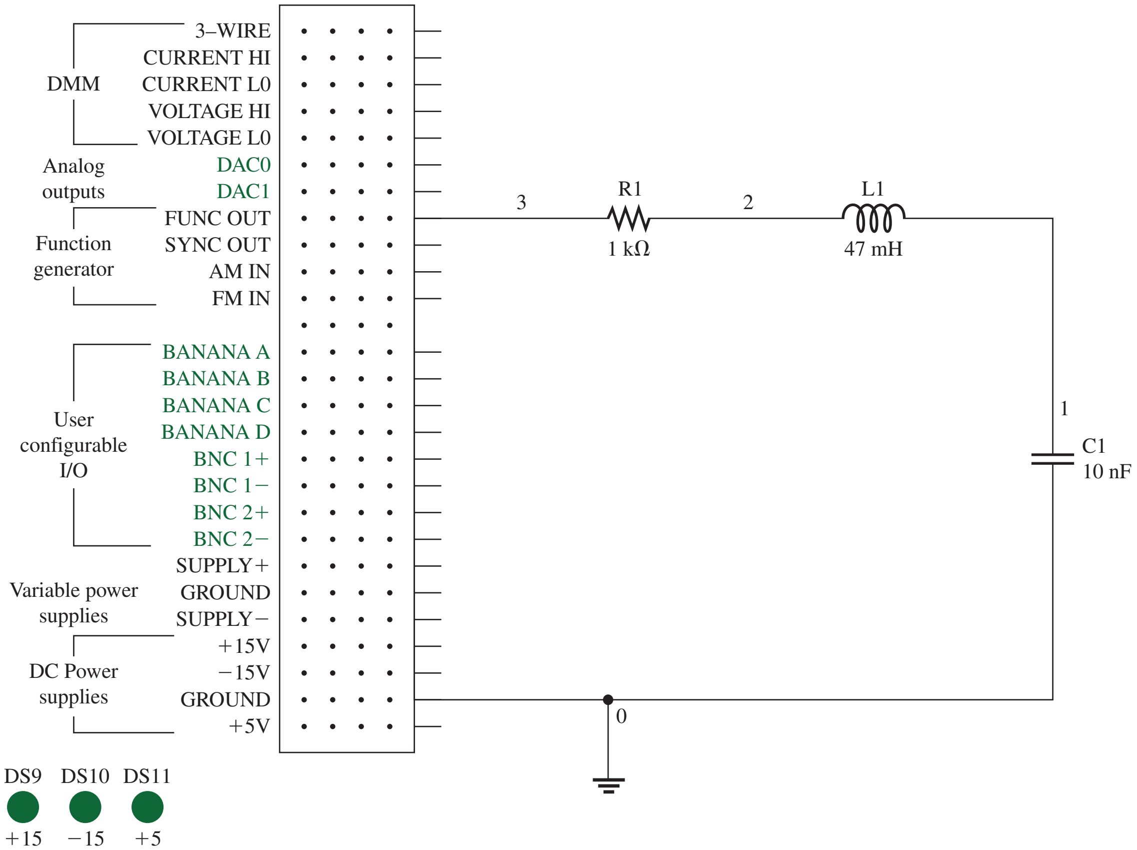
NI Multisim

Multisim integrates industry standard SPICE simulation with an interactive schematic environment to instantly visualize and analyze electronic circuits behavior. Multisim for Education has been developed with educators to enable students to easily visualize and understand the behavior of electronics with 30+ intuitive simulated instruments, 20+ easy-to-configure analyses, and interactive components that are proven to reinforce theory and prepare students for authentic design challenges.

Using Multisim with Principles of Electric Circuits Create an example from the textbook to get familiar with the Multisim environment. First, launch Multisim and open a new schematic window (**File >> New >> Schematic Capture**). Design circuits in the circuit window by placing components from the component toolbar. Clicking on the component toolbar opens the component browser. Choose the family of components and select an individual component to place on the circuit window by double-clicking on it.

Once you have selected a component, it attaches itself and "ghosts" the mouse cursor. Place the component by clicking again on the desired location in the schematic. If you are new to Multisim, you should use the **BASIC_VIRTUAL** family of components, which you can assign any arbitrary value. As an example of a simple Multisim circuit, an *RLC* circuit is shown in Figure D–2. The circuit connects a 1 kΩ resistor, a 47 mH inductor, and a 10 nF capacitor. All these components are found in the Basic Group of the Component Database.

The next step is to wire the components together. Simply left-click on the source terminal and left-click on the destination terminal. Multisim automatically chooses the best path for the virtual wire between the two terminals. Always be sure you have



▲ **FIGURE D–2**

Multisim schematic of *RLC* circuit.

fully captured your circuit; then you can simulate it. You can use your simulation results as a comparison with the physical circuit.

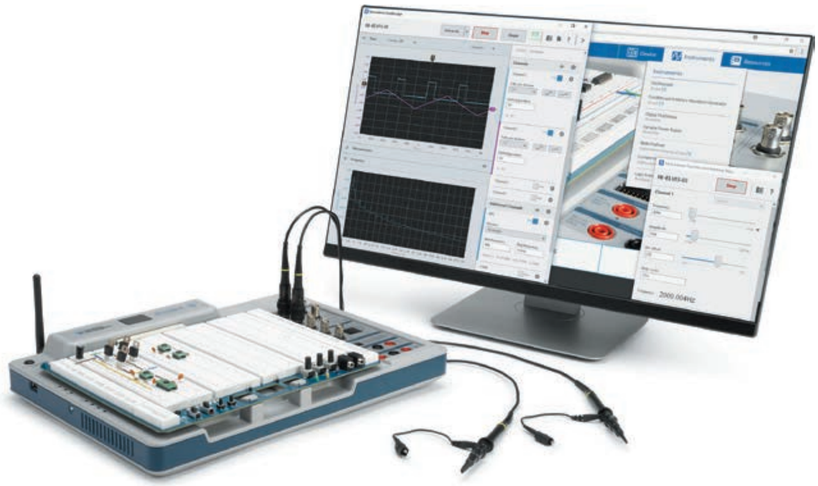
To analyze the circuit, use a measurement probe to measure the voltages and other characteristics from the circuit while the simulation is running. Use the virtual oscilloscope to analyze the output signal from our sample *RLC* circuit.

NI ELVIS

NI ELVIS is a project-based learning solution combining instrumentation, embedded design, and web connectivity for engineering fundamentals and system design. Students can design, build, and troubleshoot circuits using the integrated instruments and the intuitive interface.

NI ELVIS features a breadboard prototyping environment and build-in instruments including: Oscilloscope, Function and Arbitrary Waveform Generator, Digital Multimeter, Variable Power Supply, Bode Analyzer, IV Analyzer, and Logic Analyzer and Pattern Generator. The breadboard is detachable, so you can work on your projects and labs independently of the NI ELVIS unit. NI ELVIS provides software based on LabVIEW for interacting with virtual instruments.

Using NI ELVIS with Principles of Electric Circuits Returning to the *RLC* circuit introduced with Multisim as an example, you can continue the prototyping step. With prototyping hardware, you can quickly construct a circuit on a standard protoboard and test it with the laboratory instruments to complete the design.



▶ **FIGURE D–3**

The NI ELVIS workstation.

Alternatively, you can repeat the simulation step but this time as a prototype using the Virtual 3D NI ELVIS from within Multisim. To construct a 3D NI ELVIS prototype, open the 3D breadboard by clicking **Tools** >> **Show Breadboard**. Place components and wires to build up your circuit. The corresponding connection points and symbols on the NI ELVIS schematic turn green, indicating the 3D connections are correct. If you create a traditional schematic, you see a standard breadboard.

After constructing the circuit, launch the NI ELVIS Oscilloscope to measure the output signal of this circuit. The most important step in the process is to compare the measurement of the prototyped circuit to the simulation. This helps you determine where potential errors exist in the design. After comparing the measurement with the theoretical values, you can revisit your design to improve it or prepare it for layout on a PCB board, using software such as NI Ultiboard.

NI Multisim Circuit Files Download the Multisim circuit files to develop in-depth understanding of circuit behavior. To download the pre-built circuit files and Multisim resources, visit:

Learn more and download a free evaluation.

ni.com/multisim

Access tutorials for getting started.

http://www.ni.com/tutorial/11996/en/

Use Multisim Live to design and simulate circuits online from any device.

multisim.com

NI Multisim Resources The link provides references to the following resources to help you get started with NI Multisim:

Download the free Multisim 30-day evaluation version

View the Getting Started Guide to Multisim

Learn Multisim in 3-Hours tutorial

Discuss Multisim in an online discussion forum

ANSWERS TO ODD-NUMBERED PROBLEMS

Chapter 1

1. **(a)** 3×10^3 **(b)** 7.5×10^4 **(c)** 2×10^6

3. **(a)** 8.4×10^3 **(b)** 9.9×10^4 **(c)** 2×10^5

5. **(a)** 3.2×10^4 **(b)** 6.8×10^{-3} **(c)** 8.7×10^{10}

7. **(a)** 0.0000025 **(b)** 500 **(c)** 0.39

9. **(a)** 4.32×10^7 **(b)** 5.00085×10^3 **(c)** 6.06×10^{-8}

11. **(a)** 2.0×10^9 **(b)** 3.6×10^{14} **(c)** 1.54×10^{-14}

13. **(a)** 4.20×10^2 **(b)** 6×10^{12} **(c)** 11×10^4

15. **(a)** 89×10^3 **(b)** 450×10^3 **(c)** 12.04×10^{12}

17. **(a)** 345×10^{-6} **(b)** 25×10^{-3} **(c)** 1.29×10^{-9}

19. **(a)** 7.1×10^{-3} **(b)** 101×10^6 **(c)** 1.50×10^6

21. **(a)** 22.7×10^{-3} **(b)** 200×10^6 **(c)** 848×10^{-3}

23. **(a)** 345 μA **(b)** 25 mA **(c)** 1.29 nA

25. **(a)** 3 μF **(b)** 3.3 MΩ **(c)** 350 nA

27. **(a)** 7.5×10^{-12} A **(b)** 3.3×10^9 Hz **(c)** 2.8×10^{-7} W

29. **(a)** 5000 μA **(b)** 3.2 mW **(c)** 5 MV **(d)** 10,000 kW

31. **(a)** 50.68 mA **(b)** 2.32 MΩ **(c)** 0.0233 μF

33. **(a)** 3 **(b)** 2 **(c)** 5 **(d)** 2 **(e)** 3 **(f)** 2

Chapter 2

1. 4.64×10^{-18} C

3. 80×10^{12} C

5. **(a)** 10 V **(b)** 2.5 V **(c)** 4 V

7. 12 V

9. 10 V

11. Electromagnetic induction

13. 100 mA

15. 0.2 A

17. 0.15 C

19. **(a)** 200 mS **(b)** 40 mS **(c)** 10 mS

21. **(a)** 27 kΩ $\pm$ 5% **(b)** 1.8 kΩ $\pm$ 10% **(c)** 120 Ω $\pm$ 5% **(d)** 3.6 kΩ $\pm$ 10%

23. 330 Ω: orange, orange, brown, gold
2.2 kΩ: red, red, red, gold
56 kΩ: green, blue, orange, gold
100 kΩ: brown, black, yellow, gold
39 kΩ: orange, white, orange, gold

25. **(a)** 27 kΩ $\pm$ 10% **(b)** 100 Ω $\pm$ 10% **(c)** 5.6 MΩ $\pm$ 5% **(d)** 6.8 kΩ $\pm$ 10% **(e)** 33 Ω $\pm$ 10% **(f)** 47 kΩ $\pm$ 5%

27. **(a)** yellow, violet, silver, gold
(b) red, violet, yellow, gold
(c) green, brown, green, gold

29. **(a)** brown, yellow, violet, red, brown
(b) orange, white, red, gold, brown
(c) white, violet, blue, brown, brown

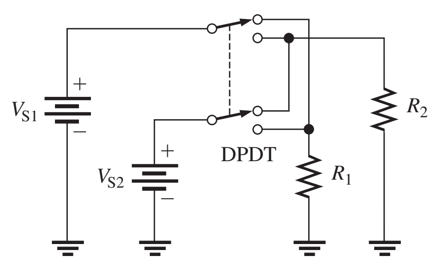
31. 4.7 kΩ

33. Through lamp 2

35. Circuit (b)

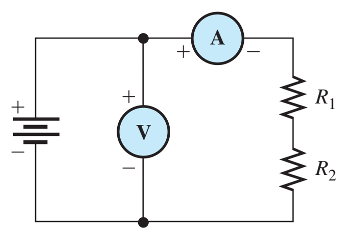
37. In Figure 2–68(b), the switch is a DPST switch.

39. See Figure P–1.



▲ FIGURE P–1

41. See Figure P–2.

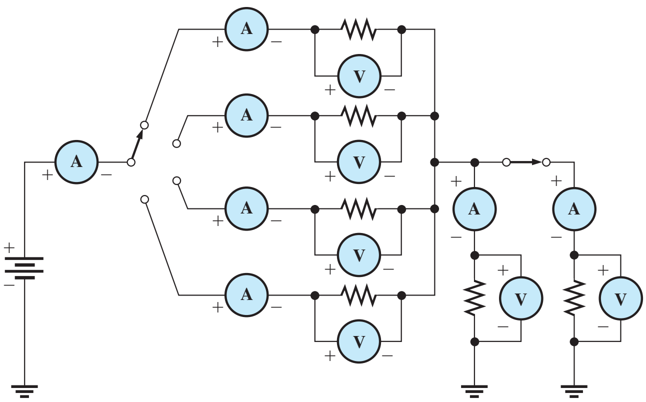


▲ FIGURE P–2

43. Position 1: V1 = 0 V, V2 = V_s

Position 2: V1 = V_s, V2 = 0 V

45. See Figure P–3.

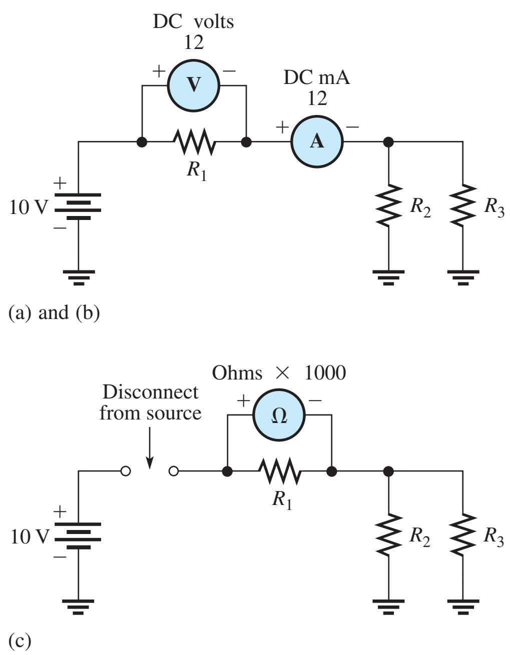


▲ FIGURE P–3

47. 250 V

49. **(a)** 20 Ω **(b)** 1.50 MΩ **(c)** 4500 Ω

51. See Figure P–4.



▲ FIGURE P–4

Chapter 3

1. **(a)** Current triples. **(b)** Current is reduced 75%.

(c) Current is halved. **(d)** Current increases 54%.

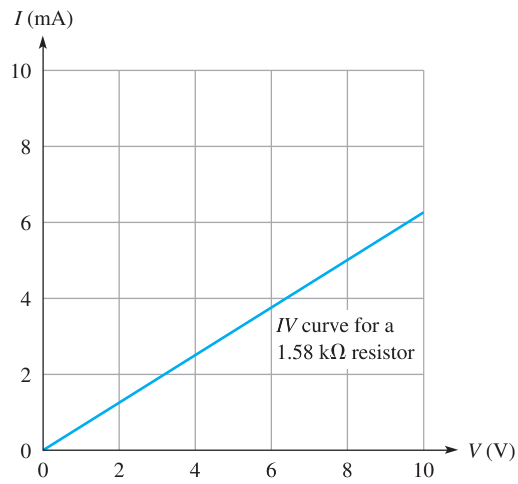
(e) Current quadruples. **(f)** Current is unchanged.

3. $V = IR$

5. The graph is a straight line, indicating a linear relationship between V and I.

7. $R_1 = 0.5\ \Omega$, $R_2 = 1.0\ \Omega$, $R_3 = 2\ \Omega$

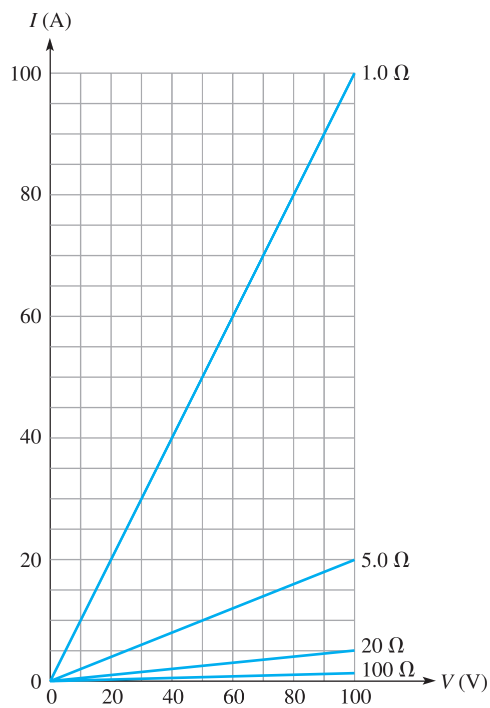
9. See Figure P–5.



▲ FIGURE P–5

11. The voltage decreased by 4 V (from 10 V to 6 V).

13. See Figure P–6.



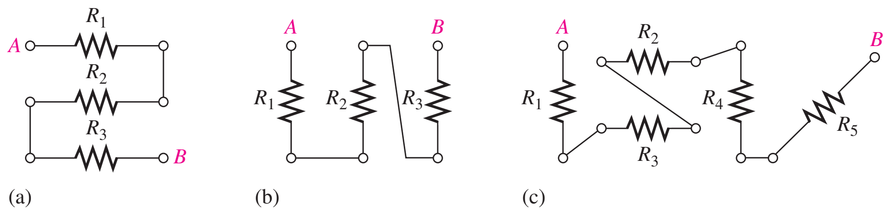
▲ FIGURE P–6

15. The resistance increases as the voltage increases.

17. **(a)** 5 A **(b)** 1.5 A **(c)** 500 mA

(d) 2 mA **(e)** 44.6 μA

▲ FIGURE P–7



19. 0.606 A

21. 532 μA

23. Yes. The current is now 0.642 A, which exceeds the rating of the fuse.

25. 1.5 A

27. 11.1 mA

29. **(a)** 36 V **(b)** 280 V **(c)** 1700 V **(d)** 28.2 V **(e)** 56 V

31. 81 V

33. **(a)** 59.9 mA **(b)** 5.99 V **(c)** 4.61 mV

35. **(a)** 2 kΩ **(b)** 3.5 kΩ **(c)** 2 kΩ **(d)** 100 kΩ **(e)** 1.0 MΩ

37. 150 Ω

39. **(a)** 360 Ω **(b)** 180 Ω

(c) the source can be shorted if the rheostat is set to 0 Ω

41. Five

43. $R_A = 560\text{ k}\Omega$; $R_B = 2.2\text{ M}\Omega$;
$R_C = 1.8\text{ k}\Omega$; $R_D = 33\ \Omega$

45. $V = 18$ V; $I = 5.453$ mA;
$R = 3.3\text{ k}\Omega$

Chapter 4

1. volt = joule/coulomb
amp = coulomb/second
VI = joule/coulomb × coulomb/second = joule/sec = watt

3. 350 W

5. 20 kW

7. **(a)** 1 MW **(b)** 3 MW **(c)** 150 MW **(d)** 8.7 MW

9. **(a)** 2,000,000 μW **(b)** 500 μW **(c)** 250 μW **(d)** 6.67 μW

11. 8640 J

13. 2.02 kW/day

15. 0.00186 kWh

17. 37.5 Ω

19. 360 W

21. 100 μW

23. 40.2 mW

25. **(a)** 0.480 Wh **(b)** Equal

27. 2 W, to provide a safety margin

29. At least 12 W, to allow a safety margin of 20%

31. 7.07 V

33. 50,544 J

35. 4 A

37. 100 mW, 80%

39. 0.08 kWh

41. $V = 5$ V; $I = 5$ mA;
$R = 1\text{ k}\Omega$

Chapter 5

1. See Figure P–7.

3. 170 kΩ

5. R_1, R_7, R_8, and R_{10} are in series.
R_2, R_4, R_6, and R_{11} are in series.
R_3, R_5, R_9, and R_{12} are in series.

7. **(a)** 1560 Ω **(b)** 103 Ω **(c)** 13.7 kΩ **(d)** 3.671 MΩ

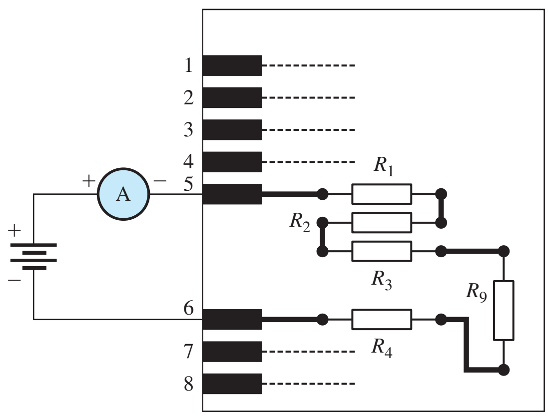
9. 67.2 kΩ

11. 3.9 kΩ

13. 17.8 MΩ

15. $I = 100$ mA

17. See Figure P–8. The current through R_2, R_3, R_4, and R_9 is also measured by this set-up.



▲ FIGURE P–8

19. **(a)** 625 μA **(b)** 4.26 μA

21. **(a)** 34 mA **(b)** 16 V **(c)** 0.545 W

23. $R_1 = 330\ \Omega$, $R_2 = 220\ \Omega$, $R_3 = 100\ \Omega$, $R_4 = 470\ \Omega$

25. **(a)** 331 Ω

(b) Position *B:* 9.15 mA

Position *C:* 14.3 mA

Position *D:* 36.3 mA

(c) No

27. $R_1 = 5.0\ \text{k}\Omega$; $R_2 = 1.0\ \text{k}\Omega$

29. 14 V

31. **(a)** 23 V **(b)** 85 V

33. 4 V

35. 22 Ω

37. Position *A:* 4.0 V

Position *B:* 4.5 V

Position *C:* 5.4 V

Position *D:* 7.2 V

39. 4.82%

41. *A* output = 15 V

B output = 10.6 V

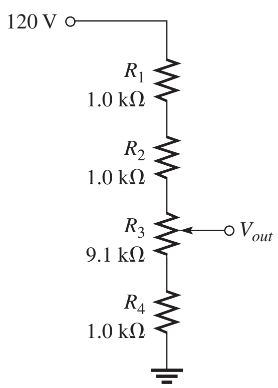
C output = 2.62 V

43. $V_R = 6$ V, $V_{2R} = 12$ V, $V_{3R} = 18$ V,

$V_{4R} = 24$ V, $V_{5R} = 30$ V

45. $V_2 = 1.79$ V, $V_3 = 1$ V, $V_4 = 17.9$ V

47. See Figure P–9.



▲ FIGURE P–9

49. The power increases by 4X

51. 54.9 mW

53. 12.5 MΩ

55. $V_A = 100$ V, $V_B = 57.7$ V, $V_C = 15.2$ V, $V_D = 7.58$ V

57. $V_A = 14.82$ V, $V_B = 12.97$ V, $V_C = 12.64$ V, $V_D = 9.34$ V

59. −2.18 V

61. **(a)** R_4 is open. **(b)** Short from *A* to *B*

63. Table 5–1 is correct.

65. Yes. There is a short between pin 4 and the upper side of R_{11}.

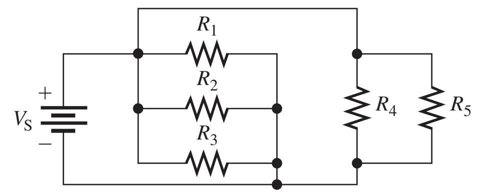
67. $R_T = 7.481\ \text{k}\Omega$

69. $R_3 = 22\ \Omega$

71. R_1 shorted

Chapter 6

1. See Figure P–10.



▲ FIGURE P–10

3. R_1, R_2, R_5, R_9, R_{10}, and R_{12} are in parallel.

R_4, R_6, R_7, and R_8 are in parallel.

R_3 and R_{11} are in parallel.

5. 100 V

7. Position A: $V_1 = 15$ V, $V_2 = 0$ V, $V_3 = 0$ V, $V_4 = 15$ V

Position B: $V_1 = 15$ V, $V_2 = 0$ V, $V_3 = 15$ V, $V_4 = 0$ V

Position C: $V_1 = 15$ V, $V_2 = 15$ V, $V_3 = 0$ V, $V_4 = 0$ V

9. 1.35 A

11. $R_2 = 22\ \Omega$, $R_3 = 100\ \Omega$, $R_4 = 33\ \Omega$

13. 11.4 mA

15. **(a)** 6.4 A **(b)** 6.4 A

17. **(a)** 359 Ω **(b)** 25.6 Ω

(c) 819 Ω **(d)** 997 Ω

19. 567 Ω

21. 24.6 Ω

23. **(a)** 510 kΩ **(b)** 245 kΩ

(c) 510 kΩ **(d)** 193 kΩ

25. 1.5 A

27. 50 mA; When one bulb burns out, the others remain on.

29. 53.7 Ω

31. $I_2 = 167$ mA, $I_3 = 83.3$ mA, $I_T = 300$ mA,

$R_1 = 2\ \text{k}\Omega$, $R_2 = 600\ \Omega$

33. Position *A:* 2.25 mA

Position *B:* 4.75 mA

Position *C:* 7 mA

35. **(a)** $I_1 = 6.88\ \mu$A, $I_2 = 3.12\ \mu$A

(b) $I_1 = 5.25$ mA, $I_2 = 2.39$ mA, $I_3 = 1.59$ mA,

$I_4 = 772\ \mu$A

37. $R_1 = 3.3\ \text{k}\Omega$, $R_2 = 1.8\ \text{k}\Omega$, $R_3 = 5.6\ \text{k}\Omega$, $R_4 = 3.9\ \text{k}\Omega$

39. **(a)** 1 mΩ **(b)** 5 μA

41. **(a)** 68.8 μW **(b)** 52.5 mW

43. $P_1 = 1.25$ W, $I_2 = 75$ mA, $I_1 = 125$ mA, $V_S = 10$ V, $R_1 = 80\ \Omega$, $R_2 = 133\ \Omega$

45. 625 mA, 3.13 A

47. The 8.2 kΩ resistor is open.

49. Connect ohmmeter between the following pins:

Pins 1-2

Correct reading: $R = 1.0\ \text{k}\Omega \| 3.3\ \text{k}\Omega = 767\ \Omega$

R_1 open: $R = 3.3\ \text{k}\Omega$

R_2 open: $R = 1.0\ \text{k}\Omega$

Pins 3-4

Correct reading: $R = 270\ \Omega \| 390\ \Omega = 159.5\ \Omega$

R_3 open: $R = 390\ \Omega$

R_4 open: $R = 270\ \Omega$

Pins 5-6

Correct reading:

$R = 1.0\ \text{M}\Omega \| 1.8\ \text{M}\Omega \| 680\ \text{k}\Omega \| 510\ \text{k}\Omega = 201\ \text{k}\Omega$

R_5 open: $R = 1.8\ \text{M}\Omega \| 680\ \text{k}\Omega \| 510\ \text{k}\Omega = 251\ \text{k}\Omega$

R_6 open: $R = 1.0\ \text{M}\Omega \| 680\ \text{k}\Omega \| 510\ \text{k}\Omega = 226\ \text{k}\Omega$

R_7 open: $R = 1.0\ \text{M}\Omega \| 1.8\ \text{M}\Omega \| 510\ \text{k}\Omega = 284\ \text{k}\Omega$

R_8 open: $R = 1.0\ \text{M}\Omega \| 1.8\ \text{M}\Omega \| 680\ \text{k}\Omega = 330\ \text{k}\Omega$

51. Short between pins 3 and 4:

(a) $R_{1\text{-}2} = (R_1 \| R_2 \| R_3 \| R_4 \| R_{11} \| R_{12}) + (R_5 \| R_6 \| R_7 \| R_8 \| R_9 \| R_{10}) = 940\ \Omega$

(b) $R_{2\text{-}3} = R_5 \| R_6 \| R_7 \| R_8 \| R_9 \| R_{10} = 518\ \Omega$

(c) $R_{2\text{-}4} = R_5 \| R_6 \| R_7 \| R_8 \| R_9 \| R_{10} = 518\ \Omega$

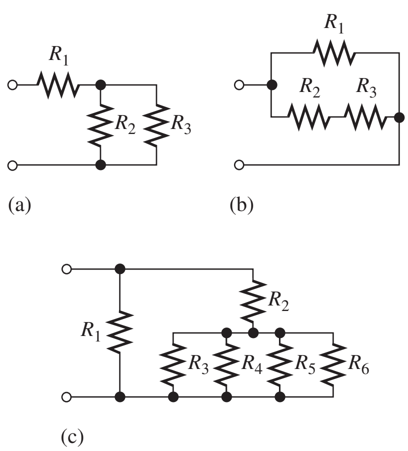
(d) $R_{1\text{-}4} = R_1 \| R_2 \| R_3 \| R_4 \| R_{11} \| R_{12} = 422\ \Omega$

53. R_2 open

55. $V_S = 3.30$ V

Chapter 7

1. See Figure P–11.



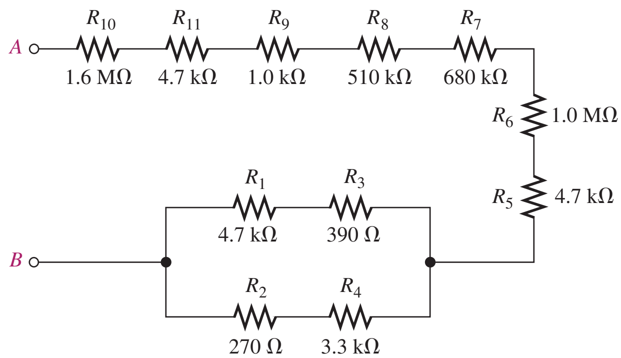
▲ FIGURE P–11

3. (a) R_1 and R_4 are in series with the parallel combination of R_2 and R_3.

(b) R_1 is in series with the parallel combination of R_2, R_3, and R_4.

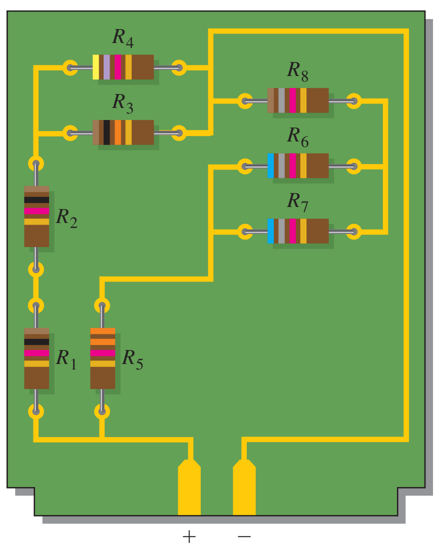
(c) The parallel combination of R_2 and R_3 is in series with the parallel combination of R_4 and R_5. This is all in parallel with R_1.

5. See Figure P–12.



▲ FIGURE P–12

7. See Figure P–13.



▲ FIGURE P–13

9. (a) 133 Ω **(b)** 779 Ω **(c)** 852 Ω

11. (a) $I_1 = I_4 = 11.3$ mA, $I_2 = I_3 = 5.64$ mA, $V_1 = 633$ mV, $V_2 = V_3 = 564$ mV, $V_4 = 305$ mV

(b) $I_1 = 3.85$ mA, $I_2 = 563\ \mu$A, $I_3 = 1.16$ mA, $I_4 = 2.13$ mA, $V_1 = 2.62$ V, $V_2 = V_3 = V_4 = 383$ mV

(c) $I_1 = 5$ mA, $I_2 = 303\mu$A, $I_3 = 568\ \mu$A, $I_4 = 313\mu$A, $I_5 = 558\ \mu$A, $V_1 = 5$ V, $V_2 = V_3 = 1.88$ V, $V_4 = V_5 = 3.13$ V

13. SW1 closed, SW2 open: 220 Ω

SW1 closed, SW2 closed: 200 Ω

SW1 open, SW2 open: 320 Ω

SW1 open, SW2 closed: 300 Ω

15. $V_A = 100$ V, $V_B = 61.5$ V, $V_C = 15.7$ V, $V_D = 7.87$ V

17. Measure the voltage at A with respect to ground and the voltage at B with respect to ground. The difference is V_{R2}.

19. 303 kΩ

21. **(a)** 110 kΩ

(b) 110 mW

23. $R_{AB} = 1.32$ kΩ

$R_{BC} = 1.32$ kΩ

$R_{CD} = 0$ Ω

25. 7.5 V unloaded, 7.29 V loaded

27. 47 kΩ

29. 8.77 V

31. $R_1 = 1000$ Ω; $R_2 = R_3 = 500$ Ω;

lower tap loaded: $V_{lower} = 1.82$ V, $V_{upper} = 4.55$ V

upper tap loaded: $V_{lower} = 1.67$ V, $V_{upper} = 3.33$ V

33. **(a)** $V_G = 1.75$ V, $V_S = 3.25$ V

(b) $I_1 = I_2 = 6.48\ \mu$A, $I_D = I_S = 2.17$ mA

(c) $V_{DS} = 2.55$ V, $V_{DG} = 4.05$ V

35. 1000 V

37. **(a)** 0.5 V range **(b)** Approximately 1 mV

39. 33.3%

41. **(a)** 271 Ω **(b)** 221 mA **(c)** 58.7 mA **(d)** 12 V

43. 621 Ω, $I_1 = I_9 = 16.1$ mA, $I_2 = 8.27$ mA,

$I_3 = I_8 = 7.84$ mA, $I_4 = 4.06$ mA, $I_5 = I_6 = I_7 = 3.78$ mA

45. 971 mA

47. **(a)** 9 V **(b)** 3.75 V **(c)** 11.25 V

49. 6 mV (right side positive with respect to left side)

51. No, it should be 4.39 V.

53. The 2.2 kΩ resistor (R_3) is open.

55. The 3.3 kΩ resistor (R_4) is open.

57. $R_T = 296.744$ Ω

59. $R_3 = 560$ kΩ

61. R_5 shorted

Chapter 8

1. $I_S = 6$ A, $R_S = 50$ Ω

3. 200 mΩ

5. $V_S = 720$ V, $R_S = 1.2$ kΩ

7. 845 μA

9. 1.13 mA

11. 1.6 mA

13. $V_{max} = 3.72$ V; $V_{min} = 1.32$ V

15. 90.7 V

17. $I_{S1} = 2.28$ mA, $I_{S2} = 1.35$ mA

19. 116 μA

21. $R_{TH} = 88.6$ Ω, $V_{TH} = 1.09$ V

23. 100 μA

25. **(a)** $I_N = 110$ mA, $R_N = 76.7$ Ω

(b) $I_N = 11.1$ mA, $R_N = 73$ Ω

(c) $I_N = 50\ \mu$A, $R_N = 35.9$ kΩ

(d) $I_N = 68.8$ mA, $R_N = 1.3$ kΩ

27. 17.9 V

29. $I_N = 953\ \mu$A, $R_N = 1175$ Ω

31. $I_N = -48.2$ mA, $R_N = 56.9$ Ω

33. 11.1 Ω

35. $R_{TH} = 48$ Ω, $R_4 = 160$ Ω

37. **(a)** $R_A = 39.8$ Ω, $R_B = 73$ Ω, $R_C = 48.7$ Ω

(b) $R_A = 21.2$ kΩ, $R_B = 10.3$ kΩ, $R_C = 14.9$ kΩ

39. R_1 resistance shifted to 10 Ω

41. $I_N = 383\ \mu$A; $R_N = 9.674$ kΩ

43. $I_{AB} = 1.206$ mA; $V_{AB} = 3.432$ V;

$R_L = 2.846$ kΩ

Chapter 9

1. $I_1 = 371$ mA; $I_2 = -143$ mA

3. $I_1 = 0$ A, $I_2 = 2$ A

5. **(a)** −16,470 **(b)** −1.59

7. $I_1 = 1.24$ A, $I_2 = 2.05$ A, $I_3 = 1.89$ A

9. X1 = .371428571429 ($I_1 = 371$ mA)

X2 = −.142857142857 ($I_2 = -143$ mA)

11. $I_1 - I_2 - I_3 = 0$

13. $V_1 = 5.66$ V, $V_2 = 6.33$ V, $V_3 = 325$ mV

15. −1.84 V

17. $I_1 = -5.11$ mA, $I_2 = -3.52$ mA

19. $V_1 = 5.11$ V, $V_3 = 890$ mV, $V_2 = 2.89$ V

21. $I_1 = 15.6$ mA, $I_2 = -61.3$ mA, $I_3 = 61.5$ mA

23. −11.2 mV

25. Note: all Rs (coefficients) are in kΩ.

Loop A: $5.48I_A - 3.3I_B - 1.5I_C = 0$

Loop B: $-3.3I_A + 4.12I_B - 0.82I_C = 15$

Loop C: $-1.5I_A - 0.82I_B + 4.52I_C = 0$

27. 4.76 V

29. $I_1 = 20.6$ mA, $I_3 = 193$ mA, $I_2 = -172$ mA

31. $V_A = 1.5$ V, $V_B = -5.65$ V

33. $I_1 = 193\ \mu A$, $I_2 = 370\ \mu A$, $I_3 = 179\ \mu A$, $I_4 = 328\ \mu A$, $I_5 = 1.46$ mA, $I_6 = 522\ \mu A$, $I_7 = 2.16$ mA, $I_8 = 1.64$ mA, $V_A = -3.70$ V, $V_B = -5.85$ V, $V_C = -15.7$ V

35. No fault

37. R_4 open

39. F_2 is open

41. R_4 open

Chapter 10

1. Decreases

3. 37.5 μWb

5. 1000 G

7. 597

9. 150 At

11. **(a)** Electromagnetic field **(b)** Spring

13. Forces produced by the interaction of the electromagnetic field and the permanent magnetic field

15. Change the current.

17. Material A

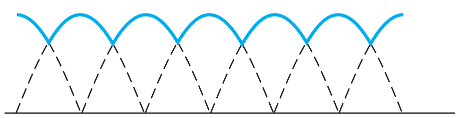
19. The strength of the magnetic field, the length of the conductor exposed to the field, and the rotational rate of the conductor

21. Lenz's law defines the polarity of the induced voltage.

23. **(a)** out **(b)** down **(c)** to the left

25. The commutator and brush arrangement electrically connect the loop to the external circuit.

27. Figure P–14.



▲ FIGURE P–14

29. **(a)** 168 W **(b)** 14 W

31. 81%

Chapter 11

1. **(a)** 1 Hz **(b)** 5 Hz **(c)** 20 Hz **(d)** 1 kHz **(e)** 2 kHz **(f)** 100 kHz

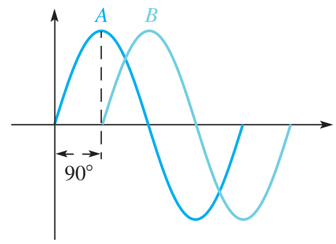
3. 2 μs

5. 10 ms

7. **(a)** 7.07 mA **(b)** 0 A (full cycle), 4.5 mA (half-cycle) **(c)** 14.14 mA

9. **(a)** 0.524 or $\pi/6$ rad **(b)** 0.785 or $\pi/4$ rad **(c)** 1.361 or $39\pi/90$ rad **(d)** 2.356 or $3\pi/4$ rad **(e)** 3.491 or $10\pi/9$ rad **(f)** 5.236 or $5\pi/3$ rad

11. 15°, A leading



▲ FIGURE P–15

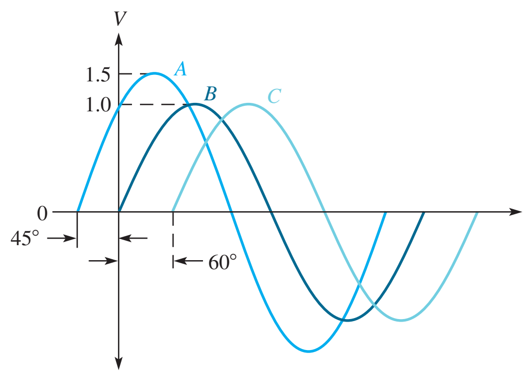
13. See Figure P–15.

15. **(a)** 57.4 mA **(b)** 99.6 mA **(c)** −17.4 mA **(d)** −57.4 mA **(e)** −99.6 mA **(f)** 0 mA

17. 30°: 13.0 V
45°: 14.5 V
90°: 13.0 V
180°: −7.5 V
200°: −11.5 V
300°: −7.5 V

19. 22.1 V

21. See Figure P–16.



▲ FIGURE P–16

23. **(a)** 156 mV **(b)** 1 V **(c)** 0 V

25. $V_{1(avg)} = 49.6$ V, $V_{2(avg)} = 31.5$ V

27. $V_{max} = 39$ V, $V_{min} = 9$ V

29. −1 V

31. 250 Hz

33. 200 rps

35. The single-phase motor requires a starting winding; the three-phase does not.

37. $t_r \cong 3.0$ ms, $t_f \cong 3.0$ ms, $t_W \cong 12.0$ ms, Ampl. $\cong 5$ V

39. 5.84 V

41. **(a)** −0.375 V **(b)** 3.01 V

43. **(a)** 50 kHz **(b)** 10 Hz

45. 75 kHz, 125 kHz, 175 kHz, 225 kHz, 275 kHz, 325 kHz

47. $V_p = 600$ mV, $T = 500$ ms

49. $V_{p(in)} = 4.44$ V, $f_{in} = 2$ Hz

51. $V_1 = 16.717\ V_{pp}$; $V_1 = 5.911\ V_{rms}$;
$V_2 = 36.766\ V_{pp}$; $V_2 = 13.005\ V_{rms}$;
$V_3 = 14.378\ V_{pp}$; $V_3 = 5.084\ V_{rms}$

53. $I_{R1} = 12.5\ mA_{rms}$; $I_{R2} = 4.545\ mA_{rms}$

55. $V_{min} = 2.015\ V_p$; $V_{max} = 21.985\ V_p$

Chapter 12

1. **(a)** 5 μF **(b)** 1 μC **(c)** 10 V

3. **(a)** 0.001 μF **(b)** 0.0035 μF **(c)** 0.00025 μF

5. 125 J

7. **(a)** 8.85×10^{-12} F/m **(b)** 35.4×10^{-12} F/m
(c) 66.4×10^{-12} F/m **(d)** 17.7×10^{-12} F/m

9. 49.8 pF

11. 0.0249 μF

13. 12.5 pF increase

15. Ceramic

17. Aluminum, tantalum; they are polarized.

19. **(a)** 0.022 μF **(b)** 0.047 μF
(c) 0.001 μF **(d)** 220 pF

21. **(a)** 0.688 μF **(b)** 69.7 pF **(c)** 2.64 μF

23. 2 μF

25. **(a)** 1057 pF **(b)** 0.121 μF

27. **(a)** 2.62 μF **(b)** 689 pF **(c)** 1.6 μF

29. **(a)** 0.411 μC
(b) $V_1 = 10.47$ V
$V_2 = 1.54$ V
$V_3 = 6.52$ V
$V_4 = 5.48$ V

31. **(a)** 13.2 ms **(b)** 247.5 μs **(c)** 11 μs **(d)** 280 μs

33. **(a)** 9.20 V **(b)** 1.24 V **(c)** 0.458 V **(d)** 0.168 V

35. **(a)** 17.9 V **(b)** 12.8 V **(c)** 6.59 V

37. 7.62 μs

39. 3.00 μs

41. See Figure P–17.

43. **(a)** 30.4 Ω **(b)** 116 kΩ **(c)** 49.7 Ω

45. 200 Ω

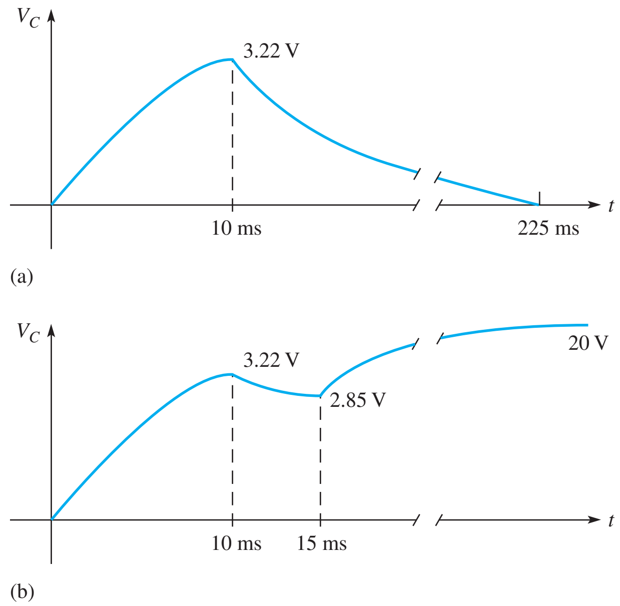
47. 0 W, 3.39 mVAR

49. 0.00541 μF

51. X_C = 1 / (hertz × farad)
= 1 / [(1 / second) × (coulombs / volts)]
= 1 / [coulombs / (second × volts)]
= volts / (coulombs / second)
= volts / amperes = ohms

53. The ripple is reduced.

55. 4.55 kΩ



▲ FIGURE P–17

57. I_C @ 1 kHz = 1.383 mA; I_C @ 500 Hz = 0.691 mA
I_C @ 2 kHz = 2.773 mA

59. C_4 shorted

Chapter 13

1. **(a)** 1000 mH **(b)** 0.25 mH **(c)** 0.01 mH **(d)** 0.5 mH

3. 50 mV

5. 20 mV

7. 0.94 μJ

9. Inductor 2 has three-fourths the inductance of inductor 1.

11. 155 μH

13. 50.5 mH

15. 7.14 μH

17. **(a)** 1.31 H **(b)** 50 mH **(c)** 57.1 μH

19. **(a)** 1 μs **(b)** 2.13 μs **(c)** 2 μs

21. **(a)** 5.52 V **(b)** 2.03 V **(c)** 747 mV
(d) 275 mV **(e)** 101 mV

23. 9.15 μs

25. **(a)** 12.3 V **(b)** 9.10 V **(c)** 3.35 V

27. 11.0 μs

29. 0.722 μs

31. 136 μA

33. **(a)** 144 Ω **(b)** 10.1 Ω **(c)** 13.4 Ω

35. **(a)** 55.5 Hz **(b)** 796 Hz **(c)** 597 Hz

37. 26.1 mA

39. 1.36 μH

41. $V_1 = 12.953$ V; $V_2 = 11.047$ V; $V_3 = 5.948$ V;
$V_4 = 5.099$ V; $V_5 = 5.099$ V

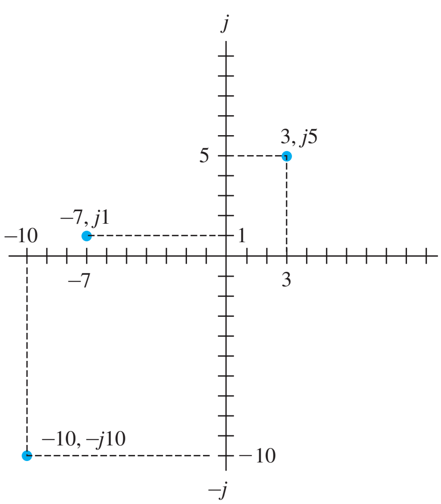
43. L_5 open

Chapter 14

1. 1.5 μH
3. 4; 0.25
5. **(a)** 100 V rms; in phase **(b)** 100 V rms; out of phase
   (c) 20 V rms; out of phase
7. 600 V
9. 0.25 (4:1)
11. 60 V
13. **(a)** 10 V **(b)** 240 V
15. **(a)** 25 mA **(b)** 50 mA **(c)** 15 V **(d)** 750 mW
17. 1.83
19. 9.76 W
21. 94.5 W
23. 0.98
25. 25 kVA
27. $V_1 = 12.0$ V, $V_2 = 24.0$ V, $V_3 = 24.0$ V, $V_4 = 48.0$ V
29. **(a)** 48 V **(b)** 25 V
31. **(a)** $V_{RL} = 35$ V, $I_{RL} = 2.92$ A, $V_C = 15$ V, $I_C = 1.5$ A
    (b) 34.5 Ω
33. Excessive primary current is drawn, potentially burning out the source and/or the transformer unless the primary is protected by a fuse.
35. Turns ratio 0.5
37. R_2 open

Chapter 15

1. Magnitude, angle
3. See Figure P–18.



▲ **FIGURE P–18**

5. **(a)** −5, +j3 and 5, −j3
   (b) −1, −j7 and 1, +j7
   (c) −10, +j10 and 10, −j10
7. 18.0
9. **(a)** 643 − j766 **(b)** −14.1 + j5.13
   (c) −17.7 − j17.7 **(d)** −3 + j0
11. **(a)** Fourth **(b)** Fourth **(c)** Fourth **(d)** First
13. **(a)** $12\angle 115°$ **(b)** $20\angle 230°$
    (c) $100\angle 190°$ **(d)** $50\angle 160°$
15. **(a)** 1.1 + j0.7 **(b)** −81 − j35
    (c) 5.28 − j5.27 **(d)** −50.4 + j62.5
17. **(a)** $3.2\angle 11°$ **(b)** $7\angle -101°$
    (c) $1.52\angle 70.6°$ **(d)** $2.79\angle -63.5°$
19. 8 kHz, 8 kHz
21. **(a)** 270 Ω − j100 Ω, $288\angle -20.3°$ Ω
    (b) 680 Ω − j1000 Ω, $1.21\angle -55.8°$ kΩ
23. **(a)** 56 kΩ − j723 kΩ
    (b) 56 kΩ − j145 kΩ
    (c) 56 kΩ − j72.3 kΩ
    (d) 56 kΩ − j28.9 kΩ
25. **(a)** $R = 33$ Ω, $X_C = 50$ Ω
    (b) $R = 272$ Ω, $X_C = 127$ Ω
    (c) $R = 698$ Ω, $X_C = 1.66$ kΩ
    (d) $R = 558$ Ω, $X_C = 558$ Ω
27. **(a)** 32.5 mA + j12.0 mA
    (b) 2.32 mA + j3.42 mA
29. **(a)** 98.3 μA + j154 μA
    (b) 466 μA + j395 μA
    (c) 0.472 mA + j1.92 mA
31. −14.5°
33. **(a)** $97.3\angle -54.9°$ Ω **(b)** $103\angle 54.9°$ mA
    (c) $5.76\angle 54.9°$ V **(d)** $8.18\angle -35.1°$ V
35. $R_X = 12$ Ω, $C_X = 13.3$ μF in series.

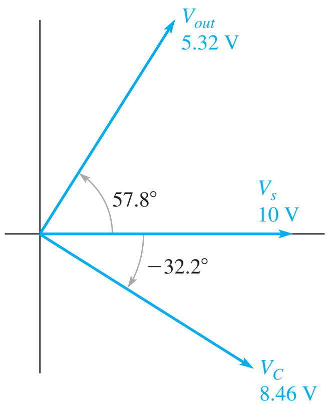
37.

0 Hz	1 V
1 kHz	723 mV
2 kHz	464 mV
3 kHz	329 mV
4 kHz	253 mV
5 kHz	205 mV
6 kHz	172 mV
7 kHz	148 mV
8 kHz	130 mV
9 kHz	115 mV
10 kHz	104 mV

39.

0 Hz	0 V
1 kHz	5.32 V
2 kHz	7.82 V
3 kHz	8.83 V
4 kHz	9.29 V
5 kHz	9.53 V
6 kHz	9.66 V
7 kHz	9.76 V
8 kHz	9.80 V
9 kHz	9.84 V
10 kHz	9.87 V

41. See Figure P–19.



▲ **FIGURE P–19**

43. 245 Ω, −80.5°

45. $\mathbf{V}_C = \mathbf{V}_R = 10\angle 0°$ V
$\mathbf{I}_{tot} = 184\angle 37.1°$ mA
$\mathbf{I}_R = 147\angle 0°$ mA
$\mathbf{I}_C = 111\angle 90°$ mA

47. **(a)** $6.59\angle -48.8°$ Ω **(b)** $10\angle 0°$ mA
(c) $11.4\angle 90°$ mA **(d)** $15.2\angle 48.8°$ mA
(e) −48.8° (I_{tot} leading V_s)

49. 18.4 kΩ resistor in series with 196 pF capacitor.

51. $\mathbf{V}_{C1} = 8.42\angle -2.9°$ V, $\mathbf{V}_{C2} = 1.58\angle -57.5°$ V
$\mathbf{V}_{C3} = 3.65\angle 6.8°$ V, $\mathbf{V}_{R1} = 3.29\angle 32.5°$ V
$\mathbf{V}_{R2} = 2.36\angle 6.8°$ V, $\mathbf{V}_{R3} = 1.29\angle 6.8°$ V

53. $\mathbf{I}_{tot} = 79.5\angle 87.1°$ mA, $\mathbf{I}_{C2R1} = 6.99\angle 32.5°$ mA
$\mathbf{I}_{C3} = 75.7\angle 96.8°$ mA, $\mathbf{I}_{R2R3} = 7.16\angle 6.8°$ mA

55. 0.103 μF

57. $\mathbf{I}_{C1} = \mathbf{I}_{R1} = 2.27\angle 74.5°$ mA
$\mathbf{I}_{R2} = 2.04\angle 72.0°$ mA
$\mathbf{I}_{R3} = 246\angle 84.3°$ μA
$\mathbf{I}_{R4} = 149\angle 41.2°$ μA
$\mathbf{I}_{R5} = 180\angle 75.1°$ μA
$\mathbf{I}_{R6} = \mathbf{I}_{C3} = 101\angle 135°$ μA
$\mathbf{I}_{C2} = 101\angle 131°$ μA

59. 4.03 VA

61. 0.914

63. **(a)** $I_{LA} = 4.8$ A, $I_{LB} = 3.33$ A
(b) $P_{rA} = 606$ VAR, $P_{rB} = 250$ VAR
(c) $P_{trueA} = 979$ W, $P_{trueB} = 759$ W
(d) $P_{aA} = 1151$ VA, $P_{aB} = 799$ VA
(e) Load A

65. 0.0796 μF

67. Reduces V_{out} to 2.83 V and θ to −56.7°

69. **(a)** No output voltage **(b)** $320\angle -71.3°$ mV
(c) $500\angle 0°$ mV **(d)** 0 V

71. No fault

73. R_1 open

75. No fault

77. $f_c = 48.114$ Hz; low-pass filter.

Chapter 16

1. 15 kHz

3. **(a)** 100 Ω + j50 Ω; $112\angle 26.6°$ Ω
(b) 1.5 kΩ + j1 kΩ; $1.80\angle 33.7°$ kΩ

5. **(a)** $17.4\angle 46.4°$ Ω **(b)** $64.0\angle 79.2°$ Ω
(c) $127\angle 84.6°$ Ω **(d)** $251\angle 87.3°$ Ω

7. 806 Ω, 4.11 mH

9. 0.370 V

11. **(a)** $43.5\angle -55°$ mA **(b)** $11.8\angle -34.6°$ mA

13. θ increases from 38.7° to 58.1°.

15. **(a)** $\mathbf{V}_R = 4.85\angle -14.1°$ V **(b)** $\mathbf{V}_R = 3.83\angle -40.0°$ V
$\mathbf{V}_L = 1.22\angle 75.9°$ V $\mathbf{V}_L = 3.21\angle 50.0°$ V
(c) $\mathbf{V}_R = 2.16\angle -64.5°$ V **(d)** $\mathbf{V}_R = 1.16\angle -76.6°$ V
$\mathbf{V}_L = 4.51\angle 25.5°$ V $\mathbf{V}_L = 4.86\angle 13.4°$ V

17. **(a)** −0.0923° **(b)** −9.15° **(c)** −58.2° **(d)** −86.4°

19. **(a)** $80.5\angle 90°$ μV **(b)** $805\angle 90°$ μV
(c) $7.95\angle 80.9°$ mV **(d)** $42.5\angle 31.8°$ mV

21. 4.99 Ω + j5.93 Ω

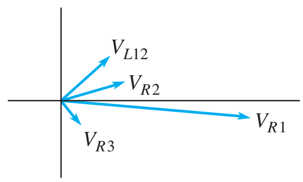
23. 2.39 kHz

25. **(a)** $274\angle 60.7°$ Ω **(b)** $89.3\angle 0°$ mA
(c) $159\angle -90°$ mA **(d)** $182\angle -60.7°$ mA
(e) 60.7° (I_{tot} lagging V_s)

27. 1.83 kΩ resistor in series with 4.21 kΩ inductive reactance

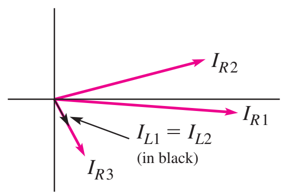
29. $\mathbf{V}_{R1} = 3.78\angle -3.4°$ V
$\mathbf{V}_{R2} = 1.26\angle 10.1°$ V
$\mathbf{V}_{R3} = 0.585\angle -52.2°$ V
$\mathbf{V}_{L1} = \mathbf{V}_{L2} = 1.11\angle 37.8°$ V

▶ **FIGURE P–20**
Voltage phasor diagram:



31. $\mathbf{I}_{R1} = 67.3\angle -3.3°$ mA
$\mathbf{I}_{R2} = 57.3\angle 10.1°$ mA
$\mathbf{I}_{R3} = 17.7\angle -52.2°$ mA
$\mathbf{I}_{L1} = \mathbf{I}_{L2} = 8.86\angle -52.2°$ mA

▶ **FIGURE P–21**
Current phasor diagram:

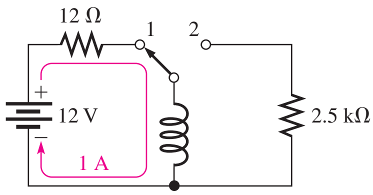


33. **(a)** $588\angle -50.5°$ mA
(b) $22.0\angle 16.1°$ V
(c) $8.63\angle -135°$ V

35. $\theta = 52.5°$ (V_{out} lags V_{in}), 0.143

37. See Figure P–22.

▶ FIGURE P–22

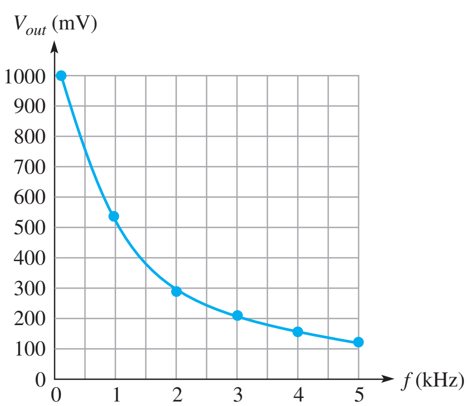


39. 117 mW, 93.4 mVAR

41. $P_{\text{true}} = 290$ mW; $P_r = 50.8$ mVAR;
$P_a = 296$ mVA; $PF = 0.985$

43. Use the formula, $V_{out} = \left(\dfrac{R}{Z_{tot}}\right)V_{in}$. See Figure P–23.

FREQUENCY (kHz)	X_L	Z_{tot}	V_{out}
0	0 Ω	39.0 Ω	1 V
1	62.8 Ω	73.9 Ω	528 mV
2	126 Ω	132 Ω	296 mV
3	189 Ω	193 Ω	203 mV
4	251 Ω	254 Ω	153 mV
5	314 Ω	317 Ω	123 mV



▲ FIGURE P–23

45. See Figure P–24.

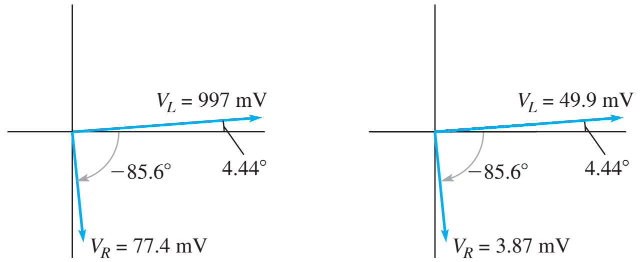
47. **(a)** 0 V **(b)** 0 V
(c) $1.62\angle -25.8°$ V **(d)** $2.15\angle -64.5°$ V

49. L_1 leaky (draws excessive current)

51. L_1 open

53. No fault

55. $f_c \approx 52.649$ kHz; high-pass filter



▲ FIGURE P–24

Chapter 17

1. $520\angle -88.9°$ Ω; 520 Ω capacitive

3. Impedance increases to 150 Ω

5. $\mathbf{I}_{tot} = 61.4\angle -43.8°$ mA
$\mathbf{V}_R = 2.89\angle -43.8°$ V
$\mathbf{V}_L = 4.91\angle 46.2°$ V
$\mathbf{V}_C = 2.15\angle -134°$ V

7. **(a)** $35.8\angle 65.1°$ mA **(b)** 181 mW
(c) 390 mVAR **(d)** 430 mVA

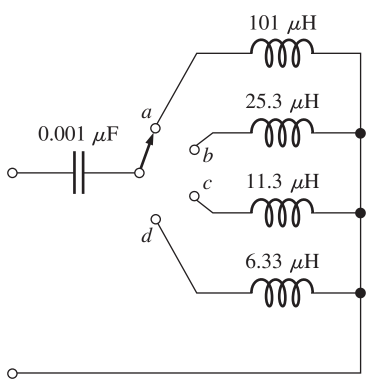
9. 12 V

11. $Z = 200$ Ω, $X_C = X_L = 2$ kΩ

13. 500 mA

15. See Figure P–25.

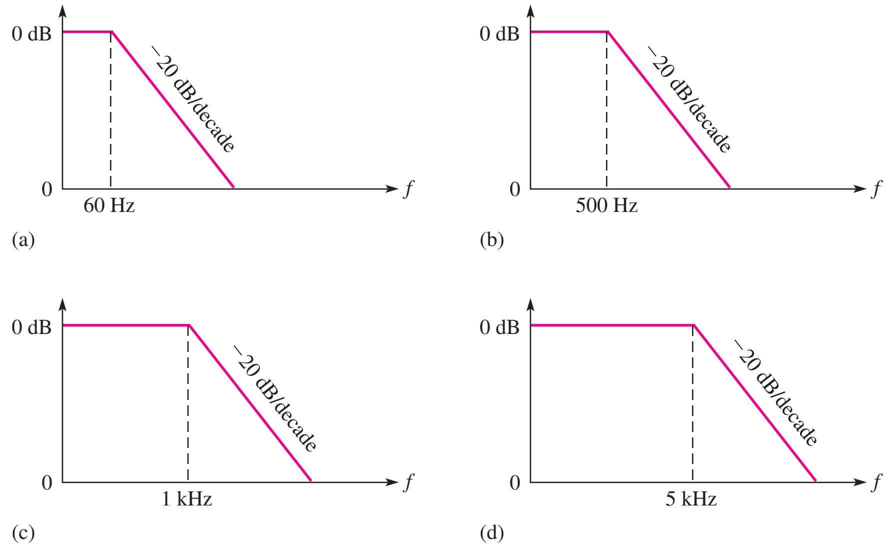
17. The phase angle of −4.43° indicates a slightly capacitive circuit.



▲ FIGURE P–25

19. $\mathbf{I}_R = 50\angle 0°$ mA
$\mathbf{I}_L = 4.42\angle -90°$ mA
$\mathbf{I}_C = 8.29\angle 90°$ mA
$\mathbf{I}_{tot} = 50.2\angle 4.43°$ mA
$\mathbf{V}_R = \mathbf{V}_L = \mathbf{V}_C = 5\angle 0°$ V

21. $\mathbf{I}_R = 50\angle 0°$ mA, $\mathbf{I}_L = 531\angle -90°$ μA,
$\mathbf{I}_C = 69.1\angle 90°$ μA, $\mathbf{I}_{tot} = 84.9\angle 53.9°$ mA



▲ FIGURE P–26

23. 53.5 MΩ, 104 kHz

25. $P_r = 0$ VAR, $P_a = 7.45\ \mu$VA, $P_{true} = 538$ mW

27. **(a)** −1.97° (V_s lags I_{tot}) **(b)** 23.0° (V_s leads I_{tot})

29. 49.1 kΩ resistor in series with 1.38 H inductor

31. 45.2° (I_2 leads V_s)

33. $\mathbf{I}_{R1} = \mathbf{I}_{C1} = 1.09\angle -25.7°$ mA

$\mathbf{I}_{R2} = 767\angle 19.3°\ \mu$A

$\mathbf{I}_{C2} = 767\angle 109.3°\ \mu$A

$\mathbf{I}_L = 1.53\angle -70.7°$ mA

$\mathbf{V}_{R2} = \mathbf{V}_{C2} = \mathbf{V}_L = 7.67\angle 19.3°$ V

$\mathbf{V}_{R1} = 3.60\angle -25.7°$ V

$\mathbf{V}_{C1} = 1.09\angle -116°$ V

35. $52.2\angle 126°$ mA

37. $f_{r(\text{series})} = 4.11$ kHz

$\mathbf{V}_{out} = 4.83\angle -61.0°$ V

$f_{r(\text{parallel})} = 2.6$ kHz

$\mathbf{V}_{out} \cong 10\angle 0°$ V

39. 62.5 Hz

41. 1.38 W

43. 200 Hz

45. C_1 leaky

47. C_1 leaky

49. No fault

51. $f_c \approx 339.625$ kHz

Chapter 18

1. $2.22\angle -77.2°$ V rms

3. **(a)** $9.36\angle -20.7°$ V **(b)** $7.18\angle -44.1°$ V

(c) $9.96\angle -5.44°$ V **(d)** $9.95\angle -5.74°$ V

5. **(a)** 12.1 μF **(b)** 1.45 μF

(c) 0.723 μF **(d)** 0.144 μF

7. See Figure P–26.

9. **(a)** 7.13 V **(b)** 5.67 V

(c) 4.01 V **(d)** 0.800 V

11. **(a)** 0 dB **(b)** −3 dB (0 dB ideal) **(c)** −20 dB

13. $9.75\angle 12.8°$ V

15. **(a)** $3.53\angle 69.3°$ V **(b)** $4.85\angle 61.0°$ V

(c) $947\angle 84.6°$ mV **(d)** $995\angle 84.3°$ mV

17. See Figure P–27.

19. **(a)** 14.5 kHz **(b)** 24.0 kHz

21. **(a)** 15.06 kHz, 13.94 kHz **(b)** 25.3 kHz, 22.7 kHz

23. **(a)** 117 V **(b)** 115 V

25. $C = 0.064\ \mu$F, $L = 989\ \mu$H, $f_r = 20$ kHz

27. **(a)** 86.3 Hz **(b)** 7.34 MHz

29. $L_1 = 0.08\ \mu$H,

$L_2 = 0.554\ \mu$H

31. C_1 is open.

33. R_3 is open.

35. L_2 is open.

37. $f_0 = 107.4$ kHz.

Chapter 19

1. $1.22\angle 28.6°$ mA

3. $81.0\angle -11.9°$ mA

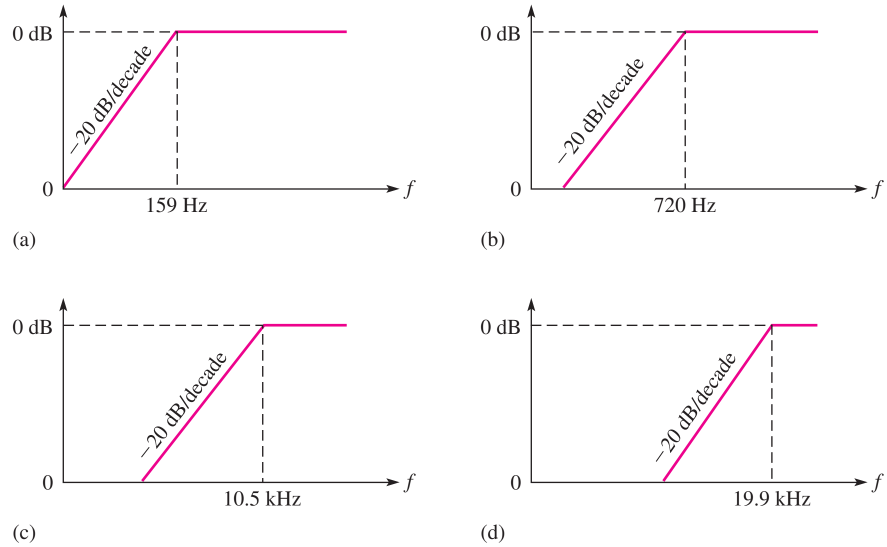
5. $V_{A(\text{dc})} = 0$ V, $V_{B(\text{dc})} = 16.1$ V, $V_{C(\text{dc})} = 15.1$ V,

$V_{D(\text{dc})} = 0$ V, $V_{A(\text{peak})} = 9$ V, $V_{B(\text{peak})} = 5.96$ V,

$V_{C(\text{peak})} = V_{D(\text{peak})} = 4.96$ V

7. $766\angle -71.7°$ mA

▶ FIGURE P–27



9. **(a)** $\mathbf{V}_{th} = 15\angle -53.1° \text{ V}$

$\mathbf{Z}_{th} = 63\ \Omega - j48\ \Omega = 79.2\angle -37.3°\ \Omega$

(b) $\mathbf{V}_{th} = 1.22\angle 0° \text{ V}$

$\mathbf{Z}_{th} = j237\ \Omega = 237\angle 90°\ \Omega$

(c) $\mathbf{V}_{th} = 12.1\angle 11.9° \text{ V}$

$\mathbf{Z}_{th} = 50\text{ k}\Omega - j20\text{ k}\Omega = 53.9\angle -21.8° \text{ k}\Omega$

11. $16.9\angle 88.2° \text{ V}$

13. **(a)** $\mathbf{I}_n = 189\angle -15.8° \text{ mA}$

$\mathbf{Z}_n = 63\ \Omega - j48\ \Omega$

(b) $\mathbf{I}_n = 5.15\angle -90° \text{ mA}$

$\mathbf{Z}_n = j237\ \Omega$

(c) $\mathbf{I}_n = 224\angle 33.7°\ \mu\text{A}$

$\mathbf{Z}_n = 50\text{ k}\Omega - j20\text{ k}\Omega$

15. $16.8\angle 88.5° \text{ V}$

17. $9.18\ \Omega + j2.90\ \Omega$

19. $95.2\ \Omega + j42.7\ \Omega$

21. C_1 leaky

23. No fault

25. Simulated: Calculated:

$\mathbf{I}_n = 171.1\angle -21.0°\ \mu\text{A}_{\text{PEAK}}$ $\mathbf{I}_n = 167.4\angle -21.0°\ \mu\text{A}_{\text{PEAK}}$

$\mathbf{Z}_n = 71.9\angle -18.7° \text{ k}\Omega$ $\mathbf{Z}_n = 67.8\angle -21.4° \text{ k}\Omega$

Chapter 20

1. 103 μs

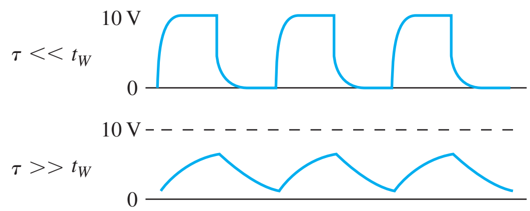
3. 12.6 V

5. See Figure P–28.

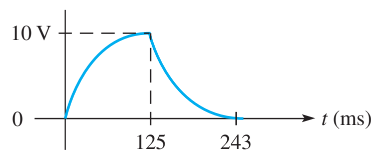
7. **(a)** 23.5 ms

(b) See Figure P–29.

9. See Figure P–30.

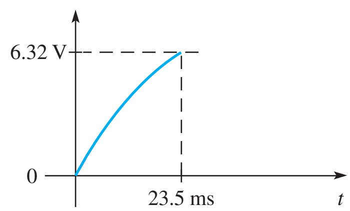


▲ FIGURE P–28

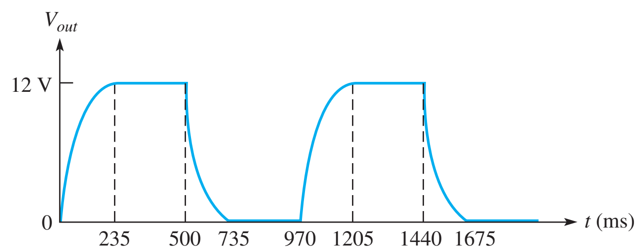


▲ FIGURE P–29

▶ FIGURE P–30

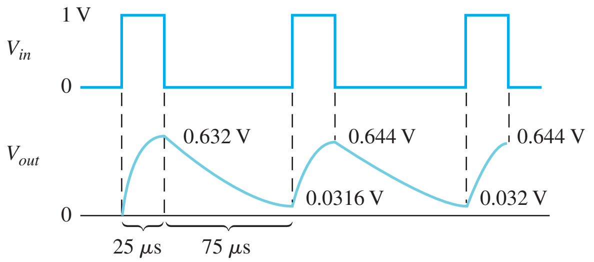


11. See Figure P–31.



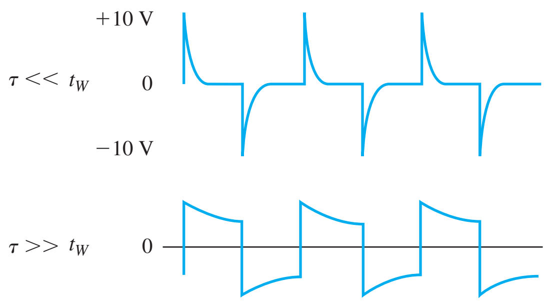
▲ FIGURE P–31

13. See Figure P–32.



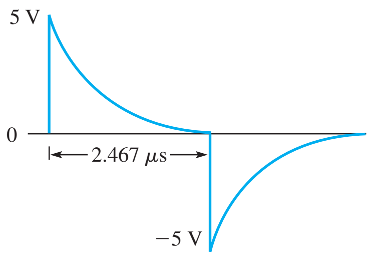
▲ FIGURE P–32

15. See Figure P–33.



▲ FIGURE P–33

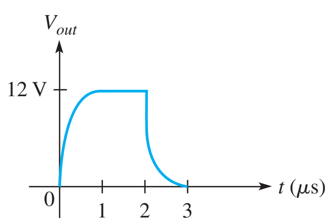
17. **(a)** 493.5 ns **(b)** See Figure P–34.



▲ FIGURE P–34

19. An approximate square wave with an average value of zero.

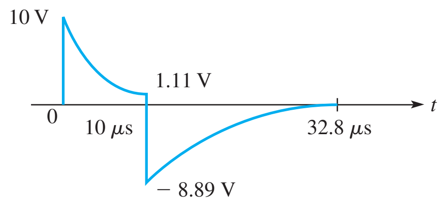
21. See Figure P–35.



▲ FIGURE P–35

23. **(a)** 4.55 μs **(b)** See Figure P–36.

25. 15.9 kHz



▲ FIGURE P–36

27. **(a)** Capacitor open or R shorted.
(b) C leaky or $R > 3.3\ \text{k}\Omega$ or $C > 0.22\ \mu\text{F}$
(c) Resistor open or capacitor shorted

29. C_1 open

31. R_1 open

Chapter 21

1. 376 mA

3. $1.32\angle 121°$ A

5. $\mathbf{I}_{La} = 8.66\angle -30°$ A
$\mathbf{I}_{Lb} = 8.66\angle 90°$ A
$\mathbf{I}_{Le} = 8.66\angle -150°$ A

7. **(a)** $\mathbf{V}_{L(ab)} = 866\angle -30°$ V
$\mathbf{V}_{L(ca)} = 866\angle -150°$ V
$\mathbf{V}_{L(bc)} = 866\angle 90°$ V
(b) $\mathbf{I}_{\theta a} = 500\angle -32°$ mA
$\mathbf{I}_{\theta b} = 500\angle 88°$ mA
$\mathbf{I}_{\theta c} = 500\angle -152°$ mA
(c) $\mathbf{I}_{La} = 500\angle -32°$ mA
$\mathbf{I}_{Lb} = 500\angle 88°$ mA
$\mathbf{I}_{Lc} = 500\angle -152°$ mA
(d) $\mathbf{I}_{Za} = 500\angle -32°$ mA
$\mathbf{I}_{Zb} = 500\angle 88°$ mA
$\mathbf{I}_{Zc} = 500\angle -152°$ mA
(e) $\mathbf{V}_{Za} = 500\angle 0°$ V
$\mathbf{V}_{Zb} = 500\angle 120°$ V
$\mathbf{V}_{Zc} = 500\angle -120°$ V

9. **(a)** $\mathbf{V}_{L(ab)} = 86.6\angle -30°$ V
$\mathbf{V}_{L(ca)} = 86.6\angle -150°$ V
$\mathbf{V}_{L(bc)} = 86.6\angle 90°$ V
(b) $\mathbf{I}_{\theta a} = 250\angle 110°$ mA
$\mathbf{I}_{\theta b} = 250\angle -130°$ mA
$\mathbf{I}_{\theta c} = 250\angle -10°$ mA
(c) $\mathbf{I}_{La} = 250\angle 110°$ mA
$\mathbf{I}_{Lb} = 250\angle -130°$ mA
$\mathbf{I}_{Lc} = 250\angle -10°$ mA
(d) $\mathbf{I}_{Za} = 144\angle 140°$ mA
$\mathbf{I}_{Zb} = 144\angle 20°$ mA
$\mathbf{I}_{Zc} = 144\angle -100°$ mA
(e) $\mathbf{V}_{Za} = 86.6\angle -150°$ V
$\mathbf{V}_{Zb} = 86.6\angle 90°$ V
$\mathbf{V}_{Zc} = 86.6\angle -30°$ V

11. $\mathbf{V}_{L(ab)} = 330\angle -120°$ V
$\mathbf{V}_{L(ca)} = 330\angle 120°$ V
$\mathbf{V}_{L(bc)} = 330\angle 0°$ V
$\mathbf{I}_{Za} = 38.2\angle -150°$ A
$\mathbf{I}_{Zb} = 38.2\angle -30°$ A
$\mathbf{I}_{Zc} = 38.2\angle 90°$ A

13. Figure 21–34: 636 W
Figure 21–35: 149 W
Figure 21–36: 12.8 W
Figure 21–37: 2.78 kW
Figure 21–38: 10.9 kW

15. 24.2 W