Introduction

CHAPTER 1

LEARNING OBJECTIVES

- To understand the system of units and standard prefixes used throughout the text
- To review the fundamental building blocks, e.g. charge, current, voltage, and power
- To learn the definition and symbols employed to describe the sources, both independent and dependent, that represent the forcing functions for electric circuits
- To present Tellegen's theorem and describe its usefulness in circuit analysis

FUNDAMENTAL CONCEPTS

To begin our study of electrical and computer engineering, we should first note that the units employed in this area of technology are not those used in the English system, i.e. feet, pounds, etc. Rather, we employ the International System of Units, which are composed of meter, kilogram, second, ampere, degree Kelvin, and candela. In addition, there are a standard set of prefixes that are employed in this technology, some of which have found their way into contemporary communication. The prefixes are

Kilo (k) – 10^3
Mega (M) – 10^6
Giga (G) – 10^9
Tera (T) – 10^{12}
Milli (m) – 10^{-3}
Micro (μ) – 10^{-6}
Nano (n) – 10^{-9}
Pico (p) – 10^{-12}

It is interesting to note that these prefixes are often used in conversation, e.g. an individual speaks of paying 25k for a car, indicating that the car costs $25,000, or stating that a company just sold for 100 Megabucks or $100 million. However, the importance of these prefixes in the current context is that they are continuously used throughout this text.

An understanding of the material in this book is typically predicated upon the fact that anyone reading this book has already taken the basic physics sequence offered at essentially every college and university where this book would be logically used. Therefore, we will provide simple and succinct discussions of the various quantities that are the fundamental building blocks in electrical and computer technology.

Electric *current* is a measure of how much charge is moved per unit of time, i.e. it is *charge* in motion, and this charge in motion results in transfer of energy. The mathematical expression for current is

$$i(t) = dq(t)/dt$$

where q is the charge in coulombs, t is the time in seconds, and i(t) is the current in amperes (A), and hence 1 ampere is equal to 1 coulomb per second. While current flow is caused by electron motion in metallic conductors, conventional current flow is the net rate of flow of positive charges. Therefore, throughout the book the convention we will adopt is that if a metal conductor, e.g. a wire, is conducting electrons to the left, then there is positive current to the right. Nevertheless, in all that follows think of current as the movement of positive charges.

It is interesting at this point to pause and mention two of the basic forms of current as well as the range of their values. The two common types of current are direct current (dc) and alternating current (ac), as shown in Figure 1.1a and b, respectively. Note that dc is independent of time, i.e. it is constant. dc is generated by batteries, such as those found in flashlights, automobiles, and a host of electronic equipment such as cell phones and iPads. In sharp contrast, ac current is the current used in the power grid and used to run all appliances and lights in the home. In the United States, it is a sine wave with a frequency of 60 Hz (60 cycles per second). The magnitude of these currents is enormous and ranges from pico amperes in nerve cells in the body to thousands of amperes in a lightning bolt, thus encompassing a range of some 15 orders of magnitude.

Current requires a path. Some type of pipeline must exist in order to facilitate the movement of charge. Without charge in motion, there is no current. It is the electric circuit that provides this path. We will learn later that it is not sufficient to specify only the magnitude of the current, we must also know the direction of the current. Furthermore, we use the convention that a positive current of 2 A flowing right to left is equivalent to −2 A flowing left to right. This symbolism is shown in Figure 1.2. This is a critical point worth mentioning even at this early stage in our discussion. The reason is simply this: when we solve for currents in a circuit, in general we will not know the direction of the current we seek, but will assume a direction and if the current value is negative, we know the current is simply flowing in the direction opposite to that assumed.

In contrast to current, which is charge in motion, the *voltage,* often referred to as potential, that exists between any two points in the circuit is defined as the difference in energy levels of a positive charge located at each of these points. In other words, if a positive charge is moved from one point to another, then the energy required is the difference in energy levels between the two points. Voltage in volts is measured in joules per coulomb, and 1 volt is the energy in joules that is necessary to move a charge of 1 coulomb from one point to another. This definition is defined mathematically as

$$v(t) = dw(t)/dq(t)$$

where v is the voltage in volts, w is the *energy* in joules, and q is the charge in coulombs.

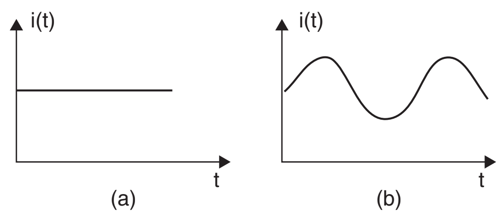


FIGURE 1.1 (a) dc current (b) ac current

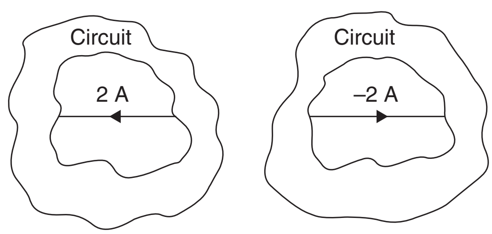


FIGURE 1.2 Equivalent currents

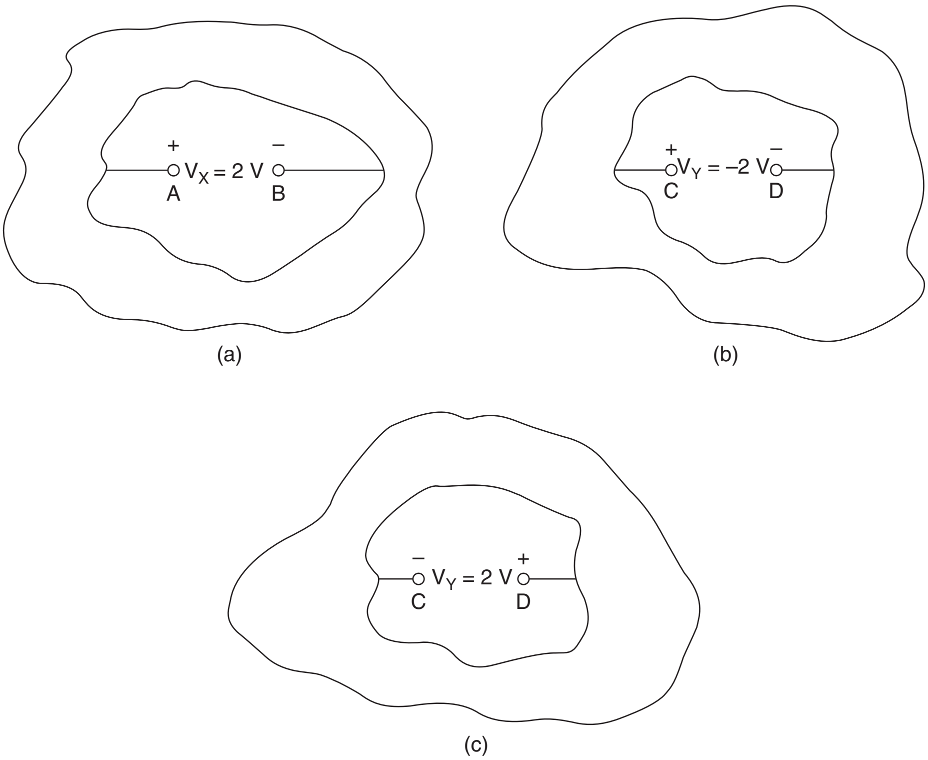


FIGURE 1.3 Voltage description

Much of what has been said for current applies to voltage as well. When describing current, we must specify both magnitude and direction. In a similar manner, when describing the voltage that exists between two points, we need to know which point is at the higher potential. In Figure 1.3a, the voltage V_x represents the voltage between points A and B, and the + and − signs define its reference direction. In this case, the voltage V_x is 2 V, and point A is at the higher potential. Thus, if a unit positive charge is moved from point B, through the circuit to point A, it will gain 2 J of energy, and if a unit positive charge is moved from point A through the circuit to point B, it will lose 2 J of energy. So point A is 2 V positive with respect to point B, and point B is 2 V negative with respect to point A.

As we indicated, if we change the direction of the current we change the sign, and the same rule applies with voltage. This concept is shown in Figure 1.3b and c. In Figure 1.3b, the voltage between points C and D is 2 V, and point D is at the higher potential. Figure 1.3c indicates that the voltage between points C and D is 2 V, and point D is at the higher potential. Note that Figure 1.3b and Figure 1.3c are equivalent and express exactly the same concept. Once again, both magnitude and direction must be specified, and if we reverse the direction, we change the sign.

Voltages, like currents, range from one end of the spectrum to the other. The voltage at the antenna of a cell phone may be in the microvolt range, while the magnitude of a lightning strike may be in millions of volts.

Recall that *power* is the time rate of change of energy and is therefore defined as

$$p(t) = dw(t)/dt$$

The relationship among voltage, current, and power is expressed by the equation

$$p(t) = dw(t)/dt = [dw(t)/dq(t)]\,[dq(t)/dt] = v(t)\,i(t)$$

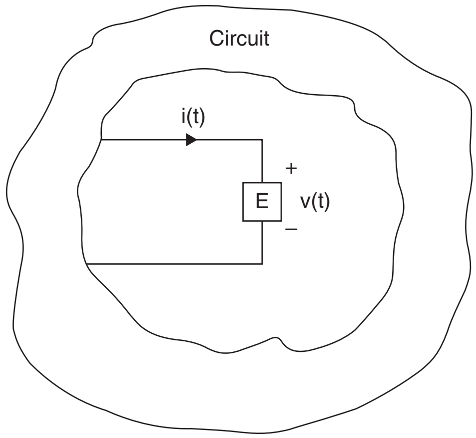


FIGURE 1.4 Circuit used to describe the passive sign convention

Thus, power can be expressed as the product of the voltage across the element and the current through it. Furthermore, the change in energy from time t_1 to t_2 can be determined by the equation

$$w(t) = \int_{t_1}^{t_2} v(t)\, i(t)\, dt$$

Clearly, it is important to know if the circuit element in question is supplying or absorbing power. A convention has been adopted to address this question. The *passive sign convention* for power is defined via the circuit in Figure 1.4. If the voltage across the element and the current through it are arranged as shown in the figure, i.e. the current enters the positive terminal, then the product of v(t) and i(t), together with their attendant signs, will generate both the magnitude of the power and specify if the element is absorbing or supplying power. If the resulting sign is positive, the element is absorbing power and if the sign is negative the element is supplying power.

Examples 1.1 and 1.2 illustrate the salient points of this discussion.

Example 1.1

Let us determine if the elements E1 and E2 in Figures 1.5 and 1.6, respectively, are absorbing or supplying power and how much.

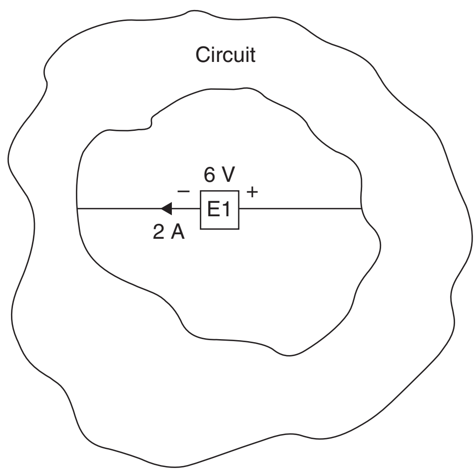


FIGURE 1.5 Circuit used in Example 1.1

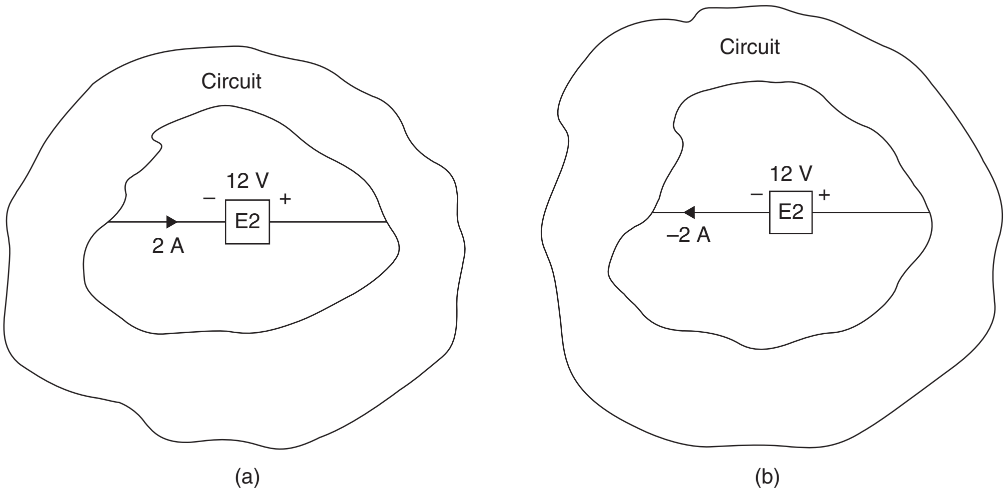


FIGURE 1.6 Circuit used in Example 1.1

First of all, note that Figure 1.5 is exactly the same as the configuration that defines the passive sign convention. The current enters the positive terminal of E1, and the equation for power is

$$P = (+6)(+2) = 12 \text{ W}$$

Since the result is positive, the element is absorbing power. An examination of Figure 1.6a indicates that the 2 A is leaving the positive terminal of E2, or equivalently −2 A is entering the positive terminal of E2 as shown in Figure 1.6b. Therefore, the power is

$$P = (+12)(-2) = -24 \text{ W}$$

and thus the negative sign indicates that element E2 is supplying power.

Example 1.2

Let us determine if element E1 in Figure 1.7a is absorbing or supplying power, and how much.

Recall that if we reverse the direction of the voltage or the current, we must change the sign. So Figure 1.7a can be changed to Figure 1.7b by reversing the direction of the current and changing the sign. Now the current enters the positive terminal of E1 and the equation for power is

$$P = (-6)(2) = -12 \text{ W}$$

and the negative sign indicates that 12 W is being supplied by E1. Likewise, we can reverse the voltage, as shown in Figure 1.7c, and then the equation for power is

$$P = (+6)(-2) = -12 \text{ W}$$

Therefore, once we place the circuit in question in the form of the passive sign convention, the result is not only the magnitude of the power but also the sign that indicates whether power is being supplied or absorbed.

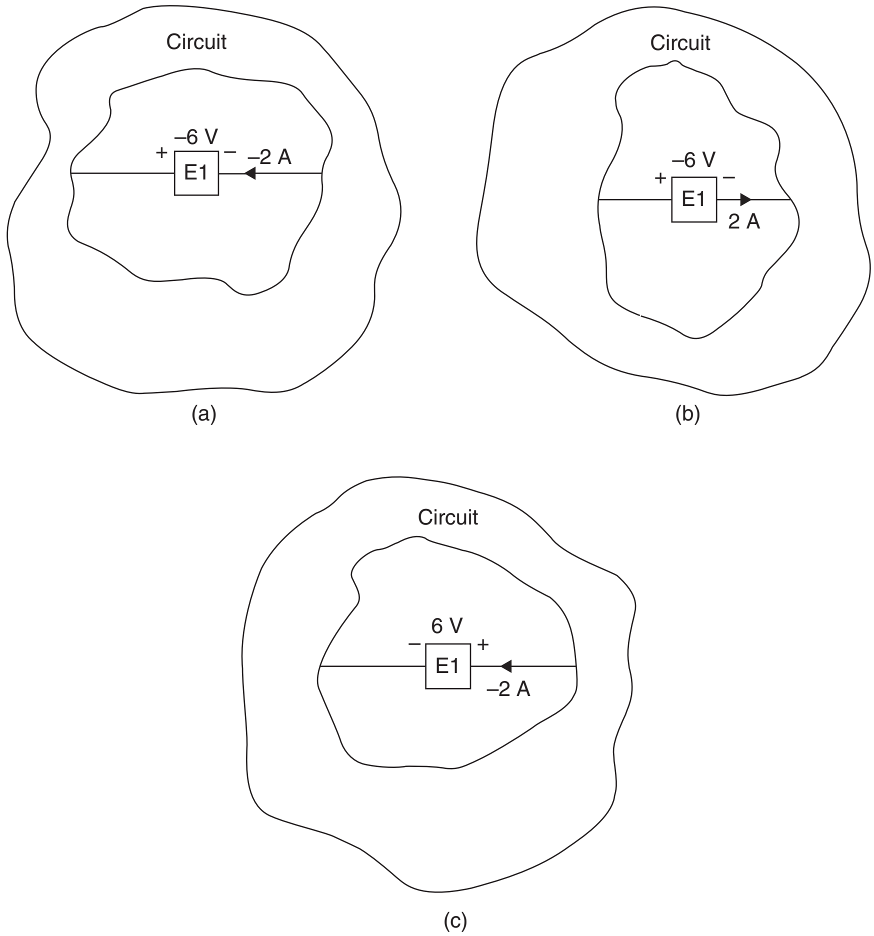


FIGURE 1.7 Circuits used in Example 1.2

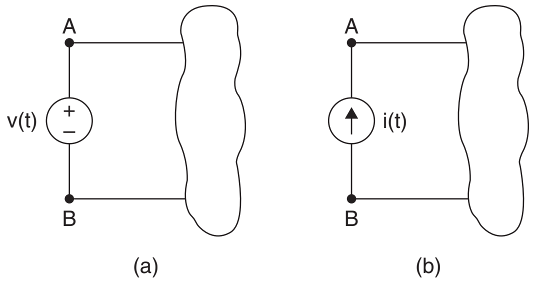
SOURCES

Throughout this book, we will assume ideal circuit elements. As we progress in our understanding of the material, the differences between ideal and nonideal elements will become clearer. However, any discussion of these differences is premature at this point.

The circuit elements we will discuss here can be broadly classified as either *passive* or *active* elements. As one might expect, passive elements only absorb power. However, as we will demonstrate later in this book, some are capable of storing power. On the other hand, active elements can supply power.

Sources may be either voltage sources or current sources, and they may be either *independent* or *dependent.* An independent voltage source, shown in Figure 1.8a, produces a voltage v(t) between terminals A–B, where terminal A is v(t) volts positive with respect to terminal B. This source produces this voltage between these terminals independent of the current in the source.

The independent current source produces a current of i(t) from terminal B to terminal A (as the arrow indicates in Figure 1.8b), and this current is independent of the voltage across the current source.



(a) (b) **FIGURE 1.8** Circuits used to define sources

These independent sources typically supply power to a circuit, but there are circumstances when they actually absorb power, e.g. charging a battery.

In sharp contrast to independent sources that produce a voltage or current completely independent of anything else in the network, dependent sources generate a voltage or current that is dependent or controlled by some voltage or current at some other location in the circuit. The importance of these dependent sources stems from the fact that we model all active devices, e.g. transistors, with these elements. While independent sources are modeled with a circle, dependent sources are modeled with a diamond. The four different types of dependent sources are shown in Figure 1.9. There are voltage sources and current sources, and they can each be controlled by a voltage or a current.

A close examination of these circuits will indicate that coefficients a and d are dimensionless constants because we are transforming voltage to voltage and current to current. The constants b and c are not dimensionless since we are transforming voltage to current and vice versa. However, we must defer a discussion of these constants until later.

Before completing our discussion of sources, it is very important that the reader understand a couple of salient points concerning sources. With reference to Figure 1.8a, the voltage between the terminals A and B is v(t) regardless of the current in the source. In fact, we can only calculate this current from the circuit components in the cloud, which represents the remainder of the circuit. Similarly, the current from B to A in the circuit in Figure 1.8b is i(t) independent of the voltage across the current source. And once again, we will have to use the circuit components in the cloud to determine this voltage.

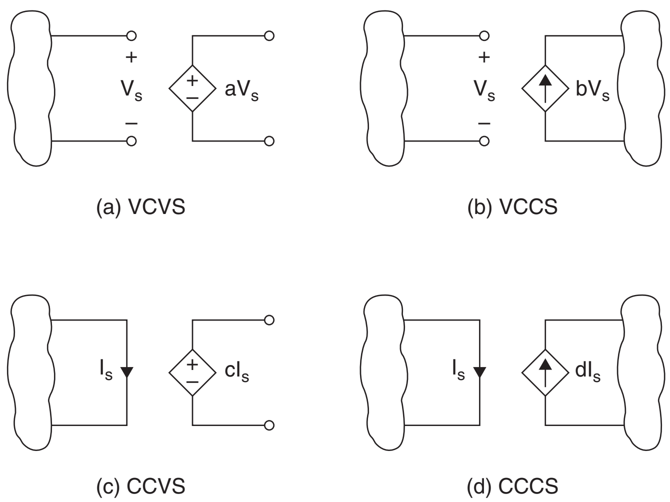


FIGURE 1.9 Dependent sources

Example 1.3

Two dependent source circuits are shown in Figure 1.10. Let us determine the outputs of each source.

Figure 1.10a is an illustration of a voltage-controlled voltage source (VCVS). The output voltage is

$$V_0 = 12\ V_S \text{ or } V_0 = 12 \times 2\ V = 24\ V$$

Similarly, Figure 1.10b is an illustration of a current-controlled current source (CCCS). The output current is

$$I_0 = 4\ I_S = 4 \times 2\,A = 8\,A$$

Note that both circuits are amplifiers. The voltage gain in the first circuit is 12 and the current gain in the second circuit is 4.

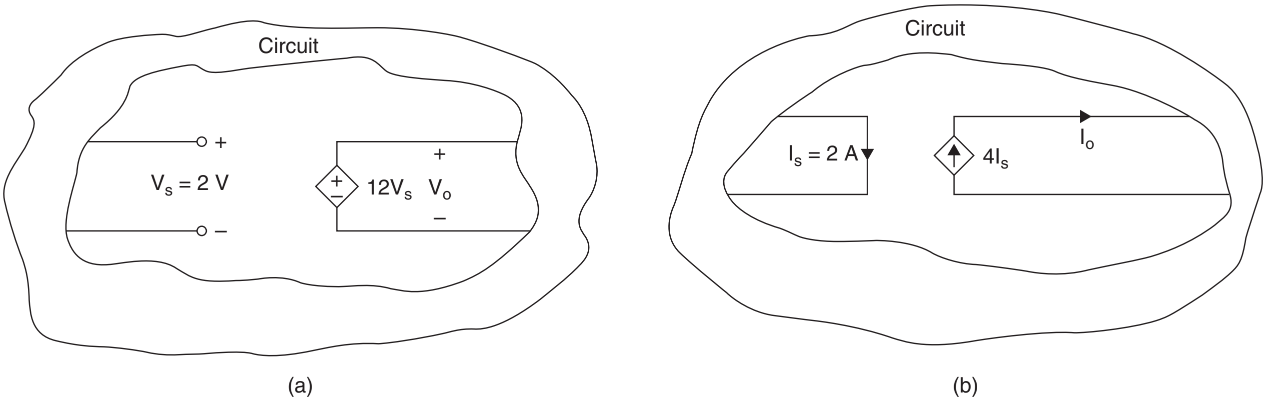


FIGURE 1.10 Circuits used in Example 1.3

TELLEGEN'S THEOREM

The law of *conservation of energy* is typically introduced in physics, and simply means that energy cannot be created or destroyed. Energy can, however, be transformed from one form to another, e.g. thermal energy to mechanical energy or mechanical energy to electrical energy. As indicated earlier, energy and power are related, and B. D. H. Tellegen formally proved that this concept is extended to electrical circuits, and thus the power supplied to an electrical network is exactly equal to that which is absorbed by the network.

We will find in the material ahead that many of the calculations performed on an electric circuit can be checked, i.e. currents and voltages in a circuit must satisfy certain laws. Tellegen's theorem provides an additional method for checking the results of an analysis since the power generated in the network must equal the power that is absorbed. Example 1.4 serves to illustrate this point.

Example 1.4

Consider the circuit in Figure 1.11. We wish to employ Tellegen's theorem to find the value of the voltage across the independent current source.

Note that the voltage and current are known for every element in the network with the exception of the voltage, V_x, across the independent current source. Therefore, we can identify the elements that are supplying power and the elements that are absorbing power.

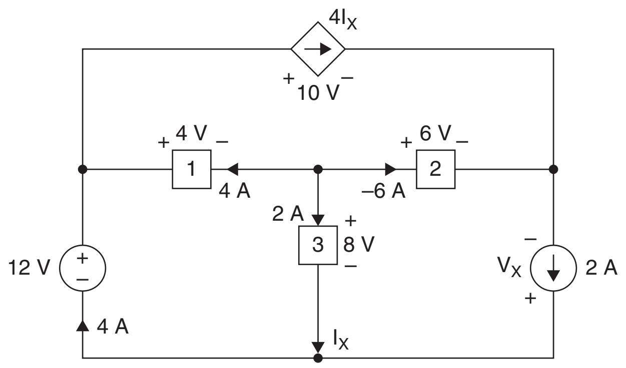


FIGURE 1.11 Circuit used in Example 1.4

The following elements are supplying power:

The 12 V independent voltage source is supplying power because a positive current of 4 A is leaving the positive terminal or equivalently –4 A is entering the positive terminal.

Element 1 is supplying power because a positive current of 4 A is leaving the positive terminal or equivalently –4 A is entering the positive terminal.

Element 2 is supplying power because a current of –6 A is entering the positive terminal.

The 2 A independent current source is supplying power because a positive current of –2 A is entering the positive terminal of the source.

The following elements are absorbing power:

The dependent current source, 4 I_x, is absorbing power since the positive current is entering the positive terminal.

Element 3 is absorbing power because the positive current of 2 A is entering the positive terminal.

Summing the power for each individual element and setting the result to zero yield the equation

$$(12)(-4) + (4)(-4) + (6)(-6) + (V_x)(-2) + (10)(4\,I_x) + (8)(2) = 0$$

However, note that $I_x = 2$ A, and therefore

$$-48 - 16 - 36 - 2V_x + 80 + 16 = 0$$

Solving for V_x yields

$$V_x = -2\text{ V}$$

Since power must be conserved in a network, i.e. whatever is generated must be absorbed, the use of Tellegen's theorem provides a means to check the analysis results when determining a voltage, current, or power within a network. In the following chapter, we will learn other methods for calculating these quantities.

Problems

1.1 A dc source supplies 6×10^{20} electrons in 5 s to a load. How much current is supplied to the load? (The charge of an electron is 1.9×10^{-19} Coulombs).

1.2 One of the connecting wires in an electronic circuit has 4×10^{18} electrons flowing through it in 8 s. What is the current in the wire?

1.3 When starting an automobile, the battery delivers 125 A in a 2-s period. How many electrons emanate from the battery?

1.4 How many electrons are passing through a wire in 1 s if the current in the wire is 400 mA?

1.5 A power source supplies 2 J of energy in the process of transferring 0.333 coulombs of charge to a load. What is the voltage across the source?

1.6 A 12 V battery supplies 0.6 A to a light bulb for 20 min. How many electrons pass through the bulb during this period?

1.7 Determine the power delivered to the light bulb in Problem 1.6.

1.8 Calculate the amount of energy provided to the bulb in Problem 1.6.

1.9 During ignition, a 12 V car battery supplies 125 A in a 2-s period. How much energy does the battery supply?

1.10 Two batteries are connected as shown in Figure P1.10. Is battery A supplying power to battery B or vice versa?

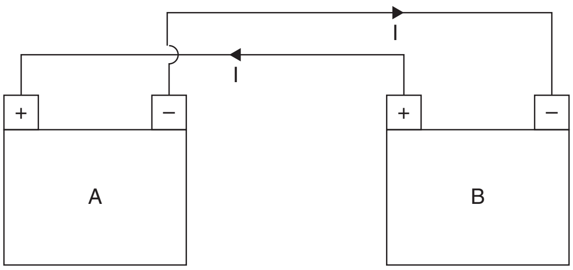


FIGURE P1.10

1.11 Determine whether the elements shown in Figure P1.11 are absorbing or supplying power.

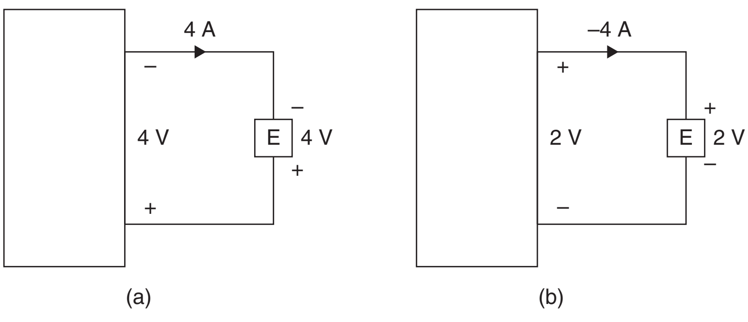


FIGURE P1.11

1.12 Determine the amount of power absorbed or supplied by the elements in Figure P1.12.

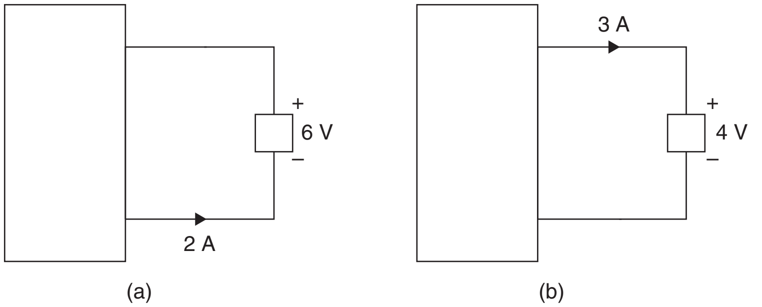


FIGURE P1.12

1.13 Determine the amount of power absorbed or supplied by the elements in Figure P1.13.

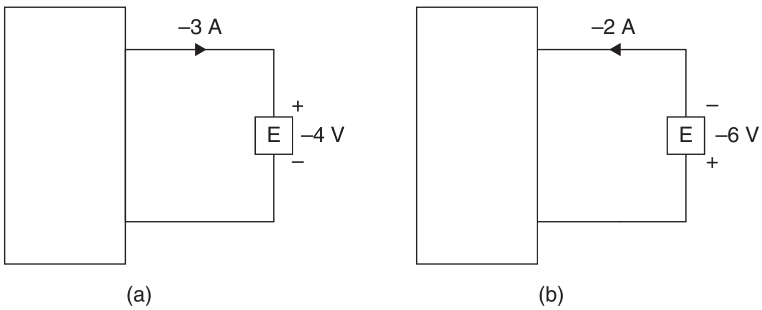


FIGURE P1.13

1.14 Determine whether the elements shown in Figure P1.14 are absorbing or supplying power.

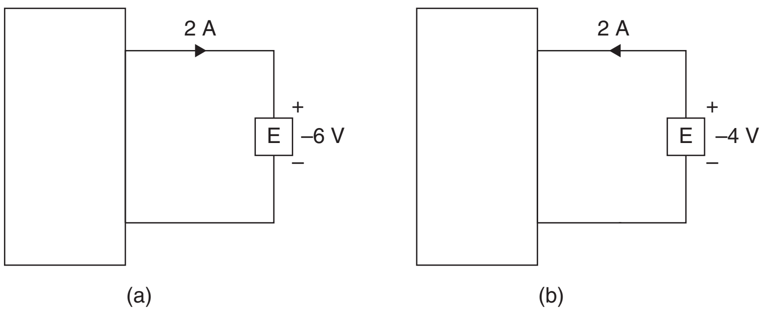


FIGURE P1.14

1.15 Determine the unknown voltages in the networks in Figure P1.15.

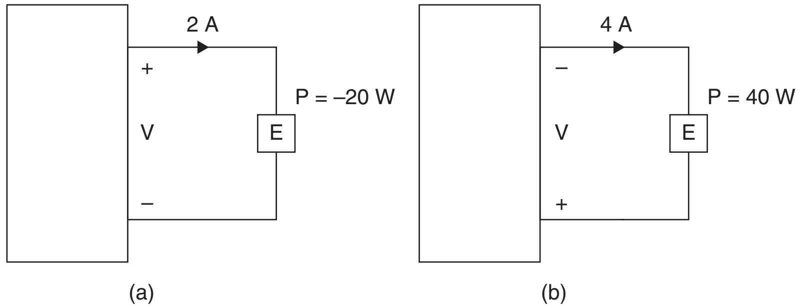


FIGURE P1.15

1.16 Determine the unknown voltages in the network in Figure P1.16.

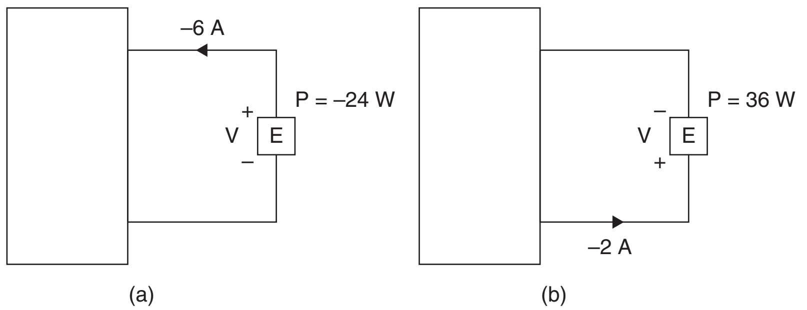


FIGURE P1.16

1.17 Determine the unknown currents in the circuits in Figure P1.17.

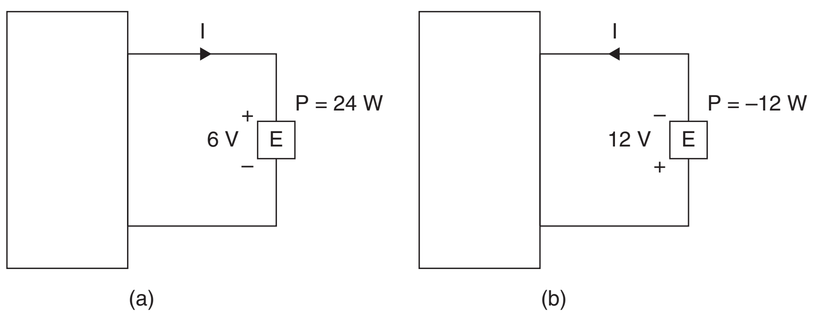


FIGURE P1.17

1.18 Determine the unknown currents in the circuits in Figure P1.18.

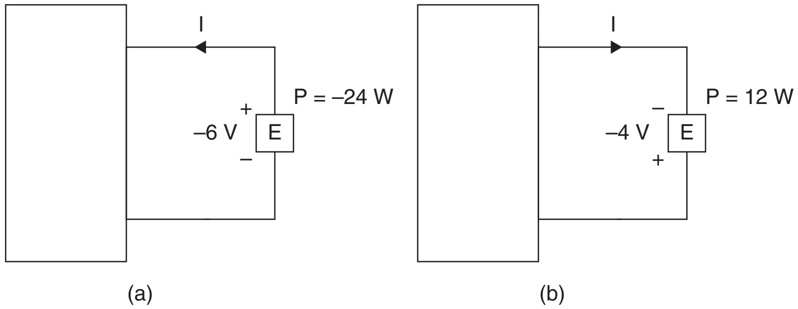


FIGURE P1.18

1.19 Determine if power is being absorbed or supplied by the elements in Figure P1.19.

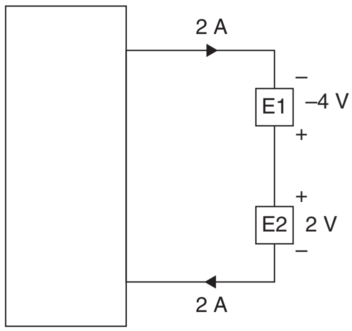


FIGURE P1.19

1.20 Determine if power is being absorbed or supplied by the elements in Figure P1.20.

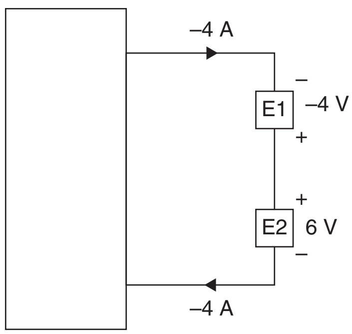


FIGURE P1.20

1.21 If element E1 in Figure P1.21 is absorbing 12 W, is element E2 absorbing or supplying power, and how much?

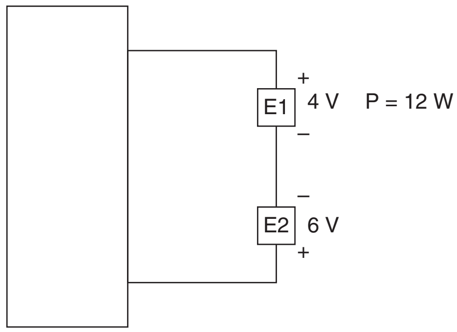


FIGURE P1.21

1.22 If element E2 in Figure P1.22 is supplying 24 W, is element E1 absorbing or supplying power, and how much?

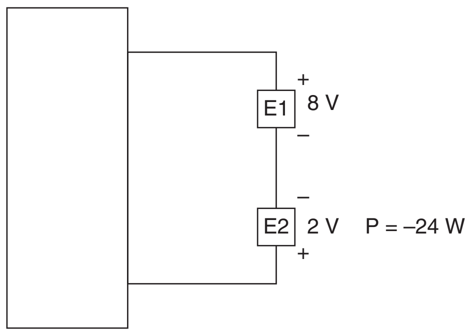


FIGURE P1.22

1.23 If element E1 in Figure P1.23 is absorbing 24 W, is element E2 absorbing or supplying power, and how much?

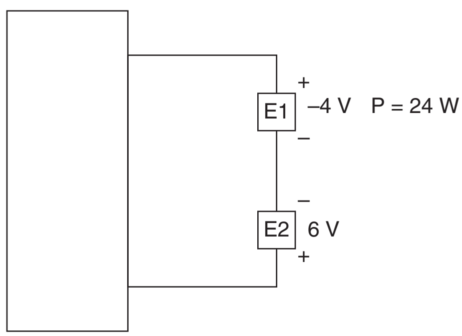


FIGURE P1.23

1.24 If element E2 in Figure P1.24 is supplying 36 W, is element E1 absorbing or supplying power, and how much?

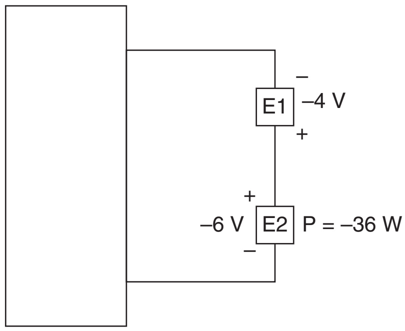


FIGURE P1.24

1.25 Determine the output voltage in the dependent source shown in Figure P1.25.

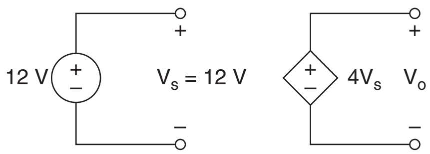


FIGURE P1.25

1.26 Determine the output voltage in the dependent source shown in Figure P1.26.

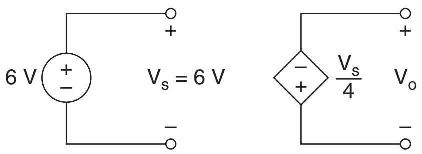


FIGURE P1.26

1.27 Determine the output current in the dependent source shown in Figure P1.27.

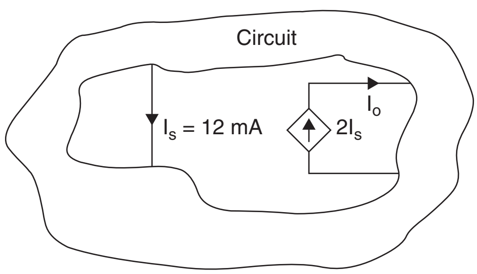


FIGURE P1.27

1.28 Determine the output current in the dependent source shown in Figure P1.28.

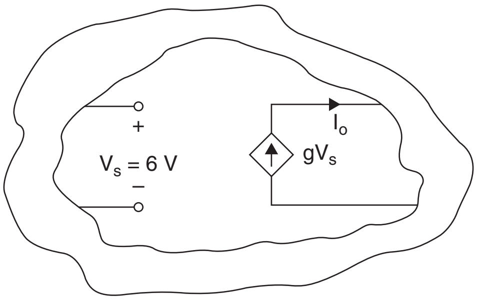


FIGURE P1.28

1.29 Determine the output voltage in the dependent source shown in Figure P1.29.

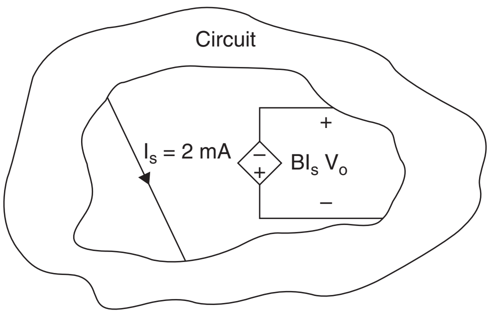


FIGURE P1.29

1.30 Find the power that is absorbed or supplied by the circuit elements in Figure P1.30.

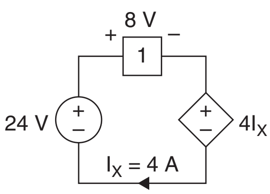


FIGURE P1.30

1.31 Determine the power that is absorbed or supplied by the circuit elements in Figure P1.31.

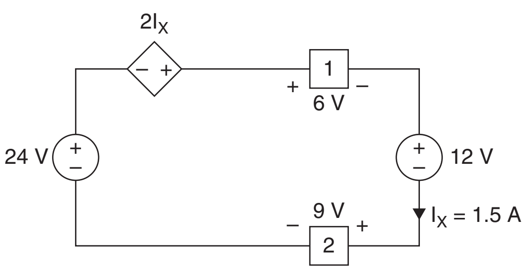


FIGURE P1.31

1.32 Use Tellegen's theorem to determine I_X in the network in Figure P1.32.

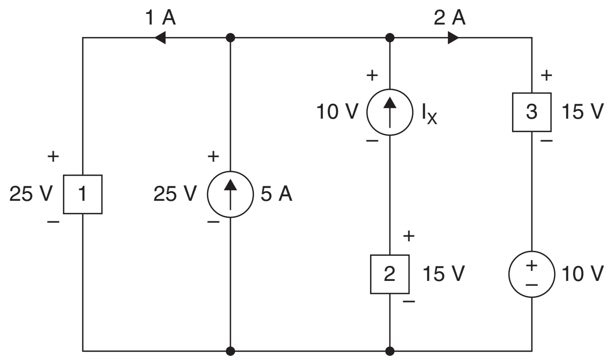


FIGURE P1.32

1.33 Determine the power absorbed or supplied by each element in the network in Figure P1.33 and verify that Tellegen's theorem is satisfied.

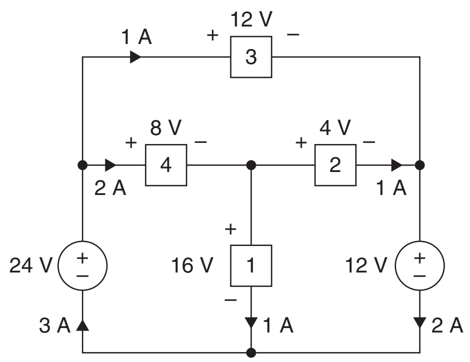


FIGURE P1.33

1.34 Use Tellegen's theorem to determine I_0 in the network in Figure P1.34.

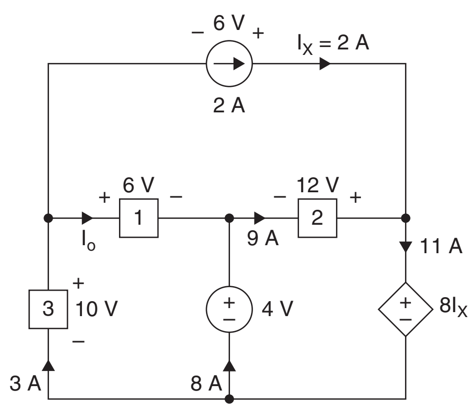


FIGURE P1.34