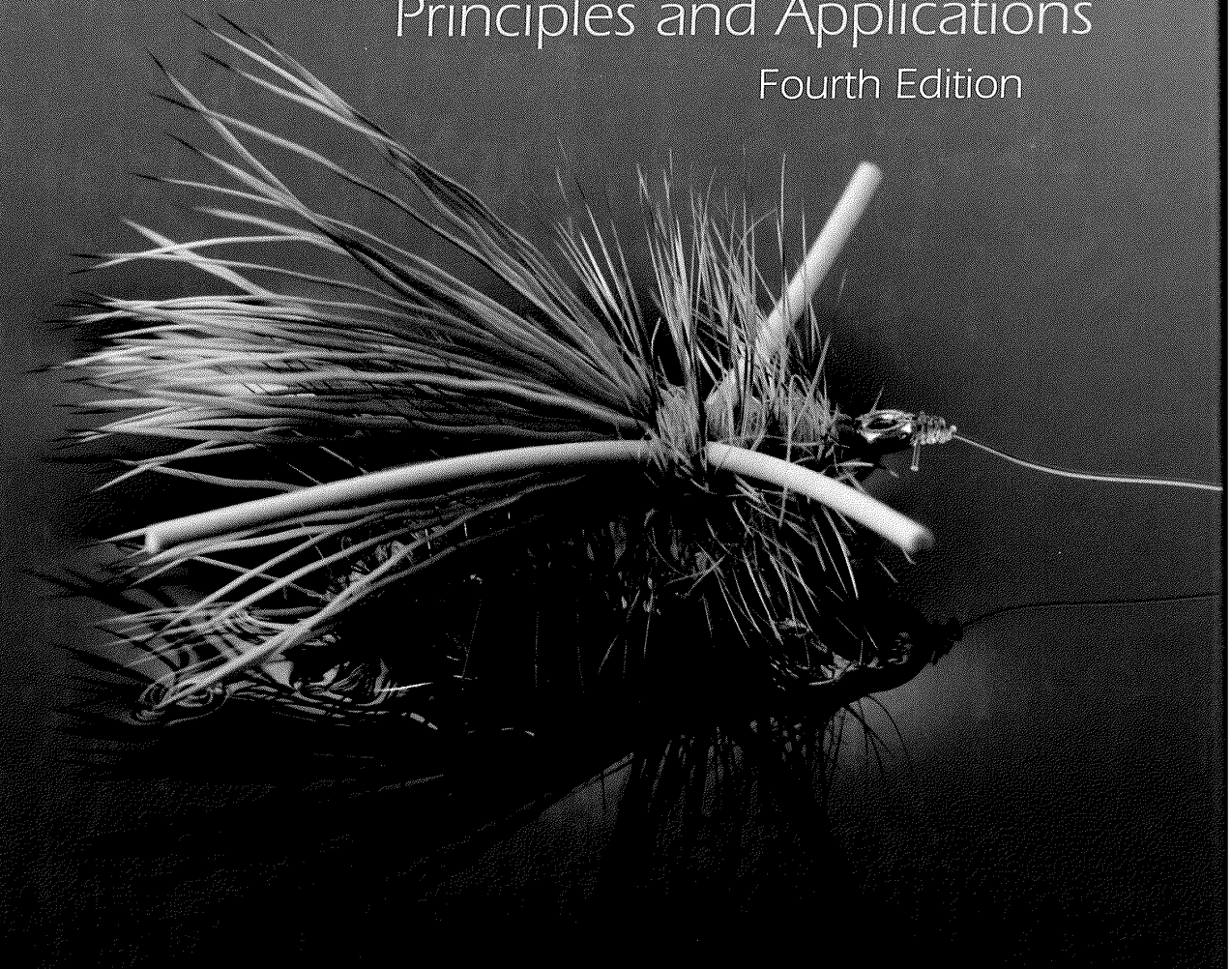




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Electrical Engineering

Principles and Applications
Fourth Edition



Allan R. Hambley

Electrical Engineering Principles and Applications

FOURTH EDITION

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Contents

Practical Applications of Electrical Engineering
Principles vi

Contents vii

Preface xi

PART ONE Circuits 1

1

Introduction 2

- 1.1 Overview of Electrical Engineering 3
- 1.2 Circuits, Currents, and Voltages 8
- 1.3 Power and Energy 15
- 1.4 Kirchhoff's Current Law 19
- 1.5 Kirchhoff's Voltage Law 22
- 1.6 Introduction to Circuit Elements 24
- 1.7 Introduction to Circuits 34
 - Summary 37
 - Problems 39

2

Resistive Circuits 47

- 2.1 Resistances in Series and Parallel 48
- 2.2 Network Analysis by Using Series and Parallel Equivalents 52
- 2.3 Voltage-Divider and Current-Divider Circuits 56
- 2.4 Node-Voltage Analysis 61
- 2.5 Mesh-Current Analysis 76
- 2.6 Thévenin and Norton Equivalent Circuits 84
- 2.7 Superposition Principle 97
- 2.8 Wheatstone Bridge 104
 - Summary 106
 - Problems 107

3

Inductance and Capacitance 120

- 3.1 Capacitance 121
- 3.2 Capacitances in Series and Parallel 130
- 3.3 Physical Characteristics of Capacitors 131
- 3.4 Inductance 135
- 3.5 Inductances in Series and Parallel 141
- 3.6 Practical Inductors 142
- 3.7 Mutual Inductance 144
 - Summary 146
 - Problems 147

4

Transients 156

- 4.1 First-Order RC Circuits 157
- 4.2 DC Steady State 161
- 4.3 RL Circuits 163
- 4.4 RC and RL Circuits with General Sources 168
- 4.5 Second-Order Circuits 175
 - Summary 189
 - Problems 190

5

Steady-State Sinusoidal Analysis 199

- 5.1 Sinusoidal Currents and Voltages 200
- 5.2 Phasors 207
- 5.3 Complex Impedances 213
- 5.4 Circuit Analysis with Phasors and Complex Impedances 218
- 5.5 Power in AC Circuits 224
- 5.6 Thévenin and Norton Equivalent Circuits 237

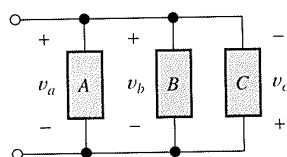


Figure 1.27 For this circuit, we can show that $v_a = v_b = -v_c$. Thus, the magnitudes and *actual* polarities of all three voltages are the same.

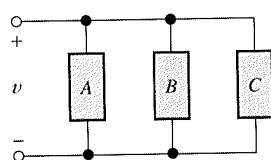


Figure 1.28 Analysis is simplified by using the same voltage variable and reference polarity for elements that are in parallel.

The voltages across parallel elements are equal in magnitude and have the same polarity. For illustration, consider the partial circuit shown in Figure 1.27. Here elements A , B , and C are connected in parallel. Consider a loop from the bottom end of A upward and then down through element B back to the bottom of A . For this clockwise loop, we have $-v_a + v_b = 0$. Thus, KVL requires that

$$v_a = v_b$$

Next, consider a clockwise loop through elements A and C . For this loop, KVL requires that

$$-v_a - v_c = 0$$

This implies that $v_a = -v_c$. In other words, v_a and v_c have opposite algebraic signs. Furthermore, one or the other of the two voltages must be negative (unless both are zero). Therefore, one of the voltages has an actual polarity opposite to the reference polarity shown in the figure. Thus, the actual polarities of the voltages are the same (either both are positive at the top of the circuit or both are positive at the bottom).

Usually, when we have a parallel circuit, we simply use the same voltage variable for all of the elements as illustrated in Figure 1.28.

Exercise 1.9 Use repeated application of KVL to find the values of v_c and v_e for the circuit of Figure 1.29.

Answer $v_c = 8 \text{ V}$, $v_e = -2 \text{ V}$. □

Exercise 1.10 Identify elements that are in parallel in Figure 1.29. Identify elements in series.

Answer Elements E and F are in parallel; elements A and B are in series. □

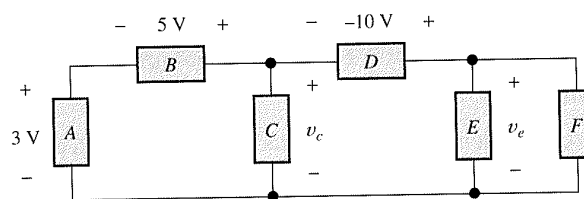


Figure 1.29 Circuit for Exercises 1.9 and 1.10.

1.6 INTRODUCTION TO CIRCUIT ELEMENTS

In this section, we carefully define several types of ideal circuit elements:

- Conductors
- Voltage sources
- Current sources
- Resistors

Later in the book, we will encounter additional elements, including inductors and capacitors. Eventually, we will be able to use these idealized circuit elements to describe (model) complex real-world electrical devices.

Conductors

We have already encountered conductors. Ideal conductors are represented in circuit diagrams by unbroken lines between the ends of other circuit elements. We define ideal circuit elements in terms of the relationship between the voltage across the element and the current through it.

The voltage between the ends of an ideal conductor is zero regardless of the current flowing through the conductor. When two points in a circuit are connected together by an ideal conductor, we say that the points are **shorted** together. Another term for an ideal conductor is **short circuit**. All points in a circuit that are connected by ideal conductors can be considered as a single node.

If no conductors or other circuit elements are connected between two parts of a circuit, we say that an **open circuit** exists between the two parts of the circuit. No current can flow through an ideal open circuit.

The voltage between the ends of an ideal conductor is zero regardless of the current flowing through the conductor.

All points in a circuit that are connected by ideal conductors can be considered as a single node.

Independent Voltage Sources

An **ideal independent voltage source** maintains a specified voltage across its terminals. The voltage across the source is independent of other elements that are connected to it and of the current flowing through it. We use a circle enclosing the reference polarity marks to represent independent voltage sources. The value of the voltage is indicated alongside the symbol. The voltage can be constant or it can be a function of time. Several voltage sources are shown in Figure 1.30.

An ideal independent voltage source maintains a specified voltage across its terminals.

In Figure 1.30(a), the voltage across the source is constant. Thus, we have a dc voltage source. On the other hand, the source shown in Figure 1.30(b) is an ac voltage source having a sinusoidal variation with time. We say that these are *independent* sources because the voltages across their terminals are independent of all other voltages and currents in the circuit.

Ideal Circuit Elements versus Reality

Here we are giving definitions of *ideal* circuit elements. It is possible to draw ideal circuits in which the definitions of various circuit elements conflict. For example,

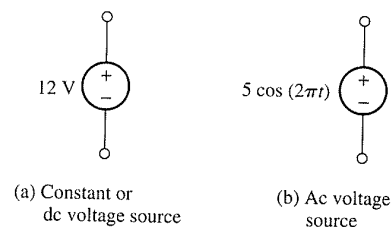


Figure 1.30 Independent voltage sources.

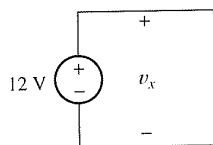


Figure 1.31 We avoid self-contradictory circuit diagrams such as this one.

Figure 1.31 shows a 12-V voltage source with a conductor connected across its terminals. In this case, the definition of the voltage source requires that $v_x = 12$ V. On the other hand, the definition of an ideal conductor requires that $v_x = 0$. In our study of ideal circuits, we avoid such conflicts.

In the real world, an automobile battery is nearly an ideal 12-V voltage source, and a short piece of heavy-gauge copper wire is nearly an ideal conductor. If we place the wire across the terminals of the battery, a very large current flows through the wire, stored chemical energy is converted to heat in the wire at a very high rate, and the wire will probably melt or the battery be destroyed.

When we encounter a contradictory idealized circuit model, we often have an undesirable situation (such as a fire or destroyed components) in the real-world counterpart to the model. In any case, a contradictory circuit model implies that we have not been sufficiently careful in choosing circuit models for the real circuit elements. For example, an automobile battery is not exactly modeled as an ideal voltage source. We will see that a better model (particularly if the currents are very large) is an ideal voltage source in series with a resistance. (We will discuss resistance very soon.) A short piece of copper wire is not modeled well as an ideal conductor, in this case. Instead, we will see that it is modeled better as a small resistance. If we have done a good job at picking circuit models for real-world circuits, we will not encounter contradictory circuits, and the results we calculate using the model will match reality very well.

Dependent Voltage Sources

A **dependent** or **controlled voltage source** is similar to an independent source except that the voltage across the source terminals is a function of other voltages or currents in the circuit. Instead of a circle, it is customary to use a diamond to represent controlled sources in circuit diagrams. Two examples of dependent sources are shown in Figure 1.32.

A **voltage-controlled voltage source** is a voltage source having a voltage equal to a constant times the voltage across a pair of terminals elsewhere in the network. An example is shown in Figure 1.32(a). The dependent voltage source is the diamond

A voltage-controlled voltage source maintains a voltage across its terminals equal to a constant times a voltage elsewhere in the circuit.

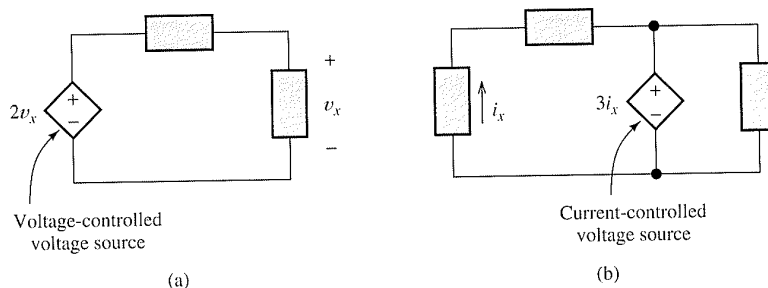


Figure 1.32 Dependent voltage sources (also known as controlled voltage sources) are represented by diamond-shaped symbols. The voltage across a controlled voltage source depends on a current or voltage that appears elsewhere in the circuit.

symbol. The reference polarity of the source is indicated by the marks inside the diamond. The voltage v_x determines the value of the voltage produced by the source. For example, if it should turn out that $v_x = 3$ V, the source voltage is $2v_x = 6$ V. If v_x should equal -7 V, the source produces $2v_x = -14$ V (in which case, the actual positive polarity of the source is at the bottom end).

A **current-controlled voltage source** is a voltage source having a voltage equal to a constant times the current through some other element in the circuit. An example is shown in Figure 1.32(b). In this case, the source voltage is three times the value of the current i_x . The factor multiplying the current is called the **gain parameter**. We assume that the voltage has units of volts and the current is in amperes. Thus, the gain parameter [which is 3 in Figure 1.32(b)] has units of volts per ampere (V/A). (Shortly, we will see that the units V/A are the units of resistance and are called ohms.)

Returning our attention to the voltage-controlled voltage source in Figure 1.32(a), we note that the gain parameter is 2 and is unitless (or we could say that the units are V/V).

Later in the book, we will see that controlled sources are very useful in modeling transistors, amplifiers, and electrical generators, among other things.

A current-controlled voltage source maintains a voltage across its terminals equal to a constant times a current flowing through some other element in the circuit.

Independent Current Sources

An ideal **independent current source** forces a specified current to flow through itself. The symbol for an independent current source is a circle enclosing an arrow that gives the reference direction for the current. The current through an independent current source is independent of the elements connected to it and of the voltage across it. Figure 1.33 shows the symbols for a dc current source and for an ac current source.

An ideal independent current source forces a specified current to flow through itself.

If an open circuit exists across the terminals of a current source, we have a contradictory circuit. For example, consider the 2-A dc current source shown in Figure 1.33(a). This current source is shown with an open circuit across its terminals. By definition, the current flowing into the top node of the source is 2 A. Also by definition, no current can flow through the open circuit. Thus, KCL is not satisfied at this node. In good models for actual circuits, this situation does not occur. Thus, we will avoid current sources with open-circuited terminals in our discussion of ideal networks.

A battery is a good example of a voltage source, but an equally familiar example does not exist for a current source. However, current sources are useful in constructing theoretical models. Later, we will see that a good approximation to an ideal current source can be achieved with electronic amplifiers.

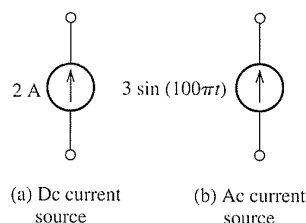


Figure 1.33 Independent current sources.

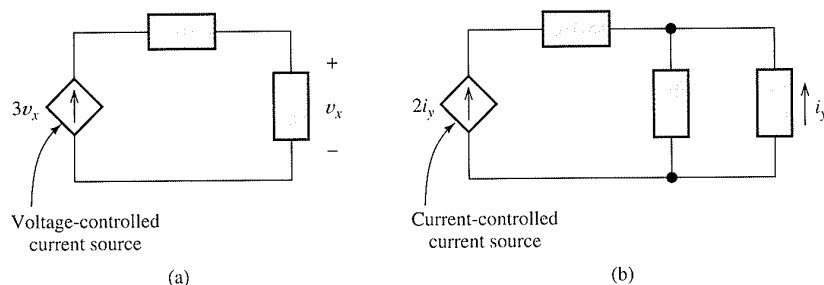


Figure 1.34 Dependent current sources. The current through a dependent current source depends on a current or voltage that appears elsewhere in the circuit.

The current flowing through a dependent current source is determined by a current or voltage elsewhere in the circuit.

Dependent Current Sources

The current flowing through a **dependent current source** is determined by a current or voltage elsewhere in the circuit. The symbol is a diamond enclosing an arrow that indicates the reference direction. Two types of controlled current sources are shown in Figure 1.34.

In Figure 1.34(a), we have a **voltage-controlled current source**. The current through the source is three times the voltage v_x . The gain parameter of the source (3 in this case) has units of A/V (which we will soon see are equivalent to siemens or inverse ohms). If it turns out that v_x has a value of 5 V, the current through the controlled current source is $3v_x = 15$ A.

Figure 1.34(b) illustrates a **current-controlled current source**. In this case, the current through the source is twice the value of i_y . The gain parameter, which has a value of 2 in this case, has units of A/A (i.e., it is unitless).

Like controlled voltage sources, controlled current sources are useful in constructing circuit models for many types of real-world devices, such as electronic amplifiers, transistors, transformers, and electrical machines. If a controlled source is needed for some application, it can be implemented by using electronic amplifiers. In sum, these are the four kinds of controlled sources:

1. Voltage-controlled voltage sources
2. Current-controlled voltage sources
3. Voltage-controlled current sources
4. Current-controlled current sources

Resistors and Ohm's Law

The voltage v across an ideal **resistor** is proportional to the current i through the resistor. The constant of proportionality is the resistance R . The symbol used for a resistor is shown in Figure 1.35(a). Notice that the current reference and voltage polarity reference conform to the passive reference configuration. In other words, the reference direction for the current is into the positive polarity mark and out of

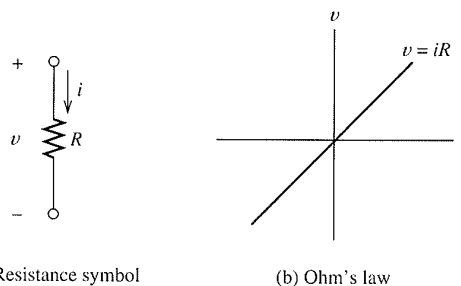


Figure 1.35 Voltage is proportional to current in an ideal resistor. Notice that the references for v and i conform to the passive reference configuration.

the negative polarity mark. In equation form, the voltage and current are related by **Ohm's law**:

$$v = iR$$

The units of resistance are V/A, which are called ohms. The uppercase Greek letter omega (Ω) represents ohms. In practical circuits, we encounter resistances ranging from milliohms ($\text{m}\Omega$) to megohms ($\text{M}\Omega$).

Except for rather unusual situations, the resistance R assumes positive values. (In certain types of electronic circuits, we can encounter negative resistance, but for now we assume that R is positive.) In situations for which the current reference direction enters the *negative* reference of the voltage, Ohm's law becomes

$$v = -iR$$

This is illustrated in Figure 1.36.

The relationship between current direction and voltage polarity can be neatly included in the equation for Ohm's law if double-subscript notation is used. (Recall that to use double subscripts, we label the ends of the element under consideration, which is a resistance in this case.) If the order of the subscripts is the same for the current as for the voltage (i_{ab} and v_{ab} , for example), the current reference direction enters the first terminal and the positive voltage reference is at the first terminal. Thus, we can write

$$v_{ab} = i_{ab}R$$

On the other hand, if the order of the subscripts is not the same, we have

$$v_{ab} = -i_{ba}R$$

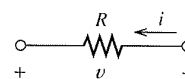


Figure 1.36 If the references for v and i are opposite to the passive configuration, we have $v = -Ri$.

Conductance

Solving Ohm's law for current, we have

$$i = \frac{1}{R}v$$

We call the quantity $1/R$ a **conductance**. It is customary to denote conductances with the letter G :

$$G = \frac{1}{R} \quad (1.8)$$

Conductances have the units of inverse ohms (Ω^{-1}), which are called siemens (abbreviated S). Thus, we can write Ohm's law as

$$i = Gv \quad (1.9)$$

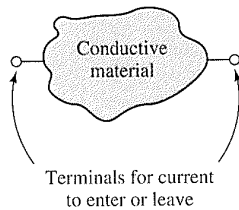


Figure 1.37 We construct resistors by attaching terminals to a piece of conductive material.

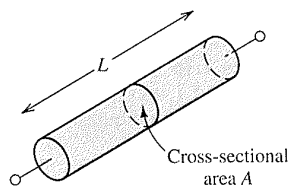


Figure 1.38 Resistors often take the form of a long cylinder (or bar) in which current enters one end and flows along the length.

Resistors

It turns out that we can construct nearly ideal resistors by attaching terminals to many types of conductive materials. This is illustrated in Figure 1.37. Conductive materials that can be used to construct resistors include most metals, their alloys, and carbon.

On a microscopic level, current in metals consists of electrons moving through the material. (On the other hand, in solutions of ionic compounds, current is carried partly by positive ions.) The applied voltage creates an electric field that accelerates the electrons. The electrons repeatedly collide with the atoms of the material and lose their forward momentum. Then they are accelerated again. The net effect is a constant average velocity for the electrons. At the macroscopic level, we observe a current that is proportional to the applied voltage.

Resistance Related to Physical Parameters

The dimensions and geometry of the resistor as well as the particular material used to construct a resistor influence its resistance. We consider only resistors that take the form of a long cylinder or bar with terminals attached at the ends, as illustrated in Figure 1.38. The cross-sectional area A is constant along the length of the cylinder or bar. If the length L of the resistor is much greater than the dimensions of its cross section, the resistance is approximately given by

$$R = \frac{\rho L}{A} \quad (1.10)$$

in which ρ is the *resistivity* of the material used to construct the resistor. The units of resistivity are ohm meters (Ωm).

Materials can be classified as conductors, semiconductors, or insulators, depending on their resistivity. **Conductors** have the lowest resistivity and easily conduct electrical current. **Insulators** have very high resistivity and conduct very little current (at least for moderate voltages). **Semiconductors** fall between conductors and insulators. We will see in Chapters 10, 12, and 13 that certain semiconductors are very useful in constructing electronic devices. Table 1.3 gives approximate values of resistivity for several materials.