高等学校教材
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CIRCUIT ANALYSIS

电路分析

马文忠　胡慧慧　董　磊　编

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Preface

"Circuit Analysis" course is an important basic course of electrical engineering and computer science majors, and an important specialty basic course for international students of electrical engineering and automation. This textbook can help students establish a solid foundation for following courses study, and understand the latest development trend of electrical theory and new technology. According to the newly revised curriculum syllabus and talent cultivation requirements, it simplifies the complex theoretical system, optimizes a wide range of knowledge and emphasizes the questions discussion. This textbook not only applies to international students, but also applies to other students of electrical engineering and computer science majors.

Wenzhong Ma is the chief editor of this book. In addition, the following have made important contributions to this edition: Wenzhong Ma (Chapter 1, Chapter 2, Chapter 3, Chapter 4, Chapter 5, and Chapter 6), Huihui Hu (Chapter 7, Chapter 8, Chapter 9, and Chapter 11) and Lei Dong (Chapter 10, Chapter 12, and Chapter 13).

There may be some errors and inappropriate in this book, we appreciate the feedback received from instructors and students.

Author

2016-10

Contents

Chapter 1

Circuit Models and Circuit Law

1.1 Systems of Units

As electrical engineers, we deal with measurable quantities. Our measurement, however, must be communicated in a standard language that virtually all professionals can understand, irrespective of the country where the measurement is conducted. Such an international measurement language is the International System of Units(SI), adopted by the General Conference on Weights and Measures in 1960. In this system, there are seven principal units from which the units of all other physical quantities can be derived. Table 1-1 shows the six basic SI units and one derived unit that are relevant to this text. The SI units are used throughout this text.

Table 1-1 Six basic SI units and one derived unit relevant to this text

Quantity	Basic unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd
Charge	coulomb	C

One great advantage of the SI unit is that it uses prefixes based on the power of 10 to relate larger and smaller units to the basic unit. Table 1-2 shows the SI prefixes and their symbols. For example, the following are expressions of the same distance in meters(m):

600 000 000 mm 600 000 m 600 km

Table 1-2 The SI prefixes

Multiplier	Prefix	Symbol	Multiplier	Prefix	Symbol
10^{18}	exa	E	10^{-1}	deci	d
10^{15}	peta	P	10^{-2}	centi	c
10^{12}	teta	T	10^{-3}	milli	m
10^{9}	giga	G	10^{-6}	micro	μ
10^{6}	mega	M	10^{-9}	nano	n
10^{3}	kilo	k	10^{-12}	pico	p
10^{2}	hecto	h	10^{-15}	femto	f
10	deka	da	10^{-18}	atto	a

1.2 Charge and Current

The concept of electric charge is the underlying principle for explaining all electrical phenomena. Also, the most basic quantity in an electric circuit is the electric charge. Charge is an electrical property of the atomic particles of which matter consists, measured in coulombs(C).

We know from elementary physics that all matter is made of fundamental building blocks known as atoms and that each atom consists of electrons, protons, and neutrons. We also know that the charge e on an electron is negative and equal in magnitude to 1.6×10^{-19} C, while a proton carries a positive charge of the same magnitude as the electron. The presence of equal numbers of protons and electrons leaves an atom neutrally charged.

The law of conservation of charge states that charge can neither be created nor destroyed, only transferred. Thus the algebraic sum of the electric charges in a system does not change. We now consider the flow of electric charges. A unique feature of electric charge or electricity is the fact that it is mobile; that is, it can be transferred from one place to another, where it can be converted to another form of energy.

When a conducting wire (consisting of several atoms) is connected to a battery (a source of electromotive force), the charges are compelled to move; positive charges move in one direction while negative charges move in the opposite direction. This motion of charges creates electric current. It is conventional to take the current flow as the movement of positive charges. That is, opposite to the flow of negative charges, as Fig. 1-1 illustrates.

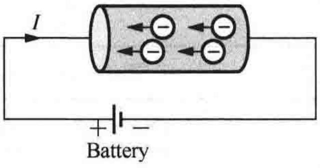


Fig. 1-1 Electric current due to flow of electric charge in a conductor

Electric current is the time rate of change of charge, measured in amperes (A). Mathematically, the relationship between current i, charge q, and time t is

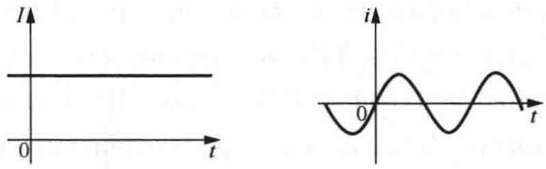
$$i=\frac{dq}{dt} \tag{1-1}$$

where current is measured in amperes, and 1 ampere = 1 coulomb/second. The charge transferred between time t_0 and t is obtained by integrating both sides of Eq. (1-1). That is

$$Q=\int_{t_0}^{t} i\,\mathrm{d}t \tag{1-2}$$

If the current does not change with time, but remains constant, we call it a **direct current(dc)**. A direct current is a current that remains constant with time. By convention the symbol I is used to represent such a constant current.

A time-varying current is represented by the symbol i. A common form of time-varying current is the sinusoidal current or **alternating current(ac)**. An alternating current is a current that varies sinusoidally with time. Such current is used in your household to run the air conditioner, refrigerator, washing machine, and other electric appliances. Fig. 1-2 shows direct current and alternating current; these are the two most common types of current.



(a) direct current (dc) (b) alternating current (ac)

Fig. 1-2 Two common types of current

Example 1-1 The total charge entering a terminal is given by $q=5t\sin(4\pi t)$ mC. Calculate the current at $t=0.5$ s.

Solution:

$$i=\frac{\mathrm{d}q}{\mathrm{d}t}=\frac{\mathrm{d}}{\mathrm{d}t}[5t\sin(4\pi t)]=[5\sin(4\pi t)+20\pi t\cos(4\pi t)]\ \mathrm{mA}$$

At $t=0.5$ s, $i=5\sin(2\pi)+10\pi\cos(2\pi)=0+10\pi=31.42$ mA.

Example 1-2 Determine the total charge entering a terminal between $t=1$ s and $t=2$ s if the current passing the terminal is $i=(3t^2-t)$ A.

Solution:

$$Q=\int_{t_0}^{t} i\,\mathrm{d}t=\int_{1}^{2}(3t^2-t)\,\mathrm{d}t=\left(t^3-\frac{1}{2}t^2\right)\Big|_{1}^{2}=(8-2)-\left(1-\frac{1}{2}\right)=5.5\ \mathrm{C}$$

1.3 Voltage

As explained briefly in the previous section, to move the electron in a conductor in a particular direction requires some work or energy transfer. This work is performed by an external electromotive force(emf), typically represented by the battery in Fig. 1-1. This emf is also known as **voltage** or **potential difference**. The voltage between two points (a and b) in an electric circuit is the energy (or work) needed to move a unit charge from a to b. Mathematically:

$$u_{ab}=\frac{dW}{dt} \tag{1-3}$$

where W is energy in joules(J) and q is charge in coulombs(C). The voltage u_{ab} or simply u is measured in volts(V), 1 volt = 1 joule/coulomb = 1 newton-meter/coulomb. Thus, voltage(or potential difference) is the energy required to move a unit charge through an element, measured in volts(V).

Fig. 1-3 shows the voltage across an element (represented by a rectangular block) connected to points a and b. The plus (+) and minus (−) signs are used to define reference direction or voltage polarity. The u_{ab} can be interpreted in two ways: ① point a is at a potential of u_{ab} volts higher than point b, or ② the potential at point a with respect to point b is u_{ab}. It follows logically that in general $u_{ab}=-u_{ba}$.

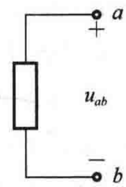


Fig. 1-3 Polarity of voltage u_{ab}

Keep in mind that electric current is always through an element and that electric voltage is always across the element or between two points. Current and voltage are the two basic variables in electric circuits. Like electric current, a constant voltage is called a dc voltage and is represented by U, whereas a sinusoidally time-varying voltage is called an ac voltage and is represented by u. A dc voltage is commonly produced by a battery; an ac voltage is produced by an electric generator.

1.4 Current and Voltage Reference Directions

To specify the current in a conductor, we need reference direction. The real direction of the current in the element has two possibilities as shown Fig. 1-4. The direction of the arrowhead is the reference direction. If the real direction of the current is from A to B, as the dashed arrows shown in Fig. 1-4(a), it is consistent with the reference direction, then the current is positive, that is $i>0$. In Fig. 1-4(b), the real direction of the current is from B to A (as the dashed arrows), so the current is negative because both two directions are inconsistent, that is $i<0$. Thus, in the current reference direction specified, positive and negative current value can reflect the real direction of current. Reference direction is also called assumed current positive direction. It can be arbitrarily specified. Two methods are used to express the reference direction of the current, the direction of the arrowhead is the reference direction, or double subscript, such as i_{AB}, and the reference direction is from A to B.

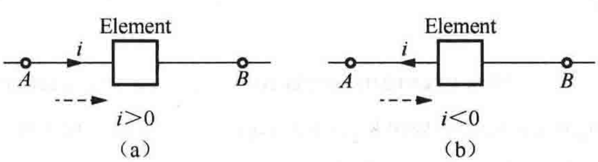


Fig. 1-4 Current reference directions

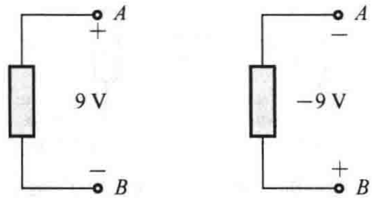
A current of 5 A may be represented positively or negatively as shown in Fig. 1-5. In other words, a negative current of −5 A flowing in one direction as shown in Fig. 1-5(b) is the same as a current of +5 A flowing in the opposite direction.

(a) positive current flow (b) negative current flow

Fig. 1-5 Conventional current flow

Similarly, reference directions of voltage must be set prior to circuit analysis. Keep in mind that electric voltage is always across the element or between two nodes. Three methods are used to express the reference direction of voltage, the direction of the arrowhead is the reference direction. The reference direction is from the positive polarity to the negative one. Double subscript: Such as u_{AB}, the reference direction is from A to B.

For example, in Fig. 1-6, we have two representations of the same voltage. In Fig. 1-6(a), point A is +9 V above point B; in Fig. 1-6(b), point B is −9 V above point A. We may say that in Fig. 1-6(a), $u_{AB}=+9$ V; in Fig. 1-6(b), $u_{BA}=-9$ V; $u_{AB}=-u_{BA}$.



(a) (b)

Fig. 1-6 Two equivalent representations of the same voltage

The reference directions of voltage u and current i of elements and branches can be independent of any specified. When the current enters the positive terminal, such directions are called associate reference directions. Oppositely, if the current enters the negative terminal, they are non-associate reference directions.

1.5 Power and Energy

Although current and voltage are two basic variables in an electric circuit, they are not sufficient by themselves. For practical purposes, we need to know how much power an electric device can handle with. We all know from experience that a 100-watt bulb gives more light than a 60-watt bulb. We also know that when pay our bills to the electric utility companies, we are paying for the electric energy consumed over a certain period of time. Thus, power and energy calculations are very important in circuit analysis.

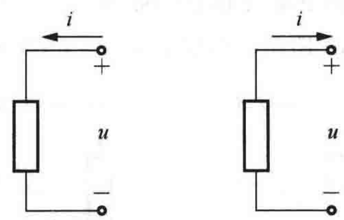
Power is the time rate of expending or absorbing energy, measured in watt(W). We write this relationship as

$$p=\frac{\mathrm{d}W}{\mathrm{d}t}=\frac{\mathrm{d}W}{\mathrm{d}q}\frac{\mathrm{d}q}{\mathrm{d}t}=ui \tag{1-4}$$

where p is power in watts(W), W is energy in joules(J), and t is time in seconds(s).

The power p in Eq. (1-4) is a time-varying quantity and is called the **instantaneous power.** Thus, the power absorbed or supplied by an element is the product of the voltage across the element and the current through it. If the power has a + sign, power is being delivered to or absorbed by the element. If, on the other hand, the power has a − sign, power is being supplied by the element. But how do we know when the power has a negative or a positive sign?

Current direction and voltage polarity play a major role in determining the sign of power. It is therefore important that we pay attention to the relationship between current i and voltage u in Fig. 1-7(a). The voltage polarity and current direction must conform to those shown in Fig. 1-7(a) in order for the power to have a positive sign. This is known as the **passive sign convention.** By the passive sign convention, current enters through the positive polarity of the voltage. In this case, $p=+ui$ or $ui>0$ implies that the element is absorbing power. However, if $p=-ui$ or $ui<0$, as shown in Fig. 1-7(b), the element is releasing or supplying power.



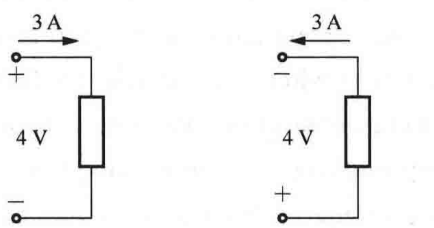
$p=+ui$ $p=-ui$

(a) absorbing power (b) supplying power

Fig. 1-7 Reference polarities for power using the passive sign convention

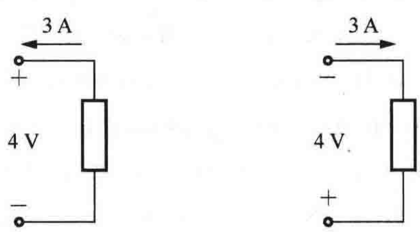
Passive sign convention is satisfied when the current enters through the positive terminal of an element and $p=+ui$. If the current enters through the negative terminal, $p=-ui$.

Unless otherwise stated, we will follow the passive sign convention throughout this text. For example, the element in both circuits of Fig. 1-8 has an absorbing power of +12 W because a positive current enters the positive terminal in both cases. In Fig. 1-9, however, the element is supplying power of +12 W because a positive current enters the negative terminal. Of course, an absorbing power of −12 W is equivalent to a supplying power of +12 W. In general, + power absorbed= −power supplied.



(a) $p=4\times3=12$ W (b) $p=4\times3=12$ W

Fig. 1-8 Two cases of an element with an absorbing power of 12 W



(a) $p=-4\times3=-12$ W (b) $p=-4\times3=-12$ W

Fig. 1-9 Two cases of an element with an supplying power of 12 W

In fact, **the law of conservation of energy** must be obeyed in any electric circuit. For this reason, the algebraic sum of power in a circuit must be zero at any instant of time.

From Eq. (1-4), the energy absorbed or supplied by an element from time t_0 to time t is

$$W = \int_{t_0}^{t} p\,\mathrm{d}t = \int_{t_0}^{t} ui\,\mathrm{d}t \qquad (1\text{-}5)$$

Energy is the capacity to do work, measured in joules(J).

Example 1-3 An energy source forces a constant current of 2 A for 10 s to flow through a light bulb. If 2.3 kJ is given off in the form of light and heat energy, calculate the voltage drop across the bulb.

Solution: The total charge is

$$\Delta q = i\Delta t = 2\times 10 = 20 \text{ C}$$

The voltage drop is

$$u = \frac{\Delta W}{\Delta q} = \frac{2.3\times 10^3}{20} = 115 \text{ V}$$

1.6 Circuit Elements

As we discussed in Section 1.1, an element is the basic building block of a circuit. An electric circuit is simply an interconnection of the elements. Circuit analysis is the process of determining voltages across(or the currents through)the elements of the circuit.

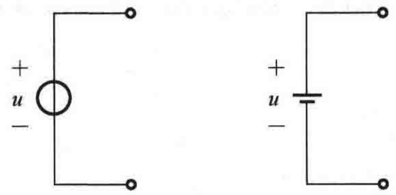
There are two types of elements found in electric circuits: **passive elements** and **active elements**. An active element is capable of generating energy while a passive element is not. Examples of passive elements are **resistors**, **capacitors**, and **inductors**. Typical active elements include generators, batteries, and operational amplifiers. Our aim in this section is to gain familiarity with some important active elements.

The most important active elements are voltage or current sources that generally deliver power to the circuit connected to them. There are two kinds of sources: independent and dependent sources.

An ideal independent source is an active element that provides a specified voltage or current that is completely independent of other circuit elements. In other words, an **ideal independent voltage source** delivers to the circuit whatever current is necessary to maintain its terminal voltage.

Physical sources such as batteries and generators may be regarded as approximations to ideal voltage sources. Fig. 1-10 shows the symbols for independent voltage sources. Notice that both symbols in Fig. 1-10(a) and Fig. 1-10(b) can be used to represent a dc voltage source, but only the symbol in Fig. 1-10(a) can be used for a time-varying voltage source.

Similarly, an **ideal independent current source** is an active element that provides a specified current completely independent of the voltage across the source. That is, the current source delivers to the circuit whatever voltage is necessary to maintain the designated current. The symbol for an independent current source is displayed in Fig. 1-11, where the arrow indicates the direction of current i.



(a) used for constant or time-varying voltage (b) used for constant voltage (dc)

Fig. 1-10 Symbols for independent voltage sources

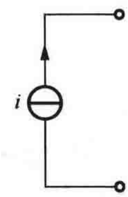


Fig. 1-11 Symbols for independent current sources

An ideal dependent (or **controlled**) **source** is an active element in which the source quantity is controlled by another voltage or current. Dependent sources are usually designated by diamond-shaped symbols, as shown in Fig. 1-12. Since a voltage or current of some other elements in the circuit can achieve the control of the dependent source, and the source can be voltage or current, it follows that there are four possible types of dependent sources, namely:

(1) A voltage-controlled voltage source (VCVS).

(2) A current-controlled voltage source (CCVS).

(3) A voltage-controlled current source (VCCS).

(4) A current-controlled current source (CCCS).

(a) dependent voltage source (b) dependent current source

Fig. 1-12 Symbols for dependent sources

Problems

1-1 Determine the current flowing through an element if the charge flow is given by

(1) $q(t)=(3t+8)$ mC.

(2) $q(t)=(8t^2+4t-2)$ C.

(3) $q(t)=10\sin(120\pi t)$ pC.

1-2 Find the charge flowing through a device if the current is:

(1) $i(t)=3$ A, $q(0)=1$ C.

(2) $i(t)=10e^{-30t}\sin(40t)$ A, $q(0)=0$.

1-3 A current of 7.4 A flows through a conductor. Calculate how much charge passes through any cross-section of the conductor in 20 s.

1-4 A rechargeable flashlight battery is capable of delivering 90 mA for about 12 h. How much charge can it release at that rate? If its terminal voltage is 1.5 V, how much energy can the battery deliver?

1-5 The current entering the positive terminal of a device is $i(t)=6e^{-2t}$ mA and the voltage across the device is $u(t)=10di/dt$ V.

(1) Find the charge delivered to the device between $t=0$ and $t=2$ s.

(2) Calculate the power absorbed.

(3) Determine the energy absorbed in 3 s.

1-6 Fig. 1-13 shows a circuit with five elements. If $p_1=-205$ W, $p_2=60$ W, $p_4=45$ W, $p_5=30$ W, calculate the power p_3 received or delivered by element 3.

1-7 Find the power absorbed by each of the elements in Fig. 1-14.

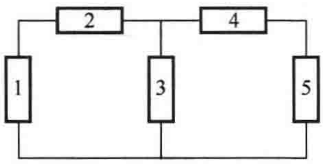


Fig. 1-13 Prob. 1-6

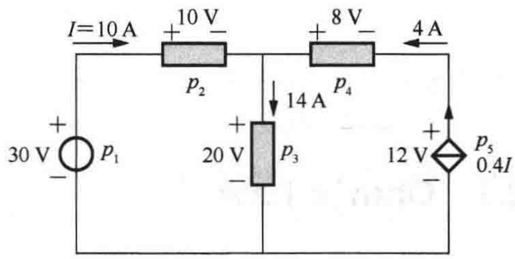


Fig. 1-14 Prob. 1-7

1-8 Find I and the power absorbed by each element in the network of Fig. 1-15.

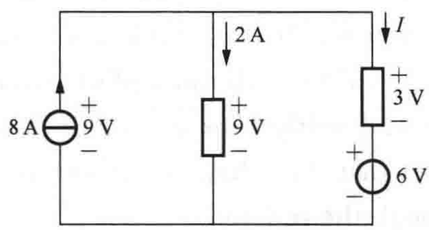


Fig. 1-15 Prob. 1-8

Chapter 2

Basic Laws

2.1 Ohm's Law

Materials in general have a characteristic behavior of resisting the flow of electric charge. This physical property, or ability to resist current, is known as resistance and is represented by the symbol R. The circuit element used to model the current-resisting behavior of a material is the **resistor.** The resistor is the simplest passive element.

Georg Simon Ohm(1787—1854), a German physicist, is credited with finding the relationship between current and voltage for a resistor. This relationship is known as Ohm's law. Ohm's law states that the voltage u across a resistor is directly proportional to the current i flowing through the resistor.

$$u=Ri \tag{2-1}$$

which is the mathematical form of Ohm's law. R in Eq. (2-1) is measured in the unit of ohms, designated. The **resistance** R of an element denotes its ability to resist the flow of electric current; it is measured in ohms(Ω).

A useful quantity in circuit analysis is the reciprocal of resistance R, known as **conductance** and denoted by G:

$$i=Gu \tag{2-2}$$

The unit of conductance is the siemens(S).

To apply Ohm's law as stated in Eq. (2-1) and Eq. (2-2), we must pay careful attention to the current direction and voltage polarity. The direction of current i and the polarity of voltage u must conform to the passive sign convention, as shown in Fig. 2-1. This implies that current flows from a higher potential to a lower potential in order for $u=Ri$ or $i=Gu$. If current flows from a lower potential to a higher potential, $u=-Ri$ or $i=-Gu$.

Since the value of R can range from zero to infinity, it is important that we consider the two extreme possible values of R. An element with $R=0$ is called a short circuit, as shown in Fig. 2-1(a). For a short circuit, $u=0$ V, showing that the voltage is zero but the current could