Fundamentals of Electric Circuits

电 路 基 础

吴国庆 张燕君 金 娃 王 伟◎编著
齐跃峰◎主审

燕山大学出版社
YANSHAN UNIVERSITY PRESS

图书在版编目(CIP)数据

电路基=Fundamentals of Electric Circuits:英文/吴国庆等编著.—秦皇岛:燕山大学出版社,2023.7
ISBN 978-7-5761-0307-6

Ⅰ.①电… Ⅱ.①吴… Ⅲ.①电路理论—高等学校—教材—英文 Ⅳ.①TM13

中国版本图书馆 CIP 数据核字(2022)第 132631 号

Fundamentals of Electric Circuits

吴国庆 张燕君 金 娃 王 伟 编著

出 版 人:陈 玉
责任编辑:朱红波　　策划编辑:朱红波
责任印制:吴 波　　封面设计:刘韦希
出版发行:燕山大学出版社 YANSHAN UNIVERSITY PRESS　　电 话:0335-8387555
地 址:河北省秦皇岛市河北大街西段 438 号　　邮政编码:066004
印 刷:中国标准出版社秦皇岛印刷厂　　经 销:全国新华书店

开 本:787 mm×1092 mm 1/16　　印 张:16.5
版 次:2023 年 7 月第 1 版　　印 次:2023 年 7 月第 1 次印刷
书 号:ISBN 978-7-5761-0307-6　　字 数:316 千字
定 价:49.00 元

Preface

The report of the Twentieth Party Congress points out that education, science and technology, and human resources are the basic and strategic support for the comprehensive construction of a modern socialist country. Excellent teaching materials are the basic guarantee for the quality of teaching and learning in higher education programmes, as well as an important tool for schools to teach and cultivate students' national identity.

The Principle of Circuit is a very important basic technical course for electrical engineering students. Through the study of this course, students can master the basic theoretical knowledge of circuit and the basic methods of technical circuit analysis, and prepare the necessary circuit knowledge for the study of subsequent courses. The study of circuit course plays an important role in cultivating students' scientific thinking ability, establishing the engineering viewpoint of combining theory and practice, and improving students' ability to analyse and solve problems. It also plays an important role in the talent training programme and curriculum system of the whole electrical speciality.

This book fully absorbs the success of the existing excellent teaching materials at home and abroad, combined with the author's years of teaching practice and experience to compile. This textbook has the following features.

1. Refining the course content, emphasizing the understanding of basic concepts and paying attention to the combination of new and old content.

2. Adapt to the teaching reform of the 21st century, and adapt to the teaching of students of different levels, different majors and different degrees.

3. This textbook pays attention to the cultivation of students' quality and ability.

The main contents of this book include:

The contents include circuit model and circuit law, resistive circuit analysis, circuit theorem, sinusoidal steady-state circuit analysis, three-phase circuit, non-sinusoidal periodic current circuit, dynamic circuit time domain analysis. This book contains reference answers to various chapter exercises.

The main contents of this book include Chapter 1, Chapter 2 and Chapter 3 are DC circuits, mainly about the basic elements and their characteristics, basic theorems, laws, and analysis methods; Chapter 4 and Chapter 5 are sinusoidal circuits, mainly about the analysis of general sinusoidal steady-state and three-phase circuits. The main authors of this book and division are Chapter 1 and Chapter 2 (Sections 1, 2 and 3) written by Wang Wei; Chapter 3 and Chapter 7 written by Jin Wa; Chapter 2 (Section 4) and Chapter 5 written by Zhang Yanjun; Chapter 4 and Chapter 6 written by Wu Guoqing. This book was edited and adjusted by Wu Guoqing.

Contents

Chapter 1 Basic Concepts and Laws

1.1 Introduction

Electrical circuits are everywhere in our lives: in our homes, schools, workplaces, and transportation vehicles, etc. In a field as diverse as electrical engineering, one might well ask whether all its branches have something in common. The answer is yes: electric circuits.

Electric circuit theory is the basis of many branches of electrical engineering, such as power, electric machines, electronics, communications, and instrumentation. Therefore, the basic course on electric circuit theory is the most important course for an electrical engineering student, and is always an excellent starting point for a beginning student in electrical engineering education.

Electric circuit theory involves circuit analysis and circuit design. This book concentrates mainly on circuit analysis. In circuit analysis, electric circuit models are analyzed instead of actual electrical circuits. An electric circuit model is a mathematical model that approximates the behaviour of an actual electrical circuit.

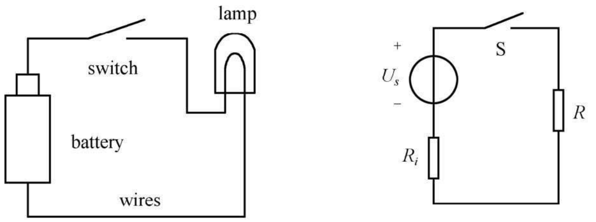
In this chapter, the definition of electric circuit model, voltage, current and their reference directions, resistance and Ohm's law, independent and dependent sources, and Kirchhoff's laws are included.

1.2 An actual electrical circuit and its electric circuit model

1.2.1 An actual electrical circuit

In electrical engineering, we are often interested in communicating or transferring energy from one point to another. To do this, we need to connect electrical devices together. Such a connection is called an electrical circuit, and each component in the circuit is known as an element. No matter how complicated an electric circuit is, it consists of three parts: sources, connecting elements and loads.

A flashlight circuit is shown in Fig. 1-1(a). It has three basic elements: a battery, a lamp, and connecting wires.



(a) The actual electrical circuit (b) The electric circuit model

Fig. 1-1 A flashlight circuit

1.2.2 An electrical circuit model

An electric circuit model is a mathematical model that approximates the behaviour of an actual electrical circuit. Note that the term "electric circuit" is commonly used to refer to both an actual electrical circuit and the model that represents it. In this book, when we talk about an electric circuit, we always mean a model unless otherwise stated. The elements that make up the circuit model are called ideal circuit components. There are two types of elements found in electric circuits: passive elements and active elements. An active element is capable of generating energy, whereas a passive element is not.

Examples of passive elements are resistors, capacitors and inductors. Resistance is the ability of materials to impede the flow of current or, more specifically, the flow of electric charge. The circuit element used to model this behaviour is the resistor. A capacitor is a passive element designed to store energy in its electric field. Apart from resistors, capacitors are the most common electrical components. An inductor is a passive element designed to store energy in its magnetic field. Inductors have many applications in electronic and power systems. They are used in power supplies, transformers, radios, televisions, radars, and electric motors. The most important active elements are voltage or current sources. An electrical source is a device that can convert non-electrical energy to electrical energy and deliver power to the circuit to which it is connected.

It is important that the ideal circuit component used in a circuit model represents the behaviour of the actual electrical component with an acceptable degree of accuracy. Fig. 1-1(b) is the electrical model of the electrical circuit shown in Fig. 1-1(a). In this model, the battery is represented by a voltage source U_s and an internal resistor R_i in series with it. The lamp is replaced by a resistor of value R and the connecting wires are assumed to be ideal without resistance.

1.3 Current and voltage's reference directions and power

1.3.1 The current and its reference directions

The most elementary quantity in the analysis of electric circuits is electric charge. Our interest in electric charge is centered on its motion, since charge in motion results in a transfer of energy. Electric current is the rate of charge change over time, measured in amperes (A). It is conventional to take the current flow as the movement of positive charges. That is, opposite to the flow of negative charges. This convention was introduced by Benjamin Franklin (1706—1790), the American scientist and inventor. Although we now know that current in metallic conductors is due to negatively charged electrons, we will follow the universally accepted convention that current is the net flow of positive charges.

Once we define current as the movement of charge, we expect current to have an associated direction of flow. However, in electric circuit analysis, the actual direction of the current along an element is often impossible to predict in advance. Sometimes the actual direction of the current is even time varying. It is difficult to mark the actual direction of the current. For this reason, it is important to define a current with a reference direction. The reference direction is an arbitrary assumed direction through the elements and is not necessarily the actual direction of flow. It is generally indicated by an arrow drawn on the component lead, as shown in Fig. 1-2. Using this reference direction, the answer can be interpreted to give the physical state in the circuit: "$i>0$" means the actual direction of current flow is the same as the assumed reference direction, while "$i<0$" means that the actual direction is opposite to the reference direction. For example, if the assumed reference direction of current i is from A to B but the calculated i has a negative value of -5 A, this means that a $+5$ A current is flowing from B to A.

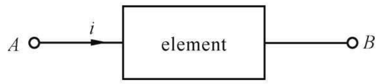


Fig. 1-2 The reference direction of a current

1.3.2 The voltage and its reference directions

To move the electron in a conductor in a particular direction requires some work or energy transfer. Voltage (or potential difference) is the energy required to move a unit charge through an element, measured in volts (V). The plus (+) and minus (−) signs are used to define the reference direction or the polarity of a voltage, as shown in Fig. 1-3. As with the reference direction of current, the reference direction of voltage can be marked in either direction across the element. For example, in Fig. 1-3, it is assumed that point A is at a higher potential than point B, as indicated by the + and − signs associated with the variable and defined in the figure. The + and − signs define a reference direction for u. If $u = 5$ V, then the potential difference between point A and B is 5 V with point A having a higher potential. We then say there is a 5 V voltage drop from A to B. If a unit positive charge is moved from point A through the circuit to point B, it will give up energy to the circuit and will have 5 J less energy when it reaches point B. If $u = -5$ V, then the potential between points A and B is still 5 V, but point B is at the higher potential. This means a 5 V voltage raise from A to B.

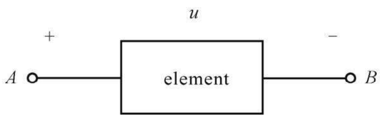


Fig. 1-3 The reference direction of the voltage

Note that it is important to define a current or a voltage together with a reference direction so that the answer can be interpreted to give the physical state in the circuit. However, it is difficult to define the variables in such a way that the answers are always positive, and it is also not necessary to do so.

1.3.3 Associated reference direction and the calculation of power

The assignments of the reference polarity for voltage and the reference direction for current are completely arbitrary. Whenever the reference direction for the current in an element is in the direction of the reference voltage drop across the element (the current enters through the positive polarity of the voltage according to the reference directions instead of the actual directions), we call this the associated reference direction, as shown in Fig. 1-4(a). Otherwise, the current entering through the negative polarity of the voltage is called the non-associated reference direction, as shown in Fig. 1-4(b).

Fig. 1-4 Associated and non-associated reference direction

Although current and voltage are two basic variables in an electric circuit, power and energy calculations are also important in circuit analysis. One reason is that although voltage and current are useful variables in the analysis and design of electrically based systems, the useful output of the system is often non-electrical, and this output is conveniently expressed in terms of power or energy. Another reason is that all practical devices have limits on the amount of power that they can handle.

We have defined voltage in Joules (J) per Coulomb (C) as the energy required to move a positive charge of 1 C through an element. If we assume that we are dealing with a differential amount of charge and energy, then

$$\mathrm{d}w = u\mathrm{d}q \tag{1-1}$$

where w is energy in J, q is electric charge in C.

Using the associated reference direction between u and i, as shown in Fig. 1-4(a), the instantaneous power p absorbed by an element is the time rate of absorbed energy, measured in watts (W). We write this relationship as:

$$p = \frac{\mathrm{d}w}{\mathrm{d}t} = u\frac{\mathrm{d}q}{\mathrm{d}t} = ui \tag{1-2}$$

where t is the time in seconds (s). The product of u and i, with their attendant signs, determines the magnitude and sign of the power. If the sign of the power is positive ($p>0$), the power is being absorbed by the element; if the sign is negative ($p<0$), the power is being supplied by the element.

If u and i have a non-associated reference direction between them, as shown in Fig. 1-4 (b), the absorbed power p can be calculated by $p=-ui$. In this case, power is still being absorbed by the element if $p>0$, and power is still being supplied by the element if $p<0$.

It is important to note that our electrical networks obey the principle of energy conservation. Because of the relationship between energy and power, it can be implied that power is also conserved in an electrical network—the sum of the powers absorbed by all elements in an electrical network is zero, i. e. $\sum p=0$. Another way of saying of this is that the power supplied in a network is exactly equal to the power absorbed.

Example 1-1 A direct current circuit (DC) is shown in Fig. 1-5, $U_1=5$ V, $U_2=-6$ V, $U_3=8$ V, $I=2$ A. Determine the power consumed or supplied by each element.

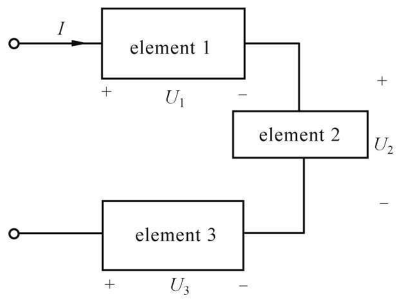


Fig. 1-5 The circuit for Example 1-1

Solution:

The associated reference directions are used on element1 and element 2, so

$$p_{1,\text{absorb}}=U_1I=5\times2=10\ \text{W (absorbing power)}$$

$$p_{2,\text{absorb}}=U_2I=-6\times2=-12\ \text{W (supplying power)}$$

The non-associated reference direction is used on element 3, so

$$p_{3,\text{absorb}}=-U_3I=-8\times2=-16\ \text{W (supplying power)}$$

1. 4 Circuit elements: resistor, independent and dependent sources

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

There are two types of elements found in electric circuits: passive elements and active elements. An active element is capable of producing energy whereas 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 resistor, independent and dependent sources.

1.4.1 Resistor

Resistance is the ability of materials to impede the flow of current or, more specifically, the flow of electric charge. The circuit element used to model this behaviour is the resistor. Conceptually, we can understand resistance by thinking about the moving electrons that make up electric current interacting with and being resisted by the atomic structure of the material through which they are moving. During these interactions, some electrical energy is converted to thermal energy and dissipated in the form of heat. This effect may be undesirable. However, many useful electrical devices take advantage of resistance heating, including stoves, toasters, irons, and space heaters. Fig. 1-6 shows the circuit symbol for the resistor, where R denotes the resistance value of the resistor.

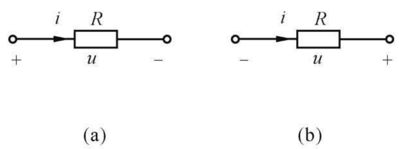


Fig. 1-6 The symbol for a resistor with a resistance *R*

For the purposes of circuit analysis, we need to reference the current across the resistor to the terminal voltage. We can do this in two ways: either using the associated reference direction that the reference direction for the current in an element is in the direction of the reference voltage drop across the element as shown in Fig. 1-6(a), or using the non-associated reference direction that the reference direction for the current in an element is in the direction of the reference voltage rise across the element as shown in Fig. 1-6(b). If we use the associated reference direction, the relationship between the voltage and current is

$$u = Ri \tag{1-3}$$

where u is the voltage in Volts (V), i is the current in Amps (A) and R is the resistance in Ohms (Ω).

If we choose the non-associated reference direction, we have

$$u=-Ri \tag{1-4}$$

where u, i, and R are also measured in Volts, Amps, and Ohms, respectively. Eq. (1-3) and (1-4) are known as Ohm's law after Georg Simon Ohm, a German physicist who established its validity in the early 19th century. Ohm's law is the algebraic relationship between voltage and current across a resistor.

Ohm's law expresses the voltage as a function of the current. However, it is also convenient to express the current as a function of the voltage. Thus, from Eq. (1-3),

$$i=\frac{1}{R}u \tag{1-5}$$

From Eq. (1-4),

$$i=-\frac{1}{R}u \tag{1-6}$$

The reciprocal of the resistance is called conductance. It is symbolized by the letter G and measured in Siemens (S). Thus

$$G=\frac{1}{R} \tag{1-7}$$

For example, a 10 Ω resistor ($R=10\ \Omega$) has a conductance value of 0.1 S ($G=0.1$ S).

A resistor that obeys Ohm's law is known as a linear resistor, which has a constant resistance. Its current-voltage characteristic is as illustrated in Fig. 1-7 when the associated reference directions are used: Its i-u curve is a straight line passing through the origin.

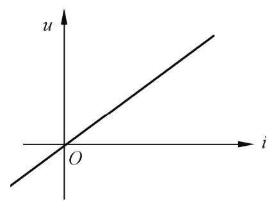


Fig. 1-7 The *i-u* characteristic of a linear resistor

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. For a short circuit, the current could theoretically be any value while $u=Ri=0$, as shown in Fig. 1-8. Similarly, an element with $R=\infty$ is known as an open circuit, as shown in Fig. 1-9. For an open circuit, the current is zero while the voltage can be any value.

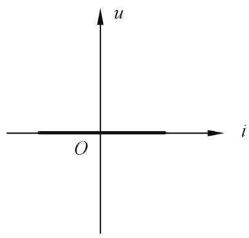


Fig. 1-8 The *i-u* characteristic when $R=0$

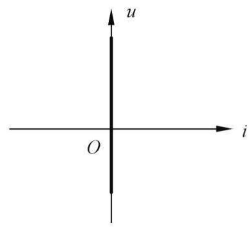


Fig. 1-9 The *i-u* characteristic when $R=\infty$

It should be noted that not all types of resistor obey Ohm's law. Non-linear resistors do not obey Ohm's law and their resistances vary with the current. Examples of nonlinear resistances are the thermistors and the diodes. In fact, all practical resistors exhibit nonlinear behaviour under certain conditions. However, in this book, we will assume that the resistors are linear.

Under associated reference directions, the power dissipated by a resistor can be expressed in terms of R or G as:

$$p=ui=Ri^2=\frac{u^2}{R}=Gu^2=\frac{i^2}{G} \tag{1-8}$$

Since R and G have positive values, the power dissipated by a resistor is always positive. Therefore, a resistor always absorbs power from the circuit.

If we use non-associated reference directions in the calculation, the power dissipated by a resistor is $p=-ui$. Taking into account Ohm's law $u=-Ri$ under non-associated reference directions, the dissipated power $p=-ui=-(-Ri)i=Ri^2$. It is still positive. This confirms the idea that a resistor is a passive element, incapable of generating energy.

The energy absorbed by a resistor from time t_0 to t is

$$W=\int_{t_0}^{t} Ri^2(\xi)\,d\xi \tag{1-9}$$

1.4.2 Independent sources

The most important active elements are voltage or current sources, which generally supply power to the circuit connected to them. There are two types 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.

Independent voltage source: An independent voltage source is a two-terminal element.

The use of an ideal model for independent voltage sources places important constraints on how we describe them mathematically.

(1) It always maintains a specified voltage $u(t)=u_s(t)$ between its terminals regardless of the current flowing through it.

(2) It is impossible to specify the current in an ideal voltage source as a function of its voltage. The current is determined by the rest of the circuit.

Fig. 1-10 shows the symbols for independent voltage sources. Both symbols in Fig. 1-10 (a) and (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. To fully specify an ideal independent voltage source in a circuit, the value of the supplied voltage and the reference polarity must be specified simultaneously. Note that in Fig. 1-10 (b) the terminal with the longer line stands for "+".

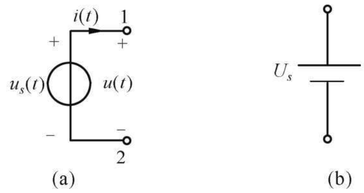


Fig. 1-10 Symbols for independent voltage sources

The i-u characteristic of a DC independent voltage source is shown in Fig. 1-11. It is a straight line parallel to the current axis (horizontal axis). Because the current i flowing through it can be negative or positive, as determined by the external circuit, the independent voltage source is capable of supplying power to, or absorbing power from the external circuit. If it is left open, no current flows through it. The voltage source neither generates nor absorbs power. In its normal mode of operation, independent voltage source supply power to the rest of the circuit. However, they can also be connected into a circuit in such a way that they absorb power. A simple example is a battery charging circuit.

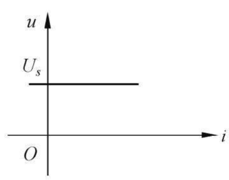


Fig. 1-11 The *i-u* characteristic of a DC independent voltage source

Physical sources such as batteries and generators may be regarded as approximations to ideal voltage sources. However, it is important that we pause here to interject a comment concerning a shortcoming of the model. In general, mathematical models approximate actual physical systems only within a certain range of conditions. Rarely does a model accurately represent a physical system under every set of conditions. To illustrate this point, let us assume that the voltage source delivers u volts regardless of what is connected to its terminals. Theoretically, we could set up an external circuit so that an infinite amount of current would flow. As a result, the voltage source would deliver an infinite amount of power. This is, of course, physically impossible. A similar argument could be made for the independent current source. Therefore, the readers are cautioned to keep in mind that models have limitations and thus are valid representations of physical systems only under certain conditions. An improved model for an actual voltage source is an ideal voltage source U_s in series with a resistor R_s, since the internal resistance of a voltage source cannot be zero, as shown in Fig. 1-12.

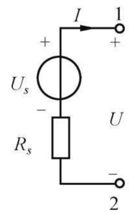


Fig. 1-12 An improved model for an actual voltage source

Independent current source: Similarly, an ideal independent current source is a circuit element that maintains a prescribed current $i(t) = i_s(t)$ through its terminals regardless of the voltage across those terminals. It is also impossible to specify the voltage for an ideal current source as a function of its current, which is determined by the rest of the circuit. Fig. 1-13 (a) shows the symbols for an independent current source.

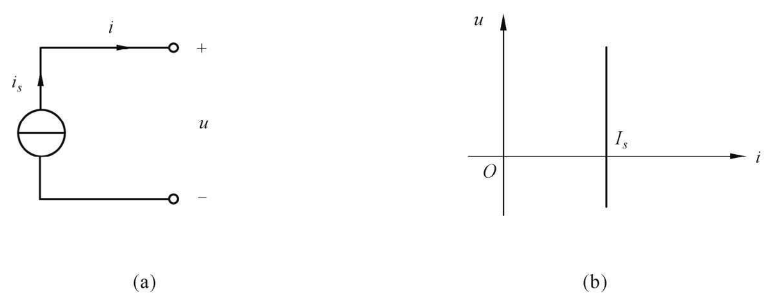


Fig. 1-13 Symbols for independent current sources and the *i-u* characteristic of a DC current source

If the output current $i_s(t) = I_s$ is a constant, this current source is a DC current source. Its