海军工程大学涉外丛书

Fundamentals of Warship Electric Circuits

舰艇电路原理

主　编　单潮龙　钟　斌
副主编　稽　斗　汪小娜　邓　波

WUHAN UNIVERSITY PRESS
武汉大学出版社

海军工程大学涉外丛书

外训系列教材

Fundamentals of Warship Electric Circuits

舰艇电路原理

主　编　单潮龙　钟　斌
副主编　稽　斗　汪小娜　邓　波

WUHAN UNIVERSITY PRESS
武汉大学出版社

图书在版编目(CIP)数据

舰艇电路原理/单潮龙,钟斌主编. —武汉: 武汉大学出版社,2018.1
海军工程大学涉外丛书
ISBN 978-7-307-18912-6

Ⅰ.舰… Ⅱ.①单… ②钟… Ⅲ.军用船—电路—高等学校—教材 Ⅳ.U674.7

中国版本图书馆 CIP 数据核字(2016)第 289074 号

责任编辑:王智梅 胡国民　　责任校对:汪欣怡　　版式设计:马 佳

出版发行: **武汉大学出版社** (430072 武昌 珞珈山)
(电子邮件: cbs22@whu.edu.cn 网址: www.wdp.com.cn)
印刷:虎彩印艺股份有限公司
开本:720×1000 1/16 印张:26 字数:467 千字 插页:1
版次:2018 年 1 月第 1 版 2018 年 1 月第 1 次印刷
ISBN 978-7-307-18912-6 定价:55.00 元

Introduction

This book is written based on the requirement of teaching standards for foreign trainee of NUE. Taking into account the application characteristics of the military institutions and the practical engineering, the main contents are: circuit model and Kirchhoff's laws, circuit system analysis method, resistive circuit equivalent and circuit theorem, sinusoidal AC circuit analysis, coupled inductor circuit analysis, resonant circuit, three-phase circuit, the first-order dynamic circuit, application of Matlab and EWB to analyze the circuit, circuit experiments.

This book can be used as training or undergraduate textbook of military academy in following professions: electrical engineering, electronic engineering, weapons engineering, navigation, communications engineering and computer applications and other profession, it can also be used as undergraduate textbook of other institutions in electronics, computer science, etc. or used by the relevant professional and technical personnel as a réference material.

Preface

This book is written in accord to the requirement of foreign training teaching and curriculum system reform. It is stroked to inherit the tradition, enhance the application and reflect the advancement in the textbook. The book content is characterized by: laying the groundwork on the basic concepts and theoretical system, focusing on the combination of theory and practical application, strengthening application of modern computer-aided analysis software to analyze the circuit. Each chapter contains examples of EWB and Matlab circuit analysis applications that are compatible with the content, it lays the basis for theoretical and methodological learning for practical circuit analysis. This is not only conducive to improving students' interest in learning, to expand their horizons, but also to improve students' ability to analyze problems and solve problems. By solving the problem in the example to show solving ideas, too much text description is removed. In the use of EWB and Matlab for the circuit analysis, in addition to direct analysis of the circuit with EWB, Matlab programming circuit analysis is also introduced through examples, so that students can have a detailed understanding of how the computer circuit analysis, rather than simply use software to solve problems, which is conducive to the cultivation of students' innovative ability.

The structure of the book and the characteristics of the system design are: Chapter 1 discusses the circuit model and Kirchhoff's laws, it lay the foundation for the book. Discussion of resistive circuit is divided into three chapters, Chapter 2 discusses the resistive circuit equivalent simplification, Chapter 3 discusses circuit systematic analysis method, Chapter 4 discusses some important circuit theorems. The analysis and reduction methods discussed in these three chapter are very useful and can be used for next chapters. Discussion of AC circuit is divided into four chapters, that is, Chapter 5 discusses the basic knowledge of sinusoidal AC circuit analysis, Chapter 6 discusses the coupled inductor AC circuit, Chapter 7 discusses the resonant circuit, and Chapter 8 discusses the three-phase circuit. The transition analysis of first-order dynamic circuit will be discussed in chapter 9. The content about experiments are given in appendix.

To help the reader to learn, the beginning of each chapter outlines the contents of the chapter and the main points, each chapter are accompanied by exercise problems, answers of exercise problems are given in appendix of the book.

The book writing is divided into: Shan Chao Long prepared the chapter 1, 2, 3, 4, 9, Wang Xiao Na prepared Chapter 5, Ji Dou prepared the chapter 6, 7, 8, Zhong Bing is responsible for the overall planning, Deng bo prepared appendix and all the exercises. The book Manuscripts is reviewed by Shan Chao Long. Thanks to Professor Wang Jian of Huazhong University of Science and Technology who reviewed the first draft of the book and made a lot of valuable amendments.

In the course of the preparation of this book, we have learned a lot from the experts and scholars of the literature. Professor Wu Zhengguo of the Naval Engineering University had provided many valuable opinions on the preparation of this book.

Due to the limitation of the authors level, there may be some omissions and mistakes in the structure of the book, the arrangement of the system, the choice and narrative of content and other aspects of book. We urge the readers' correction.

Content

Chapter 1　Circuit Model and Kirchhoff's laws ………… 1
1.1　Circuit and Circuit Model ………… 1
1.2　Voltage and Current and Their Reference Direction ………… 5
1.3　Kirchhoff's Laws ………… 8
1.4　Passive Circuit Elements ………… 13
1.5　Active Circuit Elements ………… 23
1.6　Example of Computer-Aided Analysis of Circuits ………… 31
Exercise ………… 33

Chapter 2　Equivalent Resistive Circuits ………… 41
2.1　The Equivalent Circuit of One-Port Network ………… 41
2.2　Equivalent Resistance of Passive One-Port Networks ………… 48
2.3　Delta-to-Wye Equivalent Circuits ………… 58
2.4　Equivalent Simplification of Active One-Port Networks ………… 69
2.5　Equivalent Simplification of Controlled Source Circuit ………… 79
2.6　Example of Computer-Aided Analys of Circuits ………… 83
Problems ………… 85

Chapter 3　Systematic Analysis of Circuits ………… 89
3.1　The Basic Concept of Graph Theory ………… 90
3.2　2b Method and Branch Analysis Method ………… 101
3.3　Loop Analysis and Mesh Analysis ………… 114
3.4　Node Analysis and Modified Node Analysis ………… 126
3.5　Example of Computer-Aided Analysis of Circuits ………… 140
Problems ………… 146

Chapter 4 Circuit Theorems ········ 153
4.1 Superposition Theorem ········ 153
4.2 Substitution Theorem ········ 163
4.3 Thevenin's Theorem and Norton's Theorem ········ 168
4.4 Tellegen's Theorem and Reciprocity Theorem ········ 186
4.5 Computer-Aided Analysis of Circuits ········ 199
Exercise ········ 200

Chapter 5 Sinusoidal Steady-State Analysis ········ 207
5.1 The Basic Concept of Sinusoidal Quantity ········ 207
5.2 Phasor Representation of Sinusoidal Quantity ········ 213
5.3 Kirchhoff's Laws and VCR in Phasor Form ········ 219
5.4 Impedance and Admittance ········ 225
5.5 Analysis of Sinusoidal AC Circuit ········ 234
5.6 Power in Sinusoidal AC Circuit ········ 242
5.7 Examples of Computer-Aided Analysis of Circuits ········ 252
Problems ········ 255

Chapter 6 Magnetically Coupled Circuits ········ 264
6.1 Mutual Inductance and VCR of the Coupled Inductor ········ 264
6.2 Analysis of Coupled Inductor Circuit ········ 273
6.3 Air-Core Transformer and Ideal Transformer ········ 283
6.4 Examples of Computer-Aided Circuit Analysis with Matlab ········ 297
Exercises ········ 298

Chapter 7 Resonant Circuit Analysis ········ 305
7.1 Series Resonant Circuit ········ 305
7.2 Parallel Resonant Circuit ········ 312
7.3 Examples of Computer Aided Circuit Analysis ········ 323
Exercises ········ 326

Chapter 8 Three-Phase Circuits ········ 330
8.1 Balanced Three-Phase Circuits ········ 330

8.2 Unbalanced Three-Phase Circuits ······ 339
8.3 Power of Three-Phase Circuits ······ 344
Exercises ······ 349

Chapter 9 First-Order Circuits ······ 352
9.1 The Basic Concept and Circuit Switching Rule ······ 352
9.2 Zero-Input Response of First-Order Circuit ······ 357
9.3 Zero-State Response of First-Order Circuit ······ 365
9.4 Short-Cut Method for Complete Response of First-Order Circuit ······ 369
9.5 Step Response and Impulse Response of First Order Circuit ······ 373
Exercise ······ 381

Appendix A Experiment ······ 388

Appendix B Reference Answers for Partial Exercises ······ 399

References ······ 407

Chapter 1
Circuit Model and Kirchhoff's laws

This chapter mainly introduces the concept of circuit model, the reference direction of voltage and current, Kirchhoff's laws (including Kirchhoff's current law and Kirchhoff's voltage law) and basic circuit elements (including resistors, inductors, capacitors, voltage sources, current sources, and controlled sources). Circuit model is the object for circuit research. It is required to understand the internal relationship and difference between the actual circuit and circuit model. Voltage and current reference direction is an important concept in circuit analysis. Kirchhoff's laws and elements characteristics of the circuit are the basis of the circuit analysis and should be mastered proficiently.

1.1 Circuit and Circuit Model

1.1.1 Function and Structure of Circuit

An electric circuit consists of several electrical components which are connected with each other, it is the path of the current and is also known as the electric network.

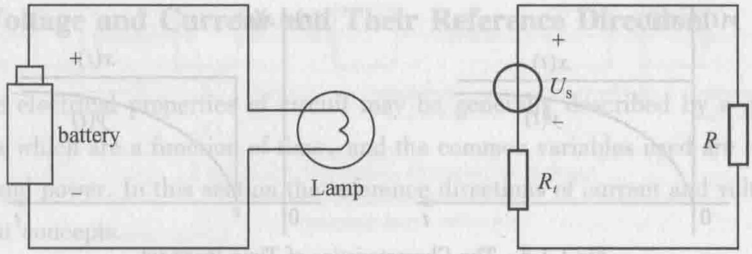
Each circuit has its specific function. Although the shape of the circuit structure and the tasks that can be accomplished are diversified, the functions of circuits can be classified into two categories. One is transmission and conversion of electric power, a typical example is power system. The other is processing and transmission of signal, for examples, temperature measurement, radio, television, etc. Regardless how complicate of the structure, a circuit is divided into three parts: a power source or a signal source, an intermediate link and a load. For the circuit with first kind of function, the power source may be a generator in which other forms of energy is transformed into electrical energy; the load may be a electric motor, lamp or oven in which electrical energy is converted into other forms of energy. The intermediate links is a transmission line or transformer which is used to connect the power source and load, it plays a role of transmission and distribution of electric energy. For the circuit with second kind of function, the signal source may be a galvanic, a receiving antenna in which the information of the temperature or electromagnetic wave are converted to voltage signal, then these signals are transmitted or processed by intermediate link (magnification, the setting, the detection, etc.) to a load (for example, millivoltmeter, speaker, kinescope, etc.) to restore the original messages.

For two kinds of circuit, voltage or current of power supply or signal source are usually called excitements which drives the current to flow in the circuit. The voltage or current in other part of the circuit driven by the excitement are called the responses. Sometimes the excitement is also called the input and the response called the output.

1.1.2 Circuit Model

The circuit consists of practical elements or devices which have different roles, such as resistor, capacitor, coil, switch, generator, transformer, motor, transistor, and so on. Their electromagnetic properties are complicate. To facilitate the circuit analysis and mathematical description, the practical elements are idealized, i.e. under certain conditions, to highlight its main electromagnetic nature, to ignore the secondary factors, they are considered to be the ideal circuit elements (also called components). For example, if the main effect of a device is shown as the electric energy loss, it can be modelled as a resistor. If main effect of a devices is shown as energy storage in magnetic field, it can be modelled as an inductor. If main effect of a device is shown as energy storage in electric field, it can be modelled as a capacitor. So, resistor, capacitor and inductor are ideal elements.

A circuit consisting of ideal circuit elements is called the circuit model of an actual circuit. For example, for the actual circuit of a electric torch, as indicated in Fig.1.1.1a, the battery inside the torch can be modeled as a voltage source in series with a internal resistor, the lamp modeled as a resistor. So, the torch can be modeled as an ideal circuit shown in Fig.1.1.1b.



(a) Actual Circuit (b) Circuit Model

Fig.1.1.1 Actual Circuit and Its Model

1.1.3 The Linear Time-Invariant and Lumping

1.1.3.1 The Linear Circuit

The circuit made up only of linear elements is called linear circuit. Basic characteristic of a linear circuit is additivity and homogeneity, as shown in Fig.1.1.2.

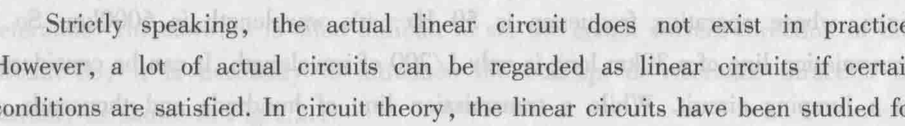


Fig.1.1.2 Description of Additivity and Homogeity

Strictly speaking, the actual linear circuit does not exist in practice. However, a lot of actual circuits can be regarded as linear circuits if certain conditions are satisfied. In circuit theory, the linear circuits have been studied for a long time, there are fine theories and methods that can be used. As an elementary course, we mainly focus on discussing linear circuit.

1.1.3.2 The Time-Invariant Circuit

The component parameters of a circuit does not change with time, is called time-invariant circuit. For this kind of circuit, the characteristic curve of element in y-x plane does not change with time, as illustrated in Fig.1.1.3.

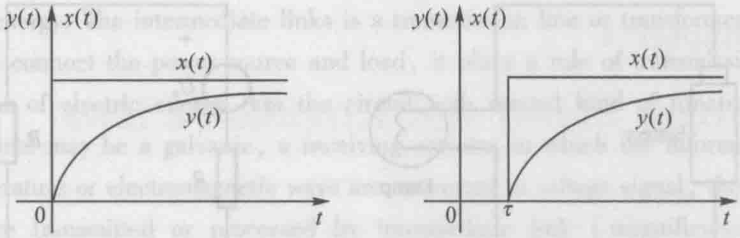


Fig.1.1.3 The Characteristics of Time-Invariant

1.1.3.3 Lumping Circuit

In circuit theory, we mainly study the electromagnetic phenomenon occurred in the circuit. Current, voltage (sometimes using charge, flux) is used to describe the process inside the circuit. Usually, we are only interested in the current through and voltage across the devices. We don't deal with the physical process involving inside the internal devices. This is reasonable only if the circuit is supposed to be a lumping circuit.

If the size of an circuit element is small enough comparing with its operational wavelength, it is called as a lumping element. The circuit consisting of lumping elements is called lumping circuit. The diagram of lumping circuit is made up of ideal wires and circuit elements according to a certain connection rule. The symbol size of circuit elements, the length and shape of the connection in the diagram is not important.

The geometry dimension of real circuits varies considerably. For transmission lines, whose operating frequency is 50 Hz, it's wavelength is 6000km. So a transmission line of a 30km long is only 1/200 of wavelength. It can be considered as a lumping circuit. While a transmission line of hundreds and thousands of kilometers cannot be considered as a lumping circuit.

To sum up, a circuit consisting of time-invariant lumping linear elements and connected by ideal wires is said to be linear time-invariant lumping circuit. This textbook discusses lumping circuits only. Because analysis of non-lumping circuits is complicate and requires to apply the distributing-parameter circuit theory, it will not be discussed in the textbook.

1.2 Voltage and Current and Their Reference Direction

The electrical properties of circuit may be generally described by a group of variables which are a function of time, and the common variables used are current, voltage and power. In this section the reference directions of current and voltage are important concepts.

1.2.1 Current

The amount of charge passing through cross section area of a conductor in the unit of times is defined as current intensity, simply said the current, represented by the symbol i,

$$i=\frac{dq}{dt} \tag{1.2.1}$$

where q is the amount of charge passing through cross section area of the conductor. When the magnitude and the direction of the current does not vary with time, it is called direct current (DC), usually denoted in capital letter I.

In the international system of units (SI), charge is coulomb (C), time is second (s), and current is measured in amperes (A).

Due to the historical reason, the direction of the movement of the positive charge is considered as the actual direction of current. But in specific circuits, the actual direction of current often varies with time. Even if the current does not vary with time, the direction of current in some places of circuit is also difficult to determine. Therefore, it is often difficult to set the actual current direction in the circuit. So, it is necessary to introduce the concept of reference direction of current, as shown in Fig.1.2.1.

The reference direction of current can be selected arbitrarily. It is also known as positive direction and can be indicated with an arrow in the circuit, as shown in Fig.1.2.1. After the reference direction of current is selected, the current becomes an algebraic quantity. If the reference direction of current is same as the real direction, the value of current is positive($i>0$), as shown in Fig.1.2.1a. If the reference direction of current is opposite to the real direction, the value of current is negative($i<0$), as shown in Fig.1.2.1b. Then, with the reference direction and

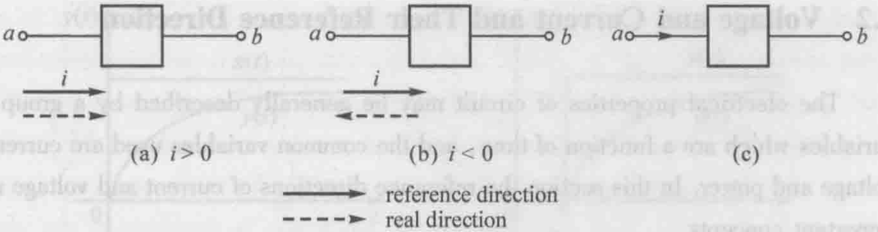


Fig.1.2.1 Reference Direction of the Current

the value of current, the real direction can be determined easily. Obviously, if the reference direction of current is not given, there are not meaning for that current is positive or negative. The reference direction of current is often denoted with an arrow in the wires, as shown in Fig.1.2.1c.

Reference direction of current can also be represented by double subscripts, for example, i_{ab} indicates that reference direction is from a to b. In this textbook, we only mark the reference directions in circuit diagrams, and don't mark the real directions.

1.2.2 Voltage

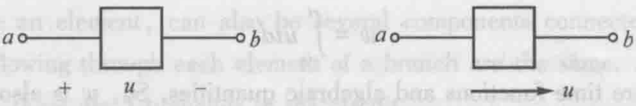
In electric circuit, the work that the electric field does in driving unit positive charge from one point to another point is defined as the voltage between the two points, also known as the potential difference:

$$u = \frac{dw}{dq} \tag{1.2.2}$$

As the same concept of current, when analyzing a circuit, we should define the reference direction or polarity of voltage. The reference polarity of voltage can be defined by using the symbols "+" and "−" in the diagram. We can also be used an arrows to indicate the reference direction of voltage, as shown in Fig.1.2.2.

In the international system of units (SI), the voltage is measured in volt (V).

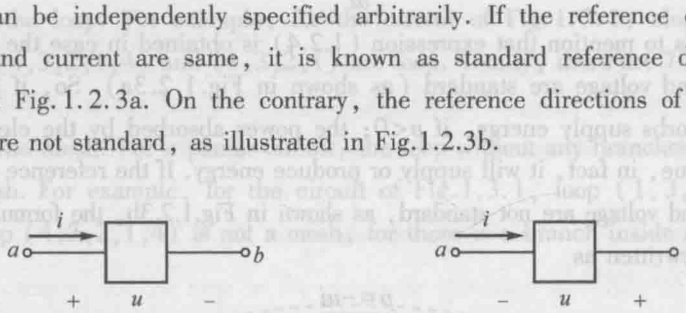
Reference direction of current or voltage plays a very important role in circuit analysis. The current or voltage are algebraic quantity. Both value and sign have their physical significances. The current or voltage that have only value without the reference direction makes no sense.



(a) (b)

Fig.1.2.2 Reference Direction of Voltage

The reference direction of voltage or current of an element or a segment of circuit can be independently specified arbitrarily. If the reference directions of voltage and current are same, it is known as standard reference direction, as shown in Fig. 1. 2. 3a. On the contrary, the reference directions of voltage and current are not standard, as illustrated in Fig.1.2.3b.



(a) Standard Reference Direction (b) Nonstandard Reference Direction

Fig.1.2.3 Reference Direction

1.2.3 Power and Energy

The power are closely related with voltage and current. The movement of positive charge from the positive polarity to the negative polarity of voltage across a circuit element is caused by work done by strength of electric field, and in this case, the element absorbs energy. Conversely, when positive charge moves from the negative polarity to the positive polarity of voltage across circuit element, it is required to do work to the charge with outside force (chemical, electromagnetic force, etc.). In this case, the circuit element supplies energy.

According to the formula (1.2.2), from t_0 to t time, the energy w absorbed by elements is

$$w = \int_{q(t_0)}^{q(t)} u dq$$

Under the condition of the standard reference direction, the energy w

absorbed by elements can be expressed from expression (1.2.1) as

$$w = \int_{t_0}^{t} uidt \tag{1.2.3}$$

where u, i are time functions and algebraic quantities. So, w is also a function of time and algebraic quantity.

The changing rate of energy with respect to the time is called electric power, simply power. Thus, power absorbed by circuit element is

$$p=\frac{dw}{dt}=ui \tag{1.2.4}$$

It needs to mention that expression (1.2.4) is obtained in case the directions of current and voltage are standard (as shown in Fig. 1.2.3a). So, if $p>0$, the element absorbs supply energy, if $p<0$; the power absorbed by the element is a negative value, in fact, it will supply or produce energy. If the reference directions of current and voltage are not standard, as shown in Fig.1.2.3b, the formula (1.2.4) should be rewritten as

$$p=-ui \tag{1.2.5}$$

In this case, if $p>0$, the element absorbs energy, and if $p<0$, the element delivers energy.

In the international system of units (SI), energy is measured in joule (J), power is measured in watt (W).

1.3 Kirchhoff's Laws

The circuit is a whole connected each other by some elements. The currents and the voltages of each element in the circuit are constrained by two types of governing equations. One is the constraints among the currents and among the voltages and they are called topological constraints. Another is the constraints of elements characteristic, i.e., the relationship existing between the currents and the voltages of element itself and it is called element constraint. The former will be discussed in this section and the element restraint will be discussed in next section.

Kirchhoff's laws are important in lumping circuits, they are the cornerstones of the circuit theory. To facilitate the illustration of Kirchhoff's laws, let's introduce some terms of circuits.