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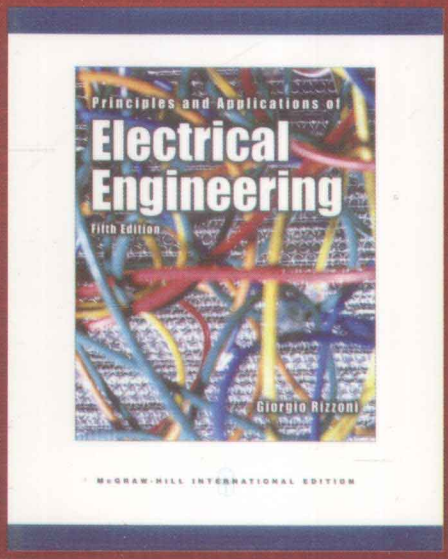

（双语版）

电气工程原理与应用

（第5版）

Principles and Applications of Electrical Engineering

(Fifth Edition)

Giorgio Rizzoni 著

段玉生 选译

清华大学出版社

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About the Author

Giorgio Rizzoni, The Ford Motor Company Chair of ElectroMechanical Systems, received the B.S., M.S., and Ph.D. degrees, all in electrical engineering, from the University of Michigan. He is currently a professor of mechanical and electrical engineering at The Ohio State University, where he teaches undergraduate courses in system dynamics, measurements, and mechatronics and graduate courses in automotive power train modeling and control, hybrid vehicle modeling and control, and system fault diagnosis.

Dr. Rizzoni has been involved in the development of innovative curricula and educational programs throughout his career. At the University of Michigan, he developed a new laboratory and curriculum for the circuits and electronics engineering service course for non-electrical engineering majors. At Ohio State, he has been involved in the development of undergraduate and graduate curricula in mechatronic systems with funding provided, in part, by the National Science Foundation through an interdisciplinary curriculum development grant. The present book has been profoundly influenced by this curriculum development.

Dr. Rizzoni and his colleagues have also developed a unique year-long graduate course sequence titled "Powertrain Modeling and Control" in collaboration with General Motors. This course sequence has been offered to General Motors employees as a series of distance-learning courses and on campus to Ohio State electrical and mechanical engineering students since 1995. In 1998, Dr. Rizzoni and colleagues were awarded funding from the U.S. Department of Energy to establish a *Graduate Automotive Technology Education Center* of excellence on Hybrid Vehicle Drivetrains and Control Systems. This activity has resulted in the development of a graduate curriculum and of research laboratories devoted to the study of hybrid-electric and fuel cell vehicle propulsion technologies.

Since 1999, Dr. Rizzoni has served as director of the Ohio State University Center for Automotive Research, an interdisciplinary research center serving the U.S. government and the automotive industry worldwide. The center conducts research in areas related to vehicle safety, energy efficiency, environmental impact, and passenger comfort. Dr. Rizzoni has published more than 200 papers in peer-reviewed journals and conference proceedings, and he has received a number of recognitions, including a 1991 NSF Presidential Young Investigator Award.

Dr. Rizzoni is a Fellow of IEEE, a Fellow of SAE, and a member of ASME and ASEE; he has served as an Associate Editor of the *ASME Journal of Dynamic Systems, Measurements, and Control* (1993 to 1998) and of the *IEEE Transactions on Vehicular Technology* (1988 to 1998). He has also served as Guest Editor of Special Issues of the *IEEE Transactions on Control System Technology,* of the *IEEE Control Systems Magazine,* and of *Control Engineering Practice;* Dr. Rizzoni is a past Chair of the ASME Dynamic Systems and Control Division, and has served as Chair of the Technical Committee on Automotive Control for the International Federation of Automatic Control (IFAC).

Giorgio Rizzoni is the Ohio State University SAE student branch faculty adviser, and has led teams of electrical and mechanical engineering students through the development of an electric vechicle that established various land speed records in 2003 and 2004. He is also coadviser of the Ohio State University FutureTruck and Challenge-X hybrid-electric vehicle competition teams sponsored by the U.S. Department of Energy, and by General Motors and Ford.

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关 于 作 者

本书作者 Giorgio Rizzoni 是美国福特汽车公司电子机械系统主管，曾在电气工程领域连续获得美国密歇根大学学士、硕士及博士学位。如今，Giorgio Rizzoni 教授在俄亥俄州立大学任教。他讲授的课程有针对本科生的系统动力学，量测技术以及机电一体化和针对研究生的自动能源机车建模及控制，混合动力汽车建模及控制，系统缺陷诊断。

Rizzoni 博士致力于创新课程及教育的研究和发展。就在密歇根大学，他主导了一个创新实验室，并发展了一系列电路电子工程的课程，以供非电类工程专业的学生学习。而在俄亥俄州立大学，他也参与改善了机械电子系统学相关的课程，这些课程面向本科生和研究生，并且作为一个跨学科课程项目，得到了国家自然科学基金会的部分支持。本书也因此受益匪浅。

Rizzoni 博士和他的同事们还与通用汽车公司合作，开发出一系列别具一格的一年制课程，名为“动力机车建模及控制”。从 1995 年起，这些课程就以课堂教学的方式对州立大学电子和机械工程专业的学生开放，同时，也以远程教学的方式对通用公司的员工开放。1998 年，Rizzoni 博士和他的同事们获得来自美国能源部门的资助，用以建立一个研究生汽车技术教育中心，主要研究混合动力汽车及其控制技术。该项目影响巨大，已有许多研究实验室和研究生课程将目光投向混合动力汽车和燃料电池汽车驱动技术的研究当中。

1999 年以来，Rizzoni 博士连任俄亥俄州立大学汽车研究中心主任，这项研究涉及学科交叉，推动了美国本土乃至全世界汽车工业发展。研究中心的主要研究任务有，车辆安全，能源效率，环境影响，以及乘员的舒适性。Rizzoni 博士已在该领域的学术期刊及会议上发表了 200 余篇文章，获得了极高的声誉，其中还包括一项 NSF 总统青年研究员奖励(1991)。

Rizzoni 博士是 IEEE、SAE 会员、ASME 和 ASEE 成员，他还兼任 *ASME Journal of Dynamic System, Measurement, and Control* 期刊副主编（1993—1998）和 *IEEE Transactions on Vehicular Technology* 副主编(1988—1998)。不仅如此，他还兼任 *IEEE Transactions on Control System Technology*(专刊)和 *Control Engineering Practice* 的特约编辑。Rizzoni 博士还参与指导 ASME 动力系统和控制部门，并亲任 IFAC(世界汽车控制联合会)技术委员会主任。

Giorgio Rizzoni 是俄亥俄州立大学 SAE 学生分部技能顾问。他领导的电气机械工程小组，在开发电力驱动的车辆上，创造了 2003 年及 2004 年很多的陆地速度纪录。Rizzoni 博士也是州立大学 FutureTruck 和 Challenge-X 混合动力汽车辆竞赛组的合作顾问，这项比赛是由美国能源部门、通用汽车公司和福特公司共同发起的。

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Preface

The pervasive presence of electronic devices and instrumentation in all aspects of engineering design and analysis is one of the manifestations of the electronic revolution that has characterized the second half of the 20th century. Every aspect of engineering practice, and even of everyday life, has been affected in some way or another by electrical and electronic devices and instruments. Computers are perhaps the most obvious manifestations of this presence. However, many other areas of electrical engineering are also important to the practicing engineer, from mechanical and industrial engineering, to chemical, nuclear, and materials engineering, to the aerospace and astronautical disciplines, to civil and the emerging field of biomedical engineering. Engineers today must be able to communicate effectively within the interdisciplinary teams in which they work.

OBJECTIVES

Engineering education and engineering professional practice have seen some rather profound changes in the past decade. The integration of electronics and computer technologies in all engineering academic disciplines and the emergence of digital electronics and microcomputers as a central element of many engineering products and processes have become a common theme over the nearly 20 years since the conception of this book.

The principal objective of the book is to present the *principles* of electrical, electronic, and electromechanical engineering to an audience composed of non–electrical engineering majors, and ranging from sophomore students in their first required introductory electrical engineering course, to seniors, to first-year graduate students enrolled in more specialized courses in electronics, electromechanics, and mechatronics.

A second objective is to present these principles by focusing on the important results and applications and presenting the students with the most appropriate *analytical and computational tools* to solve a variety of practical problems.

Finally, a third objective of the book is to illustrate, by way of concrete, fully worked examples, a number of relevant *applications* of electrical engineering principles. These examples are drawn from the author's industrial research experience and from ideas contributed by practicing engineers and industrial partners.

The three objectives listed above are met through the use of a number of pedagogical features. The next two sections of this preface describe the organization of the book and the major changes that have been implemented in this fourth edition.

ORGANIZATION AND CONTENT

The book is divided into three parts, devoted to *circuits, electronics, and electromechanics*. Changes in the contents are described next.

Part I: Circuits

The first part of the book remains essentially unchanged, after the significant revisions brought by the fourth edition. The only major change is the addition of approximately 110 new homework problems.

Part: II Electronics

Part II, on electronics, presents some new features in the treatment of transistors. Chapter 10, on bipolar transistors, and Chapter 11, on field-effect transistors, have been significantly reorganized to focus on the use of these devices in simple but useful circuits. Modeling emphasis is limited to large-signal models, which are sufficient for the intended purpose. New examples include the design of simple electric motor drivers and of battery chargers. These two chapters now present a new, uncomplicated, and practical treatment of the analysis and design of simple amplifiers and switching circuits using large-signal models. The revisions were based on a conscious decision to completely eliminate all of the material related to small-signal models of amplifiers. Chapter 12, on power electronics, includes two new examples describing power stage amplifier characteristics. The remainder of the electronics section, Chapters 8 and 9, and 13, 14, and 15, are mostly unchanged, except for the addition of a handful of new application-oriented examples. Nearly 100 new homework problems have been added to Part II.

Part III: Communication Systems

New in the fifth edition is the inclusion of two chapters on communications. These chapters have been added at the request of numerous schools, where it is felt that a modern engineer needs to have exposure to basic principles of communication systems. Chapter 16 is a revised edition of the an analog communications chapter that has been available on the book website since the third edition. The intent of the chapter is to present the basic principles of analog communications systems, leading to a basic understanding of analog AM and FM systems. Chapter 17, courtesy of Dr. Michael Carr, of the Ohio State University ElectroScience Laboratory, introduces the basic principles of digital communications systems. Both chapters focus on applications.

Part IV: Electromechanics

Part IV on Electromechanics has been revised for accuracy and pedagogy, but its contents are largely unchanged. This part has been used for many years by the author as a supplement in a junior-year "System Dynamics" course for mechanical engineers. The chapters include some New examples and approximately 20 new problems.

Instructors will find additional suggestions on the organization of course materials at the book's website **http://www.mhhe.com/rizzoni.** Suggestions and sample curricula from users of the book are welcome!

FEATURES OF THE FIFTH EDITION

Pedagogy

The fifth edition continues to offer all of the time-tested pedagogical features available in the earlier editions.

- **Learning Objectives** offer an overview of key chapter ideas. Each chapter opens with a list of major objectives, and throughout the chapter the learning objective icon indicates targeted references to each objective.

- **Focus on Methodology** sections summarize important methods and procedures for the solution of common problems and assist the student in developing a methodical approach to problem solving.
- **Clearly Illustrated Examples** illustrate relevant applications of electrical engineering principles. The examples are fully integrated with the "Focus on Methodology" material, and each one is organized according to a prescribed set logical steps.
- **Check Your Understanding** exercises follow each example in the text and allow students to confirm their mastery of concepts.
- **Make the Connection** sidebars present analogies to students to help them see the connection of electrical engineering concepts to other engineering disciplines.
- **Focus on Measurements** boxes emphasize the great relevance of electrical engineering to the science and practice of measurements.
- **Find It on the Web** links included throughout the book give students the opportunity to further explore practical engineering applications of the devices and systems that are described in the text.

Supplements

The book includes a wealth of supplements, many available in electronic form. These include

- A **CD-ROM** containing computer-aided example solutions, a list of Web references for further research, device data sheets, Hewlett-Packard Instrumentation examples, and a motor control tutorial.
- A **website** (Online Learning Center) will be updated to provide students and instructors with additional resources for teaching and learning. You can find this site at **http://www.mhhe.com/rizzoni**

Online Learning Center

(http://www.mhhe.com/rizzoni)
Resources on this site include:

For Students:

- **Algorithmic Problems** that allow step-by-step problem-solving using a recursive computational procedure to create an infinite number of problems.
- **Device Data Sheets**
- **Hewlett-Packard Instrumentation Examples**
- A **Motor Control Tutorial,** and more...

For Instructors:

- **PowerPoint presentation slides** of important figures from the text
- **Instructor's Solutions Manual** with complete solutions (for instructors only)
- ***COSMOS*** (Complete Online Solutions Manual Organizing System)
- **MATLAB** Solution files for selected problems

For Instructors and Students:

- ***Find It on the Web links***, which give students the opportunity to explore, in greater depth, practical engineering applications of the devices and systems that are described in the text. In addition, several links to tutorial sites extend the boundaries of the text recnt research developments, late-breaking science and technology news, learning resources, and study guides to help you in your studies and research
- **News feeds** provide current daily news from *The New York Times* and other reliable online news resources related to the topics in the text. While most students and instructors have access to currents news online, these feeds are selected based on the topics presented in each chapter of Rizzoni's text.

ACKNOWLEDGMENTS

This edition of the book requires a special acknowledgment for the effort put forth by my friend Tom Hartley of the University of Akron, who has become a mentor, coach, and inspiration for me throughout this project. Professor Hartley, who is an extraordinary teacher and a devoted user of this book, has been closely involved in the development of the fifth edition by suggesting topics for new examples and exercises, creating new homework problems, providing advice and coaching through all of the revisions, and sometimes just by lifting my spirits. I look forward to many more years of such collaborations.

I would also like to recognize the focused effort of Dr. Michael Carr, of the Ohio State University ElectroScience Laboratory, who is responsible for creating Chapter 17 on Digital Communications. His efforts and the assistance provided by graduate students Adam Margetts and Aditi Kothiyal are very much appreciated.

This book has been critically reviewed by the following people.

- Ravel Ammerman, Colorado School of Mines
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In addition, I would like to thank the many colleagues who have pointed out errors and inconsistencies in the fourth edition. We have gladly accepted all of their suggestions. The following is a a partial list of those who have contributed to improving the accuracy of this book.

- Suresh Kumar R., Amrita School of Engineering, India
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- T. S. Liu, Professor, Chiao Tung University, Taiwan
- Mohan Krishnan, University of Detroit Mercy
- Stephen Deese
- Rony Shahidain
- Jing Sun, University of Michigan

The author is also grateful to Mr. David Mikesell and Mr. Qi Ma, graduate students at Ohio State, for help and advice.

Book prefaces have a way of marking the passage of time. When the first edition of this book was published, the birth of our first child, Alex, was nearing. Each of the following two editions was similarly accompanied by the births of Maria and Michael. Now that we have successfully reached the fifth edition (but only the third child) I am observing that Alex is beginning to understand some of the principles exposed in this book through his passion for the FIRST Lego League and the Lego Mindstorms robots. Through the years, our family continues to be the center of my life, and I am grateful to Kathryn, Alessandro, Maria, and Michael for all their love.

前　言

电子设备和仪器在工程设计与分析领域的各个方面无所不在，是电子技术革命的表现之一，是20世纪后半段的主要特点。工程实践的每个方面，甚至日常生活的方方面面，都或多或少地受到了电工电子设备与仪器的影响。也许，计算机是这方面的最显著的代表。然而，电机工程的其他知识对于应用工程师也是重要的，譬如机械工程、工业工程，还有化学、原子能、材料工程，乃至航空航天学科，以及生物医学工程新兴领域。新时代的工程师必须有能力在其所涉及的学科交叉方面进行有效的沟通。

目标

过去的十年里，工程教育和工程专业实践已经发生了相当深刻的变化。从本书孕育到现在的二十多年里，电子技术和计算机技术的结合，数字电子技术的发展和微型计算机作为许多工程生产过程的中心部件，已经成为所有工程学科中的共同课题。

这本书的首要目标是阐述电工、电子以及机电工程的原理。读者对象是工科非电专业学生，包括正学习基本电气工程课程的大二学生，以及学习电子学、机电工程和机电一体化课程的一年级研究生。

第二个目的是通过集中介绍重要结论和应用来阐述原理，为学生提供最适于解决多种实际问题的分析计算工具。

最后，本书的第三个目的是通过例举完全实用的例子，形象地展示电气工程原理的一系列相关应用。这些例子都来自作者的工程研究经验，应用工程师与我们的业界合作伙伴也有所贡献。

上述三个目的通过一些教学方法糅合在一起。本前言的下面两个部分描述了本书的主要结构以及第四版较之以前的版本的主要变化。

结构和目录

本书分为四部分：电路、电子技术、通信系统、机电系统。目录的变化下面将会谈到。

第一部分：电路

经过第4版的重要修订，本书的这部分基本上没什么变化。唯一算得上大的改变的是增加了约110道习题。

第二部分：电子技术

第二部分讲述电子学，在介绍晶体管时用了一些新的处理方法。第10章，双极性晶体管，第11章，场效应晶体管，经过重新编排，主要集中在介绍这两种器件在简单而实用的电路中的应用。建模重点限于大信号模型，这对于一般目的性的建模已经足够了。新增加的例子包括简单电机驱动器、蓄电池充电器的设计。关于用大信号模型分析、设计简单放大

器和开关电路，这两章阐述了新的、简单实用的处理方式。我们有意决定去掉所有与小信号放大器模型有关的材料，基于此，对此部分内容进行了修订。第 12 章，讲述功率电子学，包含了两个描述了功率放大器的特性的新例子。电子学部分的其他章节——第 8、9、13、14、15 章，大部分未做改动，除了增加了一些面向实际的例子。另外，本部分大约增添了 100 道习题。

第三部分：通信系统

通信方面的两章内容是第 5 版新添加进来的。很多学校要求加入关于通信的内容，他们认为一个现代的工程师，迫切需要了解通信系统的基本原理。从第 3 版开始，在本书的网站上就有与模拟通信相关的章节，而本书第 16 章，正是这些内容的修订版本。这一章的目的就是阐述模拟通信系统的基本原理，让读者对于调幅和调频系统有基本的理解。第 18 章，介绍了数字通信系统的基本原理。感谢俄亥俄州立大学电子科学技术实验室的 Michael Carr 博士协助编写这部分。第 16、17 章都着眼于应用。

第四部分：机电系统

为了使机电一体化部分更为严谨和适合教学需要，对其进行了修订，不过这部分的目录大部分没有改变。作为机械工程高年级学生“系统动力学”的补充读物，这部分内容作者已经使用了很多年。这其中的章节包括了新例子以及约 20 道新习题。

在本书网站（http：//www. mhhe. com/rizzoni），教师可以找到有关教学材料编排的额外建议。欢迎本书的使用者提出建议和教学样本。

第 5 版特色

教学

第 5 版延续了以往版本的经受了时间考验的教学特色。

学习目标 提纲挈领地指出了章节重点。每章开篇列出主要目标，贯穿整章，**“学习目标”**的图标指明了每个目标的主旨所在。

侧重方法 章节总结了共同问题的重要解决方法及其过程，并帮助学生制定一个有条理的办法解决问题。

清晰阐述的例子 阐述了电气工程原理的相关应用。这些例子是和**“侧重方法”**的材料完全综合的，并且每个例子都是根据一套合乎逻辑的步骤来组织的。

检查你的理解 课本中每个例子后面的练习能让学生加强他们掌握的概念。

建立联系 侧边栏向学生们显示了一些类比，帮助他们明白电气工程原理和其他工程学科的联系。

注重测量 方框强调了电子工程和测量科学与实践的重大联系。

网站查询 贯穿于全书的链接可以让学生对于本书描述的设备和系统的实际工程应用有更进一步的探索。

补充

这本书包含了丰富的补充内容，许多以电子形式提供。

- 一张包括了计算机辅助例题解答的光盘，一份提供进一步研究的网络参考列表，器件数据表格，Hewlett-Packard 测量仪器例子，一份电动机控制教程。
- 网站（在线学习中心）将及时更新，并为学生和教师的学习和教学提供额外的资源。网站地址：http：//www. mhhe. com/rizzoni。

在线学习中心

http：//www. mhhe. com/rizzoni
这个网站的资源包括：

对于学生：

- 算法问题　使用递归计算一步一步解决问题，并创造无限的若干问题。
- 设备数据表格。
- Hewlett-Packard 测量仪器例子。
- 一份电动机控制教程，还有更多……。

对于教师：

- 含有课本重要图表的 PPT 演示文稿幻灯片。
- 附有完全解答的教师答案手册（仅提供给教师）。
- COSMOS（完全在线答案手册组织系统）。
- 对于一些精选问题的 MATLAB 求解文件。

对于教师和学生：

- 网站链接　提供给学生进一步探索本书描述的设备和系统的实际工程应用的机会。此外，几个教程网站的链接扩展了本书内容，最新的研究发展，科学技术的最新突破的新闻，学习资源，还有学习指导，都可以在学习和研究方面帮助你。
- 新闻供稿　提供了选自 *The New York Times* 的每日新闻及其他相关网站上的新闻，这些新闻是与本书内容相关的一些话题。尽管大多数学生和老师能够在网上看到时事新闻，但这些供稿是基于本书每一章节的话题而精选的。

致谢

本版本需要特别感谢我的阿克伦大学的朋友 Tom Hartley 付出的努力，在出版的整个过程中，对于我而言，他既是良师益友，也是我的灵感来源。Hartley 教授是这本书的一位非同寻常的老师，也是一位忠实的读者。在第 5 版的编写过程中，他一直给予密切的关注，并且提议了一些新例题和练习，以及一些新的作业，还提供了很多宝贵的意见和指导，有时还给了我很多鼓励。我期待这样的合作能多年持续下去。

我也要指出俄亥俄州立大学电子科学实验室的 Michael Carr 博士的精心努力，他负责编写了第 17 章的数字通信部分。对于他的努力，以及研究生 Adam Margetts 和 Aditi Kothiyal 的帮助，我深表谢意。

这本书已被如下人士严格审查：

- Ravel Ammerman，Colorado School of Mines
- Glen Archer，Michigan Technological University
- Ray Bellem，Embry-Riddle Aeronautical University
- Keith Burgers，University of Arkansas

- Doroteo Chaverria, University of Texas—San Antonio
- Randy Collins, Clemson University
- Marcelo J. Dapino, The Ohio State University
- Alexandros Eleftheriadis, Colunmbia University
- Otto M. Friedrich, University of Texas—Austin
- Takis Kasparis, University Central Florida
- Rasool Kenarangui, University of Texas—Arlington
- Andy Mayers, Penn State University
- Nathan Shenck, U. S. Naval Academy
- B. J. Shrestha, University of Missouri—Rolla
- Miklos N. Sziagyi, University of Arizona
- Albert H. Titus, SUNY Buffalo
- Trac D. Tran, Johns Hopkins University

此外，我要感谢许多帮我指出第4版中错误的同事。我们欣然接受了他们所有的建议。他们的建议使得本书避免了很多错误，在此，我仅将部分名单列出：

- Suresh Kumar R. , Amrita School of Engineering, India
- Thomas Schubert, University of San Diego
- T. S. Liu, Professor, Chiao Tung University, Taiwan
- Mohan Krishnan, University of Detroit Mercy
- Stephen Deese
- Rony Shahidain
- Jing Sun, University of Michigan

作者对于俄亥俄州立大学研究生 Mr. David Mikesell 以及 Mr. Qi Ma 提供的帮助和意见同样深表感谢。

书的前言是一种标明时间推移的方式。当此书的第1版出版时，我的第一个孩子 Alex 也即将出生。紧接着的两版也似乎同样巧合地伴随着 Maria 和 Michael 的出生。现在我们已经成功地出版了第5版(但是只有三个孩子)，我观察到 Alex 正开始明白这本书揭示的一些原理，因为他对于 FIRST Lego League 和 the Lego Mindstorms 机器人充满了热情。这些年来，家庭一直是我的生活中心，对于 Kathryn, Alessandro, Maria 和 Michael 给予我的爱，我深深感激。

GUIDED TOUR

Learning Objectives offer an overview of key chapter ideas. Each chapter opens with a list of major objectives and throughout the chapter. The learning objective icon indicates targeted references to each objective.

Learning Objectives

1. Compute the solution of circuits containing linear resistors and independent and dependent sources by using *node analysis. Sections 3.2 and 3.4.*
2. Compute the solution of circuits containing linear resistors and independent and dependent sources by using *mesh analysis. Sections 3.3 and 3.4.*
3. Apply the *principle of superposition* to linear circuits containing independent sources. *Section 3.5.*
4. Compute *Thévenin and Norton equivalent circuits* for networks containing linear resistors and independent and dependent sources. *Section 3.6.*
5. Use equivalent-circuit ideas to compute the *maximum power transfer* between a source and a load. *Section 3.7.*
6. Use the concept of equivalent circuit to determine voltage, current, and power for nonlinear loads by using *load-line analysis* and analytical methods. *Section 3.8.*

3.1 Network Analysis

The analysis of an electric network consists of determining each of the unknown branch currents and node voltages. It is therefore important to define all the relevant variables as clearly as possible, and in systematic fashion. Once the known and unknown variables have been identified, a set of equations relating these variables is constructed, and these equations are solved by means of suitable techniques. The analysis of electric circuits consists of writing the smallest set of equations sufficient to solve for all the unknown variables. The procedures required to write these equations are the subject of Chapter 3 and are very well documented and codified in the form of simple rules. The analysis of electric circuits is greatly simplified if some standard conventions are followed.

Example 3.1 defines all the voltages and currents that are associated with a

Focus on Methodology section summarize important methods and procedures for the solution of common problems and assist the student in developing a methodical approach to problem solving.

FOCUS ON METHODOLOGY

COMPUTING THE THÉVENIN VOLTAGE

1. Remove the load, leaving the load terminals open-circuited.
2. Define the open-circuit voltage v_{OC} across the open load terminals.
3. Apply any preferred method (e.g., node analysis) to solve for v_{OC}.
4. The Thévenin voltage is $v_T = v_{OC}$.

The actual computation of the open-circuit voltage is best illustrated by e ples; there is no substitute for practice in becoming familiar with these computa To summarize the main points in the computation of open-circuit voltages, cor the circuit of Figure 3.36, shown again in Figure 3.44 for convenience. Recall th equivalent resistance of this circuit was given by $R_T = R_3 + R_1 \parallel R_2$. To con v_{OC}, we disconnect the load, as shown in Figure 3.45, and immediately observ no current flows through R_3, since there is no closed-circuit connection at that br Therefore, v_{OC} must be equal to the voltage across R_2, as illustrated in Figure Since the only closed circuit is the mesh consisting of v_S, R_1, and R_2, the answ are seeking may be obtained by means of a simple voltage divider:

$$v_{OC} = v_{R2} = v_S \frac{R_2}{R_1 + R_2}$$

It is instructive to review the basic concepts outlined in the example by sidering the original circuit and its Thévenin equivalent side by side, as sho Figure 3.47. The two circuits of Figure 3.47 are equivalent in the sense that th

EXAMPLE 3.8 Mesh Analysis

LO2

Problem

Write the mesh current equations for the circuit of Figure 3.19.

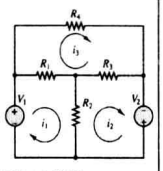


Figure 3.19

Solution

Known Quantities: Source voltages; resistor values.

Find: Mesh current equations.

Schematics, Diagrams, Circuits, and Given Data: $V_1 = 12$ V; $V_2 = 6$ V; $R_1 = 3\ \Omega$; $R_2 = 8\ \Omega$; $R_3 = 6\ \Omega$; $R_4 = 4\ \Omega$.

Analysis: We follow the Focus on Methodology steps.

1. Assume clockwise mesh currents i_1, i_2, and i_3.
2. We recognize three independent variables, since there are no current sources. Starting from mesh 1, we apply KVL to obtain

$$V_1 - R_1(i_1 - i_3) - R_2(i_1 - i_2) = 0$$

KVL applied to mesh 2 yields

$$-R_2(i_2 - i_1) - R_3(i_2 - i_3) + V_2 = 0$$

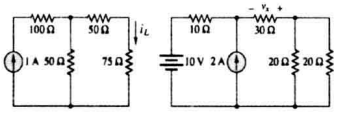
while in mesh 3 we find

$$-R_1(i_3 - i_1) - R_4 i_3 - R_3(i_3 - i_2) = 0$$

Clearly Illustrated Examples illustrate relevant applications of electrical engineering principles. The examples are fully integrated with the "Focus of Methodology" material, and each one is organized according to a prescribed set of common sense steps.

CHECK YOUR UNDERSTANDING

Find the current i_L in the circuit shown on the left, using the node voltage method.



Find the voltage v_x by the node voltage method for the circuit shown on the right.
Show that the answer to Example 3.3 is correct by applying KCL at one or more nodes.

Answers: 0.2857 A; −18 V

Check Your Understanding exercises follow each example in the text and allow students to confirm their mastery of concepts.

EXAMPLE 3.5

LO1

Problem

Use the node voltage analysis to determine the voltage v in the circuit of Figure 3.9. Assume that $R_1 = 2\ \Omega$, $R_2 = 1\ \Omega$, $R_3 = 4\ \Omega$, $R_4 = 3\ \Omega$, $I_1 = 2$ A, and $I_2 = 3$ A.

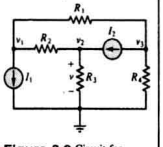


Figure 3.9 Circuit for Example 3.5

Solution

Known Quantities: Values of the resistors and the current sources.

Find: Voltage across R_3.

Analysis: Once again, we follow the steps outlined in the Focus on Methodology box.

1. The reference node is denoted in Figure 3.9.
2. Next, we define the three node voltages v_1, v_2, v_3, as shown in Figure 3.9.
3. Apply KCL at each of the $n - 1$ nodes, expressing each current in terms of the adjacent node voltages.

$$\frac{v_3 - v_1}{R_1} + \frac{v_2 - v_1}{R_2} - I_1 = 0 \quad \text{node 1}$$

$$\frac{v_1 - v_2}{R_2} - \frac{v_2}{R_3} + I_2 = 0 \quad \text{node 2}$$

$$\frac{v_1 - v_3}{R_1} - \frac{v_3}{R_4} - I_2 = 0 \quad \text{node 3}$$

Make the Connection sidebars present analogies to students to help them see the connection of electrical engineering concepts to other engineering disciplines.

equations obtained at nodes a and b (verify this, as an exercise). This observation confirms the statement made earlier:

LO1 **In a circuit containing n nodes, we can write at most $n - 1$ independent equations.**

Now, in applying the node voltage method, the currents i_1, i_2, and i_3 are expressed as functions of v_a, v_b, and v_c, the independent variables. Ohm's law requires that i_1, for example, be given by

$$i_1 = \frac{v_a - v_c}{R_1} \tag{3.5}$$

since it is the potential difference $v_a - v_c$ across R_1 that causes current i_1 to flow from node a to node c. Similarly,

$$i_2 = \frac{v_a - v_b}{R_2}$$
$$i_3 = \frac{v_b - v_c}{R_3} \tag{3.6}$$

Substituting the expression for the three currents in the nodal equations (equations 3.2 and 3.3), we obtain the following relationships:

$$i_S - \frac{v_a}{R_1} - \frac{v_a - v_b}{R_2} = 0 \tag{3.7}$$

$$\frac{v_a - v_b}{R_2} - \frac{v_b}{R_3} = 0 \tag{3.8}$$

Equations 3.7 and 3.8 may be obtained directly from the circuit, with a little practice. Note that these equations may be solved for v_a and v_b, assuming that i_S, R_1, R_2, and R_3 are known. The same equations may be reformulated as follows:

$$\left(\frac{1}{R_1} + \frac{1}{R_2}\right) v_a + \left(-\frac{1}{R_2}\right) v_b = i_S$$
$$\left(-\frac{1}{R_2}\right) v_a + \left(\frac{1}{R_2} + \frac{1}{R_3}\right) v_b = 0 \tag{3.9}$$

Examples 3.2 through 3.4 further illustrate the application of the method.

Thermal Circuit Model

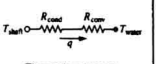
The *conduction resistance* of the shaft is described by the following equation:

$$q = \frac{kA_1}{L}\Delta T$$
$$R_{cond} = \frac{\Delta T}{q} = \frac{L}{kA_1}$$

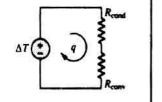
where A_1 is a cross sectional area and L is the distance from the inner core to the surface. The convection resistance is described by a similar equation, in which convective heat flow is described by the film coefficient of heat transfer, h:

$$q = hA_2\Delta T$$
$$R_{conv} = \frac{\Delta T}{q} = \frac{1}{hA_2}$$

where A_2 is the surface area of the shaft in contact with the water. The equivalent thermal resistance and the overall circuit model of the crankshaft quenching process are shown in the figures below.



Thermal resistance representation of quenching process

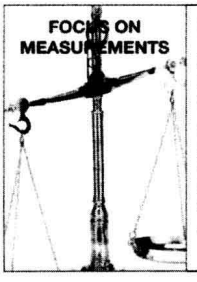


Electrical circuit representing the quenching process

LO1 **EXAMPLE 3.2 Node Analysis**

Problem

Solve for all unknown currents and voltages in the circuit of Figure 3.5.



Experimental Determination of Thévenin Equivalent Circuit

Problem:

Determine the Thévenin equivalent of an unknown circuit from measurements of open-circuit voltage and short-circuit current.

Solution:

***Known Quantities*—Measurement of short-circuit current and open-circuit voltage. Internal resistance of measuring instrument.**

***Find*—Equivalent resistance R_T; Thévenin voltage $v_T = v_{OC}$.**

***Schematics, Diagrams, Circuits, and Given Data*—Measured $v_{OC} = 6.5$ V; measured $i_{SC} = 3.75$ mA; $r_m = 15\ \Omega$.**

(Continued)

Focus on Measurements boxes emphasize the great relevance of electrical engineering to the science and practice of measurements.

Network connected for measurement of open-circuit voltage (ideal voltmeter)

Figure 3.68

***Comments*—Note how easy the experimental method is, provided we are careful to account for the internal resistance of the measuring instruments.**

Find it on the web links included throughout the book give students the opportunity to further explore practical engineering applications of the devices and systems that are described in the text.

One last comment is in order concerning the practical measurement of the internal resistance of a network. In most cases, it is not advisable to actually short-circuit a network by inserting a series ammeter as shown in Figure 3.67; permanent