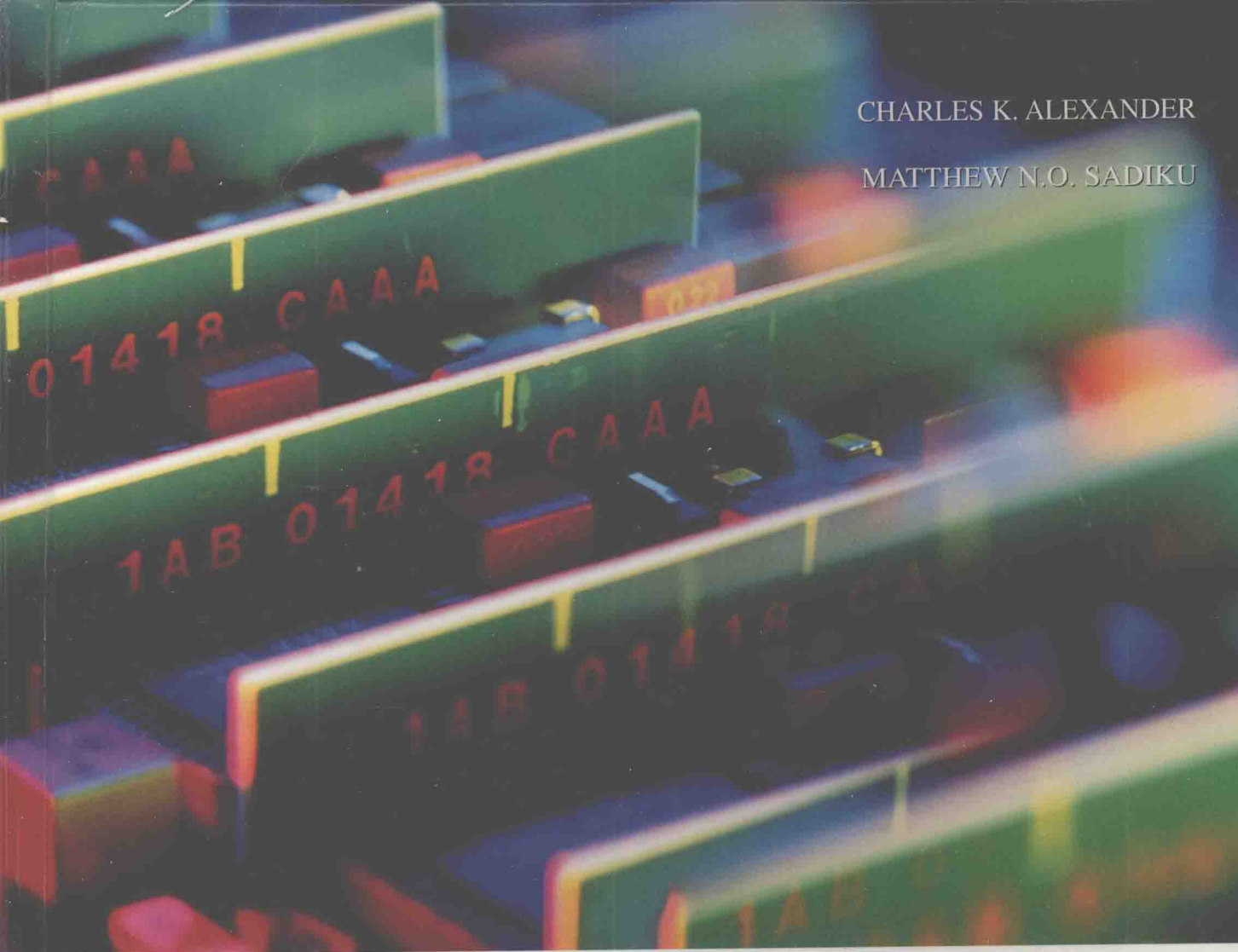


CHARLES K. ALEXANDER

MATTHEW N.O. SADIKU



F U N D A M E N T A L S O F

# ELECTRIC CIRCUITS

CD INCLUDED



---

# Fundamentals of

# ELECTRIC CIRCUITS

**CHARLES K. ALEXANDER**

*School of Electrical Engineering  
and Computer Science*

Ohio University

**MATTHEW N. O. SADIKU**

*Department of Electrical  
and Computer Engineering*

Temple University



Boston Burr Ridge, IL Dubuque, IA Madison, WI New York San Francisco St. Louis  
Bangkok Bogotá Caracas Lisbon London Madrid  
Mexico City Milan New Delhi Seoul Singapore Sidney Taipei Toronto

*We Dedicate This to Our Loving Families*

---

**McGraw-Hill Higher Education**   
A Division of The McGraw-Hill Companies

FUNDAMENTALS OF ELECTRIC CIRCUITS

Copyright © 2000 by The McGraw-Hill Companies, Inc. All rights reserved. Printed in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a data base or retrieval system, without the prior written permission of the publisher.

This book is printed on acid-free paper.

ISBN 0-256-25379-X

6 7 8 9 0 DOW/DOW 9 0 9 8 7 6 5 4 3 2

Vice president/Editor-in-Chief: *Kevin T. Kane*  
Publisher: *Thomas Casson*  
Executive editor: *Elizabeth A. Jones*  
Sponsoring editor: *Catherine Fields*  
Senior developmental editor: *Kelley Butcher*  
Marketing manager: *John T. Wannemacher*  
Project manager: *Kimberly D. Hooker*  
Senior production supervisor: *Heather D. Burbridge*  
Designer: *Jamie O'Neal*  
Cover image: *Frank Orel* © *Tony Stone Images*  
Photo research coordinator: *Sharon Miller*  
Photo researcher: *Judy Kausal*  
Supplement coordinator: *Marc Mattson*  
Compositor: *Techsetters, Inc.*  
Typeface: *10/12 Times Roman*  
Printer: *R. R. Donnelley & Sons Company*

**Library of Congress Cataloging-in-Publication Data**

Alexander, Charles K.

Fundamentals of electric circuits / Charles K. Alexander, Matthew  
N. O. Sadiku.

p. cm.

ISBN 0-256-25379-X

1. Electric circuits. I. Sadiku, Matthew N. O. II. Title.

TK454.A452 2000

621.319'24—dc21

98-55323

<http://www.mhhe.com>

## Features

In spite of the numerous textbooks on circuit analysis available in the market, students often find the course difficult to learn. The main objective of this book is to present circuit analysis in a manner that is clearer, more interesting, and easier to understand than earlier texts. This objective is achieved in the following ways:

- A course in circuit analysis is perhaps the first exposure students have to electrical engineering. We have included several features to help students feel at home with the subject. Each chapter opens with either a historical profile of some electrical engineering pioneers to be mentioned in the chapter or a career discussion on a subdiscipline of electrical engineering. An introduction links the chapter with the previous chapters and states the chapter's objectives. The chapter ends with a summary of the key points and formulas.
- All principles are presented in a lucid, logical, step-by-step manner. We try to avoid wordiness and superfluous detail that could hide concepts and impede understanding the material.
- Important formulas are boxed as a means of helping students sort what is essential from what is not; and to ensure that students clearly get the gist of the matter, key terms are defined and highlighted.
- Marginal notes are used as a pedagogical aid. They serve multiple uses—hints, cross-references, more exposition, warnings, reminders, common mistakes, and problem-solving insights.
- Thoroughly worked examples are liberally given at the end of every section. The examples are regarded as part of the text and are explained clearly, without asking the reader to fill in missing steps. Thoroughly worked examples give students a good understanding of the solution and the confidence to solve problems themselves. Some of the problems are solved in two or three ways to facilitate an understanding and comparison of different approaches.
- To give students practice opportunity, each illustrative example is immediately followed by a practice problem with the answer. The students can follow the example step-by-step to solve the practice problem without flipping pages or searching the end of the book for answers. The practice prob-

lem is also intended to test students' understanding of the preceding example. It will reinforce their grasp of the material before moving to the next section.

- In recognition of ABET's requirement on integrating computer tools, the use of *PSpice* is encouraged in a student-friendly manner. Since the Windows version of *PSpice* is becoming popular, it is used instead of the MS-DOS version. *PSpice* is covered early so that students can use it throughout the text. Appendix D serves as a tutorial on *PSpice for Windows*.
- The operational amplifier (op amp) as a basic element is introduced early in the text.
- To ease the transition between the circuit course and signals/systems courses, Fourier and Laplace transforms are covered lucidly and thoroughly.
- The last section in each chapter is devoted to applications of the concepts covered in the chapter. Each chapter has at least one or two practical problems or devices. This helps students apply the concepts to real-life situations.
- Ten multiple-choice review questions are provided at the end of each chapter, with answers. These are intended to cover the little "tricks" that the examples and end-of-chapter problems may not cover. They serve as a self-test device and help students determine how well they have mastered the chapter.

## Organization

This book was written for a two-semester or three-semester course in linear circuit analysis. The book may also be used for a one-semester course by a proper selection of chapters and sections. It is broadly divided into three parts.

- Part 1, consisting of Chapters 1 to 8, is devoted to dc circuits. It covers the fundamental laws and theorems, circuit techniques, passive and active elements.
- Part 2, consisting of Chapters 9 to 14, deals with ac circuits. It introduces phasors, sinusoidal steady-state analysis, ac power, rms values, three-phase systems, and frequency response.
- Part 3, consisting of Chapters 15 to 18, is devoted to advanced techniques for network analysis. It provides a solid introduction to the Laplace transform, Fourier series, the Fourier transform, and two-port network analysis.

The material in three parts is more than sufficient for a two-semester course, so that the instructor

must select which chapters/sections to cover. Sections marked with the dagger sign (†) may be skipped, explained briefly, or assigned as homework. They can be omitted without loss of continuity. Each chapter has plenty of problems, grouped according to the sections of the related material, and so diverse that the instructor can choose some as examples and assign some as homework. More difficult problems are marked with a star (\*). Comprehensive problems appear last; they are mostly applications problems that require multiple skills from that particular chapter.

The book is as self-contained as possible. At the end of the book are some appendixes that review solutions of linear equations, complex numbers, mathematical formulas, a tutorial on *PSPICE for Windows*, and answers to odd-numbered problems. Answers to all the problems are in the solutions manual, which is available from the publisher.

### Prerequisites

As with most introductory circuit courses, the main prerequisites are physics and calculus. Although familiarity with complex numbers is helpful in the later part of the book, it is not required.

### Supplements

**Solutions Manual**—an Instructor’s Solutions Manual is available to instructors who adopt the text. It contains complete solutions to all the end-of-chapter problems.  
**Transparency Masters**—over 200 important figures are available as transparency masters for use as overheads.

**Student CD-ROM**—100 circuit files from the book are presented as *Electronics Workbench* (EWB) files; 15–20 of these files are accessible using the free demo of *Electronics Workbench*. The students are able to experiment with the files. For those who wish to fully unlock all 100 circuit files, EWB’s full version may be purchased from Interactive Image Technologies for approximately \$79.00. The CD-ROM also contains a selection of problem-solving, analysis and design tutorials, designed to further support important concepts in the text.

**Problem-Solving Workbook**—a paperback workbook is for sale to students who wish to practice their problem solving techniques. The workbook contains a discussion of problem solving strategies and 150 additional problems with complete solutions provided.

**Online Learning Center (OLC)**—the Web site for the book will serve as an online learning center for students and as a useful resource for instructors. The OLC

will provide access to:

- 300 test questions—for instructors only
- Downloadable figures for overhead presentations—for instructors only
- Solutions manual—for instructors only
- Web links to useful sites
- Sample pages from the Problem-Solving Workbook
- PageOut Lite—a service provided to adopters who want to create their own Web site. In just a few minutes, instructors can change the course syllabus into a Web site using PageOut Lite.

The URL for the web site is [www.mhhe.com.alexander](http://www.mhhe.com.alexander). Although the textbook is meant to be self-explanatory and act as a tutor for the student, the personal contact involved in teaching is not to be forgotten. The book and supplements are intended to supply the instructor with all the pedagogical tools necessary to effectively present the material.

## ACKNOWLEDGMENTS

We wish to take the opportunity to thank the staff of McGraw-Hill for their commitment and hard work: Lynn Cox, Senior Editor; Scott Isenberg, Senior Sponsoring Editor; Kelley Butcher, Senior Developmental Editor; Betsy Jones, Executive Editor; Catherine Fields, Sponsoring Editor; Kimberly Hooker, Project Manager; and Michelle Flomenhoft, Editorial Assistant. They got numerous reviews, kept the book on track, and helped in many ways. We really appreciate their inputs. We are greatly in debt to Richard Mickey for taking the pain of checking and correcting the entire manuscript. We wish to record our thanks to Steven Durbin at Florida State University and Daniel Moore at Rose Hulman Institute of Technology for serving as accuracy checkers of examples, practice problems, and end-of-chapter problems. We wish also to thank the following reviewers for their constructive criticisms and helpful comments.

Promod Vohra, *Northern Illinois University*

Moe Wasserman, *Boston University*

Robert J. Krueger, *University of Wisconsin  
Milwaukee*

John O’Malley, *University of Florida*

Aniruddha Datta, *Texas A&M University*  
John Bay, *Virginia Tech*  
Wilhelm Eggimann, *Worcester Polytechnic  
Institute*  
A. B. Bonds, *Vanderbilt University*  
Tommy Williamson, *University of Dayton*  
Cynthia Finelli, *Kettering University*  
John A. Fleming, *Texas A&M University*  
Roger Conant, *University of Illinois  
at Chicago*  
Daniel J. Moore, *Rose-Hulman Institute of  
Technology*  
Ralph A. Kinney, *Louisiana State University*  
Cecilia Townsend, *North Carolina State  
University*  
Charles B. Smith, *University of Mississippi*  
H. Roland Zapp, *Michigan State University*  
Stephen M. Phillips, *Case Western University*  
Robin N. Strickland, *University of Arizona*  
David N. Cowling, *Louisiana State University*  
Jean-Pierre R. Bayard, *California State  
University*

Jack C. Lee, *University of Texas at Austin*  
E. L. Gerber, *Drexel University*

The first author wishes to express his appreciation to his department chair, Dr. Dennis Irwin, for his outstanding support. In addition, he is extremely grateful to Suzanne Vazzano for her help with the solutions manual.

The second author is indebted to Dr. Cynthia Hirtzel, the former dean of the college of engineering at Temple University, and Drs. Brian Butz, Richard Klafter, and John Helferty, his departmental chairpersons at different periods, for their encouragement while working on the manuscript. The secretarial support provided by Michelle Ayers and Carol Dahlberg is gratefully appreciated. Special thanks are due to Ann Sadiku, Mario Valenti, Raymond Garcia, Leke and Tolu Efuwape, and Ope Ola for helping in various ways. Finally, we owe the greatest debt to our families, without whose constant support and cooperation this project would have been impossible.

Please address comments and corrections to the publisher.

**C. K. Alexander and M. N. O. Sadiku**

## A NOTE TO THE STUDENT

---

This may be your first course in electrical engineering. Although electrical engineering is an exciting and challenging discipline, the course may intimidate you. This book was written to prevent that. A good textbook and a good professor are an advantage—but you are the one who does the learning. If you keep the following ideas in mind, you will do very well in the course.

- This course is the foundation on which most other courses in the electrical engineering curriculum rest. For this reason, put in as much effort as you can. Study the course regularly.
- Problem solving is an essential part of the learning process. Solve as many problems as you can. Begin by solving the practice problem following each example, and then proceed to the end-of-chapter problems. The best way to learn is to solve a lot of problems. An asterisk in front of a problem indicates a challenging problem.
- *Spice*, a computer circuit analysis program, is used throughout the textbook. *PSpice*, the personal computer version of *Spice*, is the popular standard circuit analysis program at most uni-

versities. *PSpice for Windows* is described in Appendix D. Make an effort to learn *PSpice*, because you can check any circuit problem with *PSpice* and be sure you are handing in a correct problem solution.

- Each chapter ends with a section on how the material covered in the chapter can be applied to real-life situations. The concepts in this section may be new and advanced to you. No doubt, you will learn more of the details in other courses. We are mainly interested in gaining a general familiarity with these ideas.
- Attempt the review questions at the end of each chapter. They will help you discover some “tricks” not revealed in class or in the textbook.

A short review on finding determinants is covered in Appendix A, complex numbers in Appendix B, and mathematical formulas in Appendix C. Answers to odd-numbered problems are given in Appendix E.

Have fun!

**C.K.A. and M.N.O.S.**

# Contents

Preface v

Acknowledgments vi

A Note to the Student ix

## PART I | DC CIRCUITS |

<b>Chapter 1</b>	Basic Concepts	3
1.1	Introduction	4
1.2	Systems of Units	4
1.3	Charge and Current	6
1.4	Voltage	9
1.5	Power and Energy	10
1.6	Circuit Elements	13
†1.7	Applications	15
	1.7.1 TV Picture Tube	
	1.7.2 Electricity Bills	
†1.8	Problem Solving	18
1.9	Summary	21
Review Questions		22
Problems		23
Comprehensive Problems		25

<b>Chapter 2</b>	Basic Laws	27
2.1	Introduction	28
2.2	Ohm's Law	28
†2.3	Nodes, Branches, and Loops	33
2.4	Kirchhoff's Laws	35
2.5	Series Resistors and Voltage Division	41
2.6	Parallel Resistors and Current Division	42
†2.7	Wye-Delta Transformations	50
†2.8	Applications	54
	2.8.1 Lighting Systems	
	2.8.2 Design of DC Meters	
2.9	Summary	60
Review Questions		61
Problems		63
Comprehensive Problems		72

<b>Chapter 3</b>	Methods of Analysis	75
3.1	Introduction	76
3.2	Nodal Analysis	76
3.3	Nodal Analysis with Voltage Sources	82
3.4	Mesh Analysis	87
3.5	Mesh Analysis with Current Sources	92
†3.6	Nodal and Mesh Analyses by Inspection	95

3.8	Nodal Versus Mesh Analysis	99
3.8	Circuit Analysis with <i>PSpice</i>	100
†3.9	Applications: DC Transistor Circuits	102
3.10	Summary	107
Review Questions		107
Problems		109
Comprehensive Problems		117

<b>Chapter 4</b>	Circuit Theorems	119
4.1	Introduction	120
4.2	Linearity Property	120
4.3	Superposition	122
4.4	Source Transformation	127
4.5	Thevenin's Theorem	131
4.6	Norton's Theorem	137
†4.7	Derivations of Thevenin's and Norton's Theorems	140
4.8	Maximum Power Transfer	142
4.9	Verifying Circuit Theorems with <i>PSpice</i>	144
†4.10	Applications	147
	4.10.1 Source Modeling	
	4.10.2 Resistance Measurement	
4.11	Summary	153
Review Questions		153
Problems		154
Comprehensive Problems		162

<b>Chapter 5</b>	Operational Amplifiers	165
5.1	Introduction	166
5.2	Operational Amplifiers	166
5.3	Ideal Op Amp	170
5.4	Inverting Amplifier	171
5.5	Noninverting Amplifier	174
5.6	Summing Amplifier	176
5.7	Difference Amplifier	177
5.8	Cascaded Op Amp Circuits	181
5.9	Op Amp Circuit Analysis with <i>PSpice</i>	183
†5.10	Applications	185
	5.10.1 Digital-to-Analog Converter	
	5.10.2 Instrumentation Amplifiers	
5.11	Summary	188
Review Questions		190
Problems		191
Comprehensive Problems		200



<b>Chapter 6</b>	<b>Capacitors and Inductors</b>	<b>201</b>			
6.1	Introduction	202			
6.2	Capacitors	202			
6.3	Series and Parallel Capacitors	208			
6.4	Inductors	211			
6.5	Series and Parallel Inductors	216			
†6.6	Applications	219			
	6.6.1	Integrator			
	6.6.2	Differentiator			
	6.6.3	Analog Computer			
6.7	Summary	225			
	Review Questions	226			
	Problems	227			
	Comprehensive Problems	235			
<b>Chapter 7</b>	<b>First-Order Circuits</b>	<b>237</b>			
7.1	Introduction	238			
7.2	The Source-free <i>RC</i> Circuit	238			
7.3	The Source-free <i>RL</i> Circuit	243			
7.4	Singularity Functions	249			
7.5	Step Response of an <i>RC</i> Circuit	257			
7.6	Step Response of an <i>RL</i> Circuit	263			
†7.7	First-order Op Amp Circuits	268			
7.8	Transient Analysis with <i>PSpice</i>	273			
†7.9	Applications	276			
	7.9.1	Delay Circuits			
	7.9.2	Photoflash Unit			
	7.9.3	Relay Circuits			
	7.9.4	Automobile Ignition Circuit			
7.10	Summary	282			
	Review Questions	283			
	Problems	284			
	Comprehensive Problems	293			
<b>Chapter 8</b>	<b>Second-Order Circuits</b>	<b>295</b>			
8.1	Introduction	296			
8.2	Finding Initial and Final Values	296			
8.3	The Source-Free Series <i>RLC</i> Circuit	301			
8.4	The Source-Free Parallel <i>RLC</i> Circuit	308			
8.5	Step Response of a Series <i>RLC</i> Circuit	314			
8.6	Step Response of a Parallel <i>RLC</i> Circuit	319			
8.7	General Second-Order Circuits	322			
8.8	Second-Order Op Amp Circuits	327			
8.9	<i>PSpice</i> Analysis of <i>RLC</i> Circuits	330			
†8.10	Duality	332			
†8.11	Applications	336			
	8.11.1	Automobile Ignition System			
	8.11.2	Smoothing Circuits			
	8.12	Summary	340		
	Review Questions	340			
	Problems	341			
	Comprehensive Problems	350			
<b>PART 2</b>	<b>AC CIRCUITS</b>	<b>351</b>			
<b>Chapter 9</b>	<b>Sinusoids and Phasors</b>	<b>353</b>			
9.1	Introduction	354			
9.2	Sinusoids	355			
9.3	Phasors	359			
9.4	Phasor Relationships for Circuit Elements	367			
9.5	Impedance and Admittance	369			
9.6	Kirchhoff's Laws in the Frequency Domain	372			
9.7	Impedance Combinations	373			
†9.8	Applications	379			
	9.8.1	Phase-Shifters			
	9.8.2	AC Bridges			
9.9	Summary	384			
	Review Questions	385			
	Problems	385			
	Comprehensive Problems	392			
<b>Chapter 10</b>	<b>Sinusoidal Steady-State Analysis</b>	<b>393</b>			
10.1	Introduction	394			
10.2	Nodal Analysis	394			
10.3	Mesh Analysis	397			
10.4	Superposition Theorem	400			
10.5	Source Transformation	404			
10.6	Thevenin and Norton Equivalent Circuits	406			
10.7	Op Amp AC Circuits	411			
10.8	AC Analysis Using <i>PSpice</i>	413			
†10.9	Applications	416			
	10.9.1	Capacitance Multiplier			
	10.9.2	Oscillators			
10.10	Summary	420			
	Review Questions	421			
	Problems	422			
<b>Chapter 11</b>	<b>AC Power Analysis</b>	<b>433</b>			
11.1	Introduction	434			
11.2	Instantaneous and Average Power	434			
11.3	Maximum Average Power Transfer	440			
11.4	Effective or RMS Value	443			
11.5	Apparent Power and Power Factor	447			
11.6	Complex Power	449			
†11.7	Conservation of AC Power	453			

11.8	Power Factor Correction	457
†11.9	Applications	459
11.9.1	Power Measurement	
11.9.2	Electricity Consumption Cost	
11.10	Summary	464
Review Questions	465	
Problems	466	
Comprehensive Problems	474	

## Chapter 12 Three-Phase Circuits 477

12.1	Introduction	478
12.2	Balanced Three-Phase Voltages	479
12.3	Balanced Wye-Wye Connection	482
12.4	Balanced Wye-Delta Connection	486
12.5	Balanced Delta-Delta Connection	488
12.6	Balanced Delta-Wye Connection	490
12.7	Power in a Balanced System	494
†12.8	Unbalanced Three-Phase Systems	500
12.9	<i>PSpice</i> for Three-Phase Circuits	504
†12.10	Applications	508
12.10.1	Three-Phase Power Measurement	
12.10.2	Residential Wiring	
12.11	Summary	516
Review Questions	517	
Problems	518	
Comprehensive Problems	525	

## Chapter 13 Magnetically Coupled Circuits 527

13.1	Introduction	528
13.2	Mutual Inductance	528
13.3	Energy in a Coupled Circuit	535
13.4	Linear Transformers	539
13.5	Ideal Transformers	545
13.6	Ideal Autotransformers	552
†13.7	Three-Phase Transformers	556
13.8	<i>PSpice</i> Analysis of Magnetically Coupled Circuits	559
†13.9	Applications	563
13.9.1	Transformer as an Isolation Device	
13.9.2	Transformer as a Matching Device	
13.9.3	Power Distribution	
13.10	Summary	569
Review Questions	570	
Problems	571	
Comprehensive Problems	582	

## Chapter 14 Frequency Response 583

14.1	Introduction	584
14.2	Transfer Function	584
†14.3	The Decibel Scale	588

14.4	Bode Plots	589
14.5	Series Resonance	600
14.6	Parallel Resonance	605
14.7	Passive Filters	608
14.7.1	Lowpass Filter	
14.7.2	Highpass Filter	
14.7.3	Bandpass Filter	
14.7.4	Bandstop Filter	
14.8	Active Filters	613
14.8.1	First-Order Lowpass Filter	
14.8.2	First-Order Highpass Filter	
14.8.3	Bandpass Filter	
14.8.4	Bandreject (or Notch) Filter	
†14.9	Scaling	619
14.9.1	Magnitude Scaling	
14.9.2	Frequency Scaling	
14.9.3	Magnitude and Frequency Scaling	
14.10	Frequency Response Using <i>PSpice</i>	622
†14.11	Applications	626
14.11.1	Radio Receiver	
14.11.2	Touch-Tone Telephone	
14.11.3	Crossover Network	
14.12	Summary	631
Review Questions	633	
Problems	633	
Comprehensive Problems	640	

## PART 3 ADVANCED CIRCUIT ANALYSIS 643

### Chapter 15 The Laplace Transform 645

15.1	Introduction	646
15.2	Definition of the Laplace Transform	646
15.3	Properties of the Laplace Transform	649
15.4	The Inverse Laplace Transform	659
15.4.1	Simple Poles	
15.4.2	Repeated Poles	
15.4.3	Complex Poles	
15.5	Application to Circuits	666
15.6	Transfer Functions	672
15.7	The Convolution Integral	677
†15.8	Application to Integrodifferential Equations	685
†15.9	Applications	687
15.9.1	Network Stability	
15.9.2	Network Synthesis	
15.10	Summary	694

Review Questions	696
Problems	696
Comprehensive Problems	705

## Chapter 16 The Fourier Series 707

16.1	Introduction	708
16.2	Trigonometric Fourier Series	708
16.3	Symmetry Considerations	717
	16.3.1 Even Symmetry	
	16.3.2 Odd Symmetry	
	16.3.3 Half-Wave Symmetry	
16.4	Circuit Applications	727
16.5	Average Power and RMS Values	730
16.6	Exponential Fourier Series	734
16.7	Fourier Analysis with <i>PSpice</i>	740
	16.7.1 Discrete Fourier Transform	
	16.7.2 Fast Fourier Transform	
†16.8	Applications	746
	16.8.1 Spectrum Analyzers	
	16.8.2 Filters	
16.9	Summary	749
Review Questions	751	
Problems	751	
Comprehensive Problems	758	

## Chapter 17 Fourier Transform 759

17.1	Introduction	760
17.2	Definition of the Fourier Transform	760
17.3	Properties of the Fourier Transform	766
17.4	Circuit Applications	779
17.5	Parseval's Theorem	782
17.6	Comparing the Fourier and Laplace Transforms	784
†17.7	Applications	785
	17.7.1 Amplitude Modulation	
	17.7.2 Sampling	

## 17.8 Summary 789

Review Questions	790
Problems	790
Comprehensive Problems	794

## Chapter 18 Two-Port Networks 795

18.1	Introduction	796
18.2	Impedance Parameters	796
18.3	Admittance Parameters	801
18.4	Hybrid Parameters	804
18.5	Transmission Parameters	809
†18.6	Relationships between Parameters	814
18.7	Interconnection of Networks	817
18.8	Computing Two-Port Parameters Using <i>PSpice</i>	823
†18.9	Applications	826
	18.9.1 Transistor Circuits	
	18.9.2 Ladder Network Synthesis	

## 18.10 Summary 833

Review Questions	834
Problems	835
Comprehensive Problems	844

## Appendix A Solution of Simultaneous Equations Using Cramer's Rule 845

## Appendix B Complex Numbers 851

## Appendix C Mathematical Formulas 859

## Appendix D *PSpice* for Windows 865

## Appendix E Answers to Odd-Numbered Problems 893

## *Selected Bibliography* 929

## *Index* 933

## DC CIRCUITS

Chapter 1 *Basic Concepts*

Chapter 2 *Basic Laws*

Chapter 3 *Methods of Analysis*

Chapter 4 *Circuit Theorems*

Chapter 5 *Operational Amplifier*

Chapter 6 *Capacitors and Inductors*

Chapter 7 *First-Order Circuits*

Chapter 8 *Second-Order Circuits*



# CHAPTER 1

## BASIC CONCEPTS

*It is engineering that changes the world.*

—Isaac Asimov

### *Historical Profiles*

**Alessandro Antonio Volta** (1745–1827), an Italian physicist, invented the electric battery—which provided the first continuous flow of electricity—and the capacitor.

Born into a noble family in Como, Italy, Volta was performing electrical experiments at age 18. His invention of the battery in 1796 revolutionized the use of electricity. The publication of his work in 1800 marked the beginning of electric circuit theory. Volta received many honors during his lifetime. The unit of voltage or potential difference, the volt, was named in his honor.



**Andre-Marie Ampere** (1775–1836), a French mathematician and physicist, laid the foundation of electrodynamics. He defined the electric current and developed a way to measure it in the 1820s.

Born in Lyons, France, Ampere at age 12 mastered Latin in a few weeks, as he was intensely interested in mathematics and many of the best mathematical works were in Latin. He was a brilliant scientist and a prolific writer. He formulated the laws of electromagnetics. He invented the electromagnet and the ammeter. The unit of electric current, the ampere, was named after him.



## 1.1 INTRODUCTION

Electric circuit theory and electromagnetic theory are the two fundamental theories upon which all branches of electrical engineering are built. Many branches of electrical engineering, such as power, electric machines, control, electronics, communications, and instrumentation, are based on electric circuit theory. Therefore, the basic electric circuit theory course is the most important course for an electrical engineering student, and always an excellent starting point for a beginning student in electrical engineering education. Circuit theory is also valuable to students specializing in other branches of the physical sciences because circuits are a good model for the study of energy systems in general, and because of the applied mathematics, physics, and topology involved.

In electrical engineering, we are often interested in communicating or transferring energy from one point to another. To do this requires an interconnection of electrical devices. Such interconnection is referred to as an *electric circuit*, and each component of the circuit is known as an *element*.

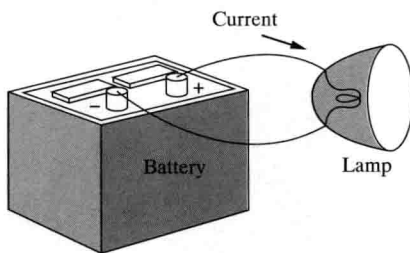
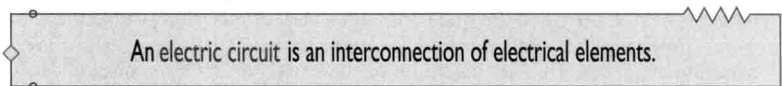


Figure 1.1 A simple electric circuit.

A simple electric circuit is shown in Fig. 1.1. It consists of three basic components: a battery, a lamp, and connecting wires. Such a simple circuit can exist by itself; it has several applications, such as a torch light, a search light, and so forth.

A complicated real circuit is displayed in Fig. 1.2, representing the schematic diagram for a radio receiver. Although it seems complicated, this circuit can be analyzed using the techniques we cover in this book. Our goal in this text is to learn various analytical techniques and computer software applications for describing the behavior of a circuit like this.

Electric circuits are used in numerous electrical systems to accomplish different tasks. Our objective in this book is not the study of various uses and applications of circuits. Rather our major concern is the analysis of the circuits. By the analysis of a circuit, we mean a study of the behavior of the circuit: How does it respond to a given input? How do the interconnected elements and devices in the circuit interact?

We commence our study by defining some basic concepts. These concepts include charge, current, voltage, circuit elements, power, and energy. Before defining these concepts, we must first establish a system of units that we will use throughout the text.

## 1.2 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,

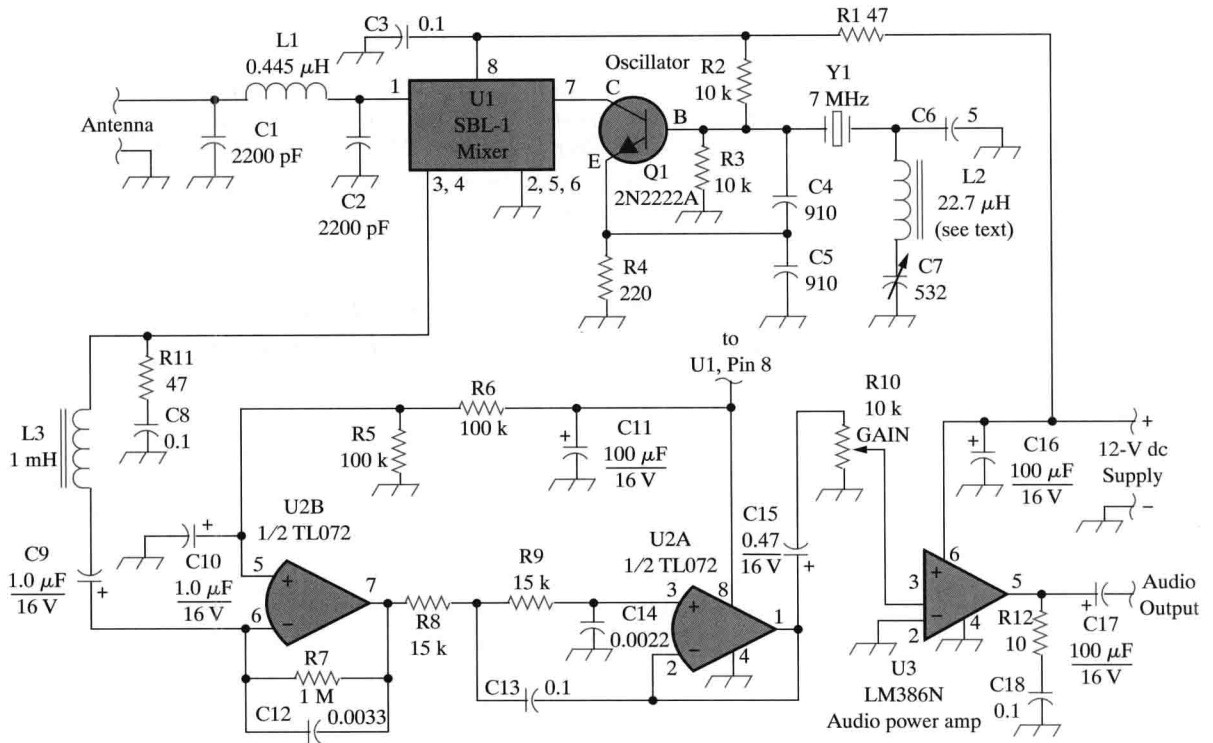


Figure 1.2 Electric circuit of a radio receiver. (Reproduced with permission from *QST*, August 1995, p. 23.)

there are six principal units from which the units of all other physical quantities can be derived. Table 1.1 shows the six units, their symbols, and the physical quantities they represent. The SI units are used throughout this text.

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):

$$600,000,000 \text{ mm} \quad 600,000 \text{ m} \quad 600 \text{ km}$$

TABLE 1.1 The six basic SI units.

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

TABLE 1.2 The SI prefixes.

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



### 1.3 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*. We all experience the effect of electric charge when we try to remove our wool sweater and have it stick to our body or walk across a carpet and receive a shock.

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  $1.602 \times 10^{-19}$  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 following points should be noted about electric charge:

1. The coulomb is a large unit for charges. In 1 C of charge, there are  $1/(1.602 \times 10^{-19}) = 6.24 \times 10^{18}$  electrons. Thus realistic or laboratory values of charges are on the order of pC, nC, or  $\mu\text{C}$ .<sup>1</sup>
2. According to experimental observations, the only charges that occur in nature are integral multiples of the electronic charge  $e = -1.602 \times 10^{-19}$  C.
3. 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. 1.3 illustrates. 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. Thus,

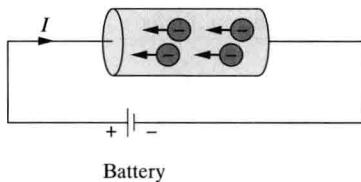


Figure 1.3 Electric current due to flow of electronic charge in a conductor.

A convention is a standard way of describing something so that others in the profession can understand what we mean. We will be using IEEE conventions throughout this book.

<sup>1</sup>However, a large power supply capacitor can store up to 0.5 C of charge.