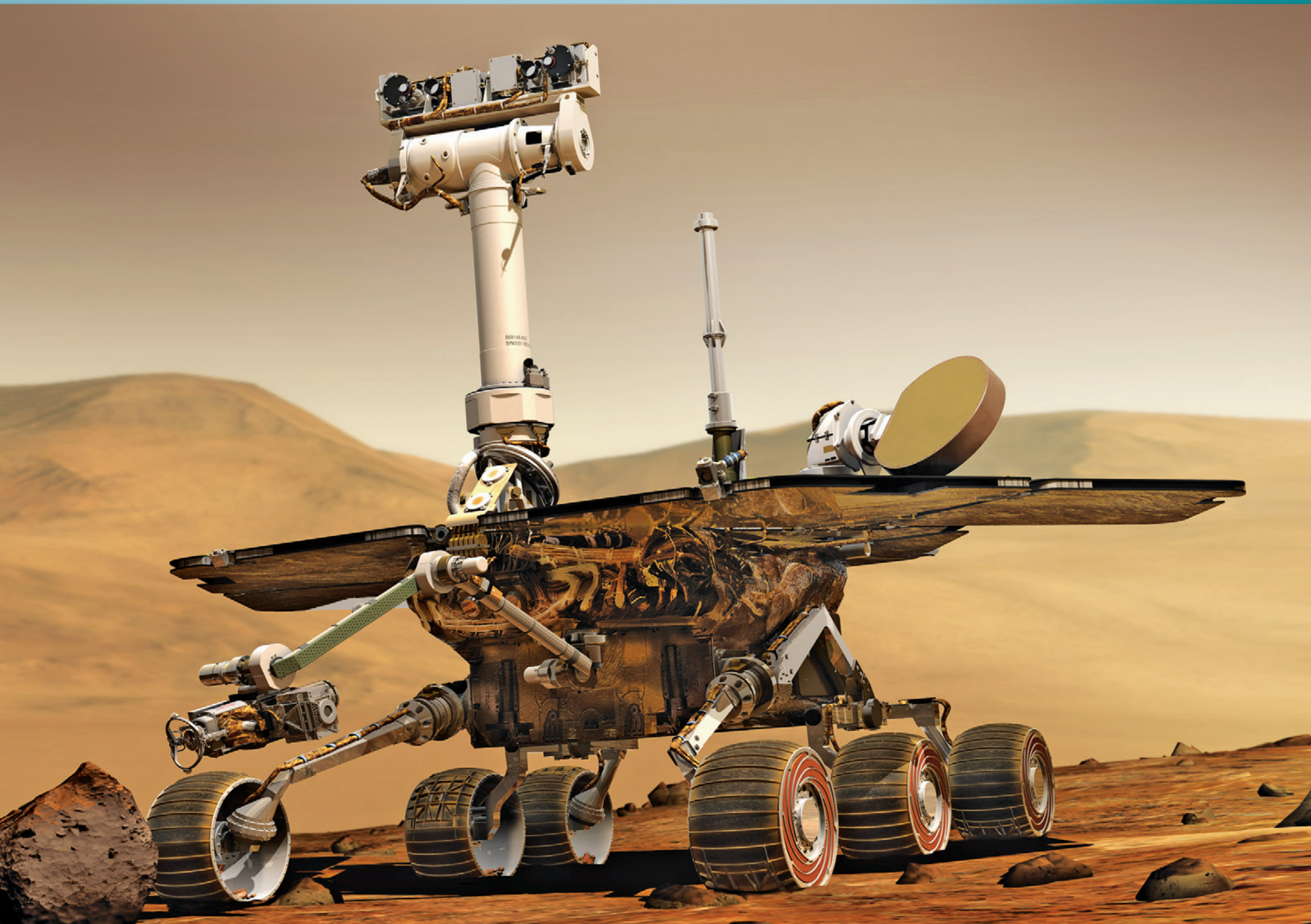
FIFTH EDITION

Fundamentals of Electric Circuits



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fifth edition

Fundamentals of
Electric Circuits

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Dedicated to our wives, Kikelomo and Hannah, whose understanding and support have truly made this book possible.

Matthew
and
Chuck

Contents

Preface

You may be wondering why we chose a photo of NASA's Mars Rover for the cover. We actually chose it for several reasons. Obviously, it is very exciting; in fact, space represents the most exciting frontier for the entire world! In addition, much of the Rover itself consists of all kinds of circuits. Circuits that must work without needing maintenance! Once you are on Mars, it is hard to find a technician!

The Rover must have a power system that can supply all the power necessary to move it, help it collect samples and analyze them, broadcast the results back to Earth, and receive instructions from Earth. One of the important issues that make the problem of working with the rover is that it takes about 20 minutes for communications to go from the Earth to Mars. So the Rover does not make changes required by NASA quickly.

What we find most amazing is that such a sophisticated and complicated electro-mechanical device can operate so accurately and reliably after flying millions of miles and being bounced onto the ground! Here is a link to an absolutely incredible video of what the Rover is all about and how it got to Mars: http://www.youtube.com/watch?v=5UmRx4dEdRI. Enjoy!

Features

New to This Edition

A model for magnetic coupling is presented in Chapter 13 that will make analysis easier as well as enhance your ability to find errors. We have successfully used this model for years and felt it was now time to add it to the book. In addition, there are over 600 new end-of-chapter problems, changed end-of-chapter problems, and changed practice problems.

We have also added National Instruments *Multisim*™ solutions for almost all of the problems solved using *PSpice*®. There is a *Multisim* tutorial available on our website. We have added National Instruments *Multisim* since it is very user-friendly with many more options for analysis than *PSpice*. In addition, it allows the ability to modify circuits easily in order to see how changing circuit parameters impacts voltages, currents, and power. We have also moved the tutorials for *PSpice, MATLAB*®, and *KCIDE* to our website to allow us to keep up with changes in the software.

We have also added 43 new problems to Chapter 16. We did this to enhance using the powerful s-domain analysis techniques to finding voltages and currents in circuits.

Retained from Previous Editions

A course in circuit analysis is perhaps the first exposure students have to electrical engineering. This is also a place where we can enhance some of the skills that they will later need as they learn how to design.

An important part of this book is our 121 ***design a problem*** problems. These problems were developed to enhance skills that are an important part of the design process. We know it is not possible to fully develop a student's design skills in a fundamental course like circuits. To fully develop design skills a student needs a design experience normally reserved for their senior year. This does not mean that some of those skills cannot be developed and exercised in a circuits course. The text already included open-ended questions that help students use creativity, which is an important part of learning how to design. We already have some questions that are open-ended but we desired to add much more into our text in this important area and have developed an approach to do just that. When we develop problems for the student to solve our goal is that in solving the problem the student learns more about the theory and the problem solving process. Why not have the students design problems like we do? That is exactly what we do in each chapter. Within the normal problem set, we have a set of problems where we ask the student to design a problem to help other students better understand an important concept. This has two very important results. The first will be a better understanding of the basic theory and the second will be the enhancement of some of the student's basic design skills. We are making effective use of the principle of learning by teaching. Essentially we all learn better when we teach a subject. Designing effective problems is a key part of the teaching process. Students should also be encouraged to develop problems, when appropriate, which have nice numbers and do not necessarily overemphasize complicated mathematical manipulations.

A very important advantage to our textbook, we have a total of 2,447 Examples, Practice Problems, Review Questions, and End-of-Chapter Problems! Answers are provided for all practice problems and the odd numbered end-of-chapter problems.

The main objective of the fifth edition of this book remains the same as the previous editions—to present circuit analysis in a manner that is clearer, more interesting, and easier to understand than other circuit textbooks, and to assist the student in beginning to see the "fun" in engineering. This objective is achieved in the following ways:

- **Chapter Openers and Summaries**
  Each chapter opens with a discussion about how to enhance skills which contribute to successful problem solving as well as successful careers or a career-oriented talk on a sub-discipline of electrical engineering. This is followed by an introduction that links the chapter with the previous chapters and states the chapter objectives. The chapter ends with a summary of key points and formulas.
- **Problem-Solving Methodology**
  Chapter 1 introduces a six-step method for solving circuit problems which is used consistently throughout the book and media supplements to promote best-practice problem-solving procedures.
- **Student-Friendly Writing Style**
  All principles are presented in a lucid, logical, step-by-step manner. As much as possible, we avoid wordiness and giving too much detail that could hide concepts and impede overall understanding of the material.

- **Boxed Formulas and Key Terms**
  Important formulas are boxed as a means of helping students sort out what is essential from what is not. Also, to ensure that students clearly understand the key elements of the subject matter, key terms are defined and highlighted.
- **Margin Notes**
  Marginal notes are used as a pedagogical aid. They serve multiple uses such as hints, cross-references, more exposition, warnings, reminders not to make some particular common mistakes, and problem-solving insights.
- **Worked Examples**
  Thoroughly worked examples are liberally given at the end of every section. The examples are regarded as a part of the text and are clearly explained without asking the reader to fill in missing steps. Thoroughly worked examples give students a good understanding of the solution process and the confidence to solve problems themselves. Some of the problems are solved in two or three different ways to facilitate a substantial comprehension of the subject material as well as a comparison of different approaches.
- **Practice Problems**
  To give students practice opportunity, each illustrative example is immediately followed by a practice problem with the answer. The student can follow the example step-by-step to aid in the solution of the practice problem without flipping pages or looking at the end of the book for answers. The practice problem is also intended to test a student's understanding of the preceding example. It will reinforce their grasp of the material before the student can move on to the next section. Complete solutions to the practice problems are available to students on the website.
- **Application Sections**
  The last section in each chapter is devoted to practical application aspects of the concepts covered in the chapter. The material covered in the chapter is applied to at least one or two practical problems or devices. This helps students see how the concepts are applied to real-life situations.
- **Review Questions**
  Ten review questions in the form of multiple-choice objective items are provided at the end of each chapter with answers. The review questions 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.
- **Computer Tools**
  In recognition of the requirements by ABET® on integrating computer tools, the use of *PSpice, Multisim, MATLAB, KCIDE for Circuits*, and developing design skills are encouraged in a student-friendly manner. *PSpice* is covered early on in the text so that students can become familiar and use it throughout the text. Tutorials on all of these are available on our website. *MATLAB* is also introduced early in the book.

- **Design a Problem Problems**
  Finally, *design a problem* problems are meant to help the student develop skills that will be needed in the design process.
- **Historical Tidbits**
  Historical sketches throughout the text provide profiles of important pioneers and events relevant to the study of electrical engineering.
- **Early Op Amp Discussion**
  The operational amplifier (op amp) as a basic element is introduced early in the text.
- **Fourier and Laplace Transforms Coverage**
  To ease the transition between the circuit course and signals and systems courses, Fourier and Laplace transforms are covered lucidly and thoroughly. The chapters are developed in a manner that the interested instructor can go from solutions of first-order circuits to Chapter 15. This then allows a very natural progression from Laplace to Fourier to AC.
- **Four Color Art Program**
  An interior design and four color art program bring circuit drawings to life and enhance key pedagogical elements throughout the text.
- **Extended Examples**
  Examples worked in detail according to the six-step problem solving method provide a roadmap for students to solve problems in a consistent fashion. At least one example in each chapter is developed in this manner.
- **EC 2000 Chapter Openers**
  Based on ABET's skill-based CRITERION 3, these chapter openers are devoted to discussions as to how students can acquire the skills that will lead to a significantly enhanced career as an engineer. Because these skills are so very important to the student while still in college as well after graduation, we use the heading, *"Enhancing your Skills and your Career."*
- **Homework Problems**
  There are 468 new or changed end-of-chapter problems which will provide students with plenty of practice as well as reinforce key concepts.
- **Homework Problem Icons**
  Icons are used to highlight problems that relate to engineering design as well as problems that can be solved using *PSpice, Multisim, KCIDE,* or *MATLAB*.

Organization

This book was written for a two-semester or three-quarter course in linear circuit analysis. The book may also be used for a one-semester course by a proper selection of chapters and sections by the instructor. 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, circuits techniques, and passive and active elements.

- Part 2, which contains Chapter 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 19, are devoted to advanced techniques for network analysis. It provides students with a solid introduction to the Laplace transform, Fourier series, Fourier transform, and two-port network analysis.

The material in the three parts is more than sufficient for a two-semester course, so the instructor must select which chapters or 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 diverse enough that the instructor can choose some as examples and assign some as homework. As stated earlier, we are using three icons with this edition. We are using to denote problems that either require *PSpice* in the solution process, where the circuit complexity is such that *PSpice* or *Multisim* would make the solution process easier, and where *PSpice* or *Multisim* makes a good check to see if the problem has been solved correctly. We are using to denote problems where *MATLAB* is required in the solution process, where *MATLAB* makes sense because of the problem makeup and its complexity, and where *MATLAB* makes a good check to see if the problem has been solved correctly. Finally, we use to identify problems that help the student develop skills that are needed for engineering design. More difficult problems are marked with an asterisk (*).

Comprehensive problems follow the end-of-chapter problems. They are mostly applications problems that require skills learned from that particular chapter.

Prerequisites

As with most introductory circuit courses, the main prerequisites, for a course using this textbook, are physics and calculus. Although familiarity with complex numbers is helpful in the later part of the book, it is not required. A very important asset of this text is that ALL the mathematical equations and fundamentals of physics needed by the student, are included in the text.

Supplements

McGraw-Hill Connect® Engineering

McGraw-Hill Connect Engineering is a web-based assignment and assessment platform that gives students the means to better connect with their coursework, with their instructors, and with the important concepts that they will need to know for success now and in the future. With Connect Engineering, instructors can deliver assignments, quizzes, and tests easily online. Students can practice important skills at their own pace and on their own schedule. Ask your McGraw-Hill representative for more details and check it out at www.mcgrawhillconnect.com/engineering.

Instructor and Student Website

Available at www.mhhe.com/alexander are a number of additional instructor and student resources to accompany the text. These include complete solutions for all practice and end-of-chapter problems, solutions in *PSpice* and *Multisim* problems, lecture PowerPoints®, text image files, transition guides to instructors, Network Analysis Tutorials, FE Exam questions, flashcards, and primers for *PSpice, Multisim, MATLAB*, and *KCIDE*. The site also features COSMOS, a complete online solutions manual organization system that allows instructors to create custom homework, quizzes, and tests using end-of-chapter problems from the text.

Knowledge Capturing Integrated Design Environment for Circuits (*KCIDE for Circuits*)

This software, developed at Cleveland State University and funded by NASA, is designed to help the student work through a circuits problem in an organized manner using the six-step problem-solving methodology in the text. *KCIDE for Circuits* allows students to work a circuit problem in *PSpice* and *MATLAB*, track the evolution of their solution, and save a record of their process for future reference. In addition, the software automatically generates a Word document and/or a PowerPoint presentation. The software package can be downloaded for free.

It is hoped that the book and supplemental materials supply the instructor with all the pedagogical tools necessary to effectively present the material.

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The fifth edition has benefited greatly from the many outstanding reviewers and symposium attendees who contributed to the success of the first four editions! In addition, the following have made important contributions to this edition (in alphabetical order):

Alok Berry, *George Mason University*
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Archie Holmes, *University of Virginia*
Anton Kruger, *University of Iowa*
Arnost Neugroschel, *University of Florida*
Arun Ravindran, *University of North Carolina-Charlotte*

Finally, we appreciate the feedback received from instructors and students who used the previous editions. We want this to continue, so please keep sending us e-mails or direct them to the publisher. We can be reached at c.alexander@ieee.org for Charles Alexander and sadiku@ieee.org for Matthew Sadiku.

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 this 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* and *Multisim*, computer circuit analysis programs, are used throughout the textbook. *PSpice*, the personal computer version of *Spice*, is the popular standard circuit analysis program at most universities. *PSpice for Windows* and *Multisim* are described on our website. Make an effort to learn *PSpice* and/or *Multisim*, because you can check any circuit problem with them and be sure you are handing in a correct problem solution.
- *MATLAB* is another software that is very useful in circuit analysis and other courses you will be taking. A brief tutorial on *MATLAB* can be found on our website. The best way to learn *MATLAB* is to start working with it once you know a few commands.
- 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.
- Clearly a lot of effort has gone into making the technical details in this book easy to understand. It also contains all the mathematics and physics necessary to understand the theory and will be very useful in your other engineering courses. However, we have also focused on creating a reference for you to use both in school as well as when working in industry or seeking a graduate degree.
- It is very tempting to sell your book after you have completed your classroom experience; however, our advice to you is *DO NOT SELL YOUR ENGINEERING BOOKS!* Books have always been expensive; however, the cost of this book is virtually the same as I paid for my circuits text back in the early 60s in terms of real dollars. In

fact, it is actually cheaper. In addition, engineering books of the past are nowhere near as complete as what is available now.

When I was a student, I did not sell any of my engineering textbooks and was very glad I did not! I found that I needed most of them throughout my career.

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 D.

Have fun!

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

About the Authors

Charles K. Alexander is professor of electrical and computer engineering in the Fenn College of Engineering at Cleveland State University, Cleveland, Ohio. He is also the Director of The Center for Research in Electronics and Aerospace Technology (CREATE). From 2002 until 2006 he was Dean of the Fenn College of Engineering. From 2004 until 2007, he was Director of Ohio ICE, a research center in instrumentation, controls, electronics, and sensors (a coalition of CSU, Case, the University of Akron, and a number of Ohio industries). From 1998 until 2002, he was interim director (2000 and 2001) of the Institute for Corrosion and Multiphase Technologies and Stocker Visiting Professor of electrical engineering and computer science at Ohio University. From 1994–1996 he was dean of engineering and computer science at California State University, Northridge.

Charles K. Alexander

From 1989–1994 he was acting dean of the college of engineering at Temple University, and from 1986–1989 he was professor and chairman of the department of electrical engineering at Temple. From 1980–1986 he held the same positions at Tennessee Technological University. He was an associate professor and a professor of electrical engineering at Youngstown State University from 1972–1980, where he was named Distinguished Professor in 1977 in recognition of "outstanding teaching and research." He was assistant professor of electrical engineering at Ohio University in 1971–1972. He received honorary Dr. Eng. from Ohio Northern University (2009), the PhD (1971) and M.S.E.E. (1967) from Ohio University and the B.S.E.E. (1965) from Ohio Northern University.

Dr. Alexander has been a consultant to 23 companies and governmental organizations, including the Air Force and Navy and several law firms. He has received over $85 million in research and development funds for projects ranging from solar energy to software engineering. He has authored 40 publications, including a workbook and a videotape lecture series, and is coauthor of *Fundamentals of Electric Circuits, Problem Solving Made* Almost *Easy*, and the fifth edition of the *Standard Handbook of Electronic Engineering*, with McGraw-Hill. He has made more than 500 paper, professional, and technical presentations.

Dr. Alexander is a fellow of the IEEE and served as its president and CEO in 1997. In 1993 and 1994 he was IEEE vice president, professional activities, and chair of the United States Activities Board (USAB). In 1991–1992 he was region 2 director, serving on the Regional Activities Board (RAB) and USAB. He has also been a member of the Educational Activities Board. He served as chair of the USAB Member Activities Council and vice chair of the USAB Professional Activities Council for Engineers, and he chaired the RAB Student Activities Committee and the USAB Student Professional Awareness Committee.

In 1998 he received the Distinguished Engineering Education Achievement Award from the Engineering Council, and in 1996 he received the Distinguished Engineering Education Leadership Award from the same group. When he became a fellow of the IEEE in 1994, the citation read “for leadership in the field of engineering education and the professional development of engineering students.” In 1984 he received the IEEE Centennial Medal, and in 1983 he received the IEEE/RAB Innovation Award, given to the IEEE member who best contributes to RAB’s goals and objectives.

Matthew N. O. Sadiku

Matthew N. O. Sadiku is presently a professor at Prairie View A&M University. Prior to joining Prairie View, he taught at Florida Atlantic University, Boca Raton, and Temple University, Philadelphia. He has also worked for Lucent/Avaya and Boeing Satellite Systems.

Dr. Sadiku is the author of over 170 professional papers and almost 30 books including *Elements of Electromagnetics* (Oxford University Press, 3rd ed., 2001), *Numerical Techniques in Electromagnetics* (2nd ed., CRC Press, 2000), *Simulation of Local Area Networks* (with M. IIyas, CRC Press, 1994), *Metropolitan Area Networks* (CRC Press, 1994), and *Fundamentals of Electric Circuits* (with C. K. Alexander, McGraw-Hill). His books are used worldwide, and some of them have been translated into Korean, Chinese, Italian, and Spanish. He was the recipient of the 2000 McGraw-Hill/Jacob Millman Award for outstanding contributions in the field of electrical engineering. He was the IEEE region 2 Student Activities Committee chairman and is an associate editor for IEEE “Transactions on Education.” He received his PhD at Tennessee Technological University, Cookeville.

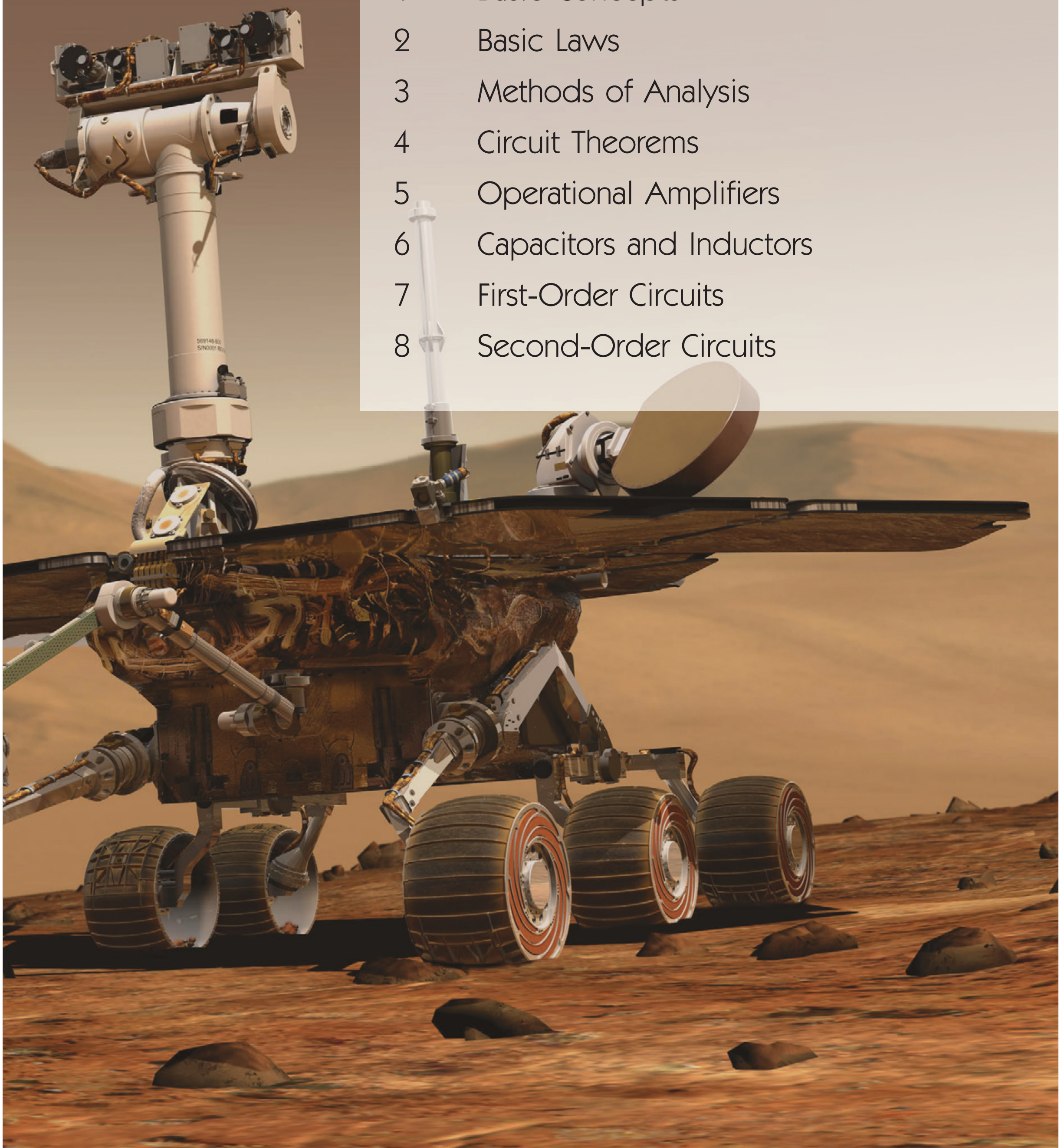
Fundamentals of

Electric Circuits

PART ONE

DC Circuits

OUTLINE



NASA

chapter

1

Basic Concepts

Some books are to be tasted, others to be swallowed, and some few to be chewed and digested.

—Francis Bacon

Enhancing Your Skills and Your Career

ABET EC 2000 criteria (3.a), *"an ability to apply knowledge of mathematics, science, and engineering."*

As students, you are required to study mathematics, science, and engineering with the purpose of being able to apply that knowledge to the solution of engineering problems. The skill here is the ability to apply the fundamentals of these areas in the solution of a problem. So how do you develop and enhance this skill?

The best approach is to work as many problems as possible in all of your courses. However, if you are really going to be successful with this, you must spend time analyzing where and when and why you have difficulty in easily arriving at successful solutions. You may be surprised to learn that most of your problem-solving problems are with mathematics rather than your understanding of theory. You may also learn that you start working the problem too soon. Taking time to think about the problem and how you should solve it will always save you time and frustration in the end.

What I have found that works best for me is to apply our six-step problem-solving technique. Then I carefully identify the areas where I have difficulty solving the problem. Many times, my actual deficiencies are in my understanding and ability to use correctly certain mathematical principles. I then return to my fundamental math texts and carefully review the appropriate sections, and in some cases, work some example problems in that text. This brings me to another important thing you should always do: Keep nearby all your basic mathematics, science, and engineering textbooks.

This process of continually looking up material you thought you had acquired in earlier courses may seem very tedious at first; however, as your skills develop and your knowledge increases, this process will become easier and easier. On a personal note, it is this very process that led me from being a much less than average student to someone who could earn a Ph.D. and become a successful researcher.

Photo by Charles Alexander

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*.

> An **electric circuit** is an interconnection of electrical elements.

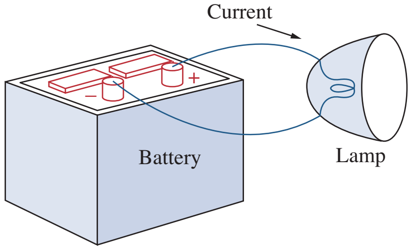


Figure 1.1
A simple electric circuit.

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

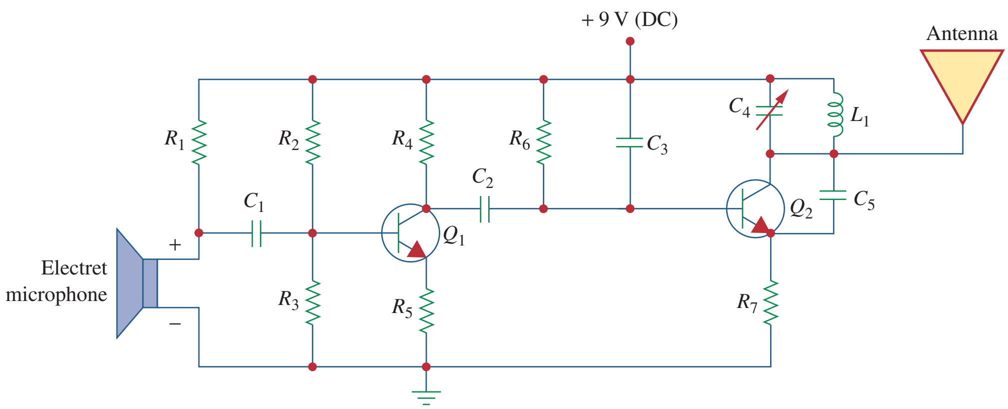


Figure 1.2
Electric circuit of a radio transmitter.

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, there are seven principal units from which the units of all other physical quantities can be derived. Table 1.1 shows the six units and one derived unit that are relevant to this text. 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 mm   600,000 m   600 km

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

TABLE 1.1

Six basic SI units and one derived unit relevant to this text.

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

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	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

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 1.602×10^{-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 μC.[1]
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,

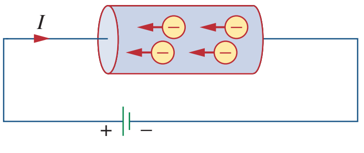


Figure 1.3
Electric current due to flow of electronic charge in a conductor.

> 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.

> **Electric current** is the time rate of change of charge, measured in amperes (A).

Mathematically, the relationship between current i, charge q, and time t is

$$i \triangleq \frac{dq}{dt} \tag{1.1}$$

[1] However, a large power supply capacitor can store up to 0.5 C of charge.

Historical

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.

The Burndy Library Collection at The Huntington Library, San Marino, California.

where current is measured in amperes (A), and

$$1 \text{ ampere} = 1 \text{ coulomb/second}$$

The charge transferred between time t_0 and t is obtained by integrating both sides of Eq. (1.1). We obtain

$$Q \triangleq \int_{t_0}^{t} i \, dt \tag{1.2}$$

The way we define current as i in Eq. (1.1) suggests that current need not be a constant-valued function. As many of the examples and problems in this chapter and subsequent chapters suggest, there can be several types of current; that is, charge can vary with time in several ways.

If the current does not change with time, but remains constant, we call it a *direct current* (dc).

> A **direct current** (dc) is a current that remains constant with time.

By convention the symbol I is used to represent such a constant current.

A time-varying current is represented by the symbol i. A common form of time-varying current is the sinusoidal current or *alternating current* (ac).

> An **alternating current** (ac) is a current that varies sinusoidally with time.

Such current is used in your household to run the air conditioner, refrigerator, washing machine, and other electric appliances. Figure 1.4

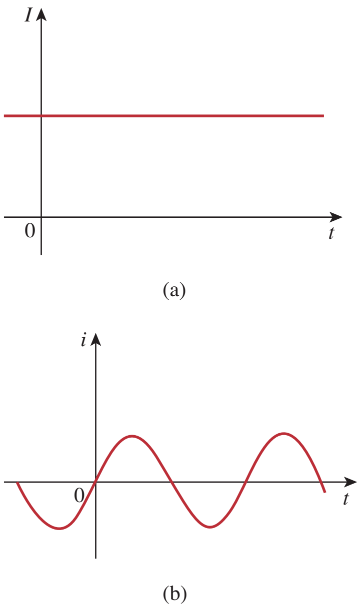


Figure 1.4
Two common types of current: (a) direct current (dc), (b) alternating current (ac).

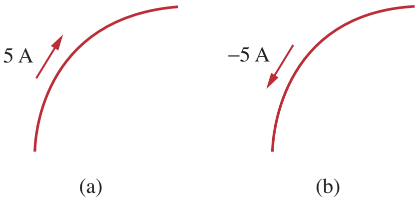


Figure 1.5
Conventional current flow: (a) positive current flow, (b) negative current flow.

shows direct current and alternating current; these are the two most common types of current. We will consider other types later in the book.

Once we define current as the movement of charge, we expect current to have an associated direction of flow. As mentioned earlier, the direction of current flow is conventionally taken as the direction of positive charge movement. Based on this convention, a current of 5 A may be represented positively or negatively as shown in Fig. 1.5. In other words, a negative current of -5 A flowing in one direction as shown in Fig. 1.5(b) is the same as a current of $+5$ A flowing in the opposite direction.

Example 1.1

How much charge is represented by 4,600 electrons?

Solution:

Each electron has -1.602×10^{-19} C. Hence 4,600 electrons will have

$$-1.602 \times 10^{-19} \text{ C/electron} \times 4{,}600 \text{ electrons} = -7.369 \times 10^{-16} \text{ C}$$

Practice Problem 1.1

Calculate the amount of charge represented by six million protons.

Answer: $+9.612 \times 10^{-13}$ C.

Example 1.2

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

Solution:

$$i = \frac{dq}{dt} = \frac{d}{dt}(5t \sin 4\pi t) \text{ mC/s} = (5 \sin 4\pi t + 20\pi t \cos 4\pi t) \text{ mA}$$

At $t = 0.5$,

$$i = 5 \sin 2\pi + 10\pi \cos 2\pi = 0 + 10\pi = 31.42 \text{ mA}$$

Practice Problem 1.2

If in Example 1.2, $q = (10 - 10e^{-2t})$ mC, find the current at $t = 1.0$ s.

Answer: 2.707 mA.

Example 1.3

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

Solution:

$$Q = \int_{t=1}^{2} i\,dt = \int_{1}^{2} (3t^2 - t)\,dt$$

$$= \left(t^3 - \frac{t^2}{2}\right)\bigg|_1^2 = (8 - 2) - \left(1 - \frac{1}{2}\right) = 5.5 \text{ C}$$

Practice Problem 1.3

The current flowing through an element is

$$i = \begin{cases} 4 \text{ A}, & 0 < t < 1 \\ 4t^2 \text{ A}, & t > 1 \end{cases}$$

Calculate the charge entering the element from $t = 0$ to $t = 2$ s.

Answer: 13.333 C.

1.4 Voltage

As explained briefly in the previous section, to move the electron in a conductor in a particular direction requires some work or energy transfer. This work is performed by an external electromotive force (emf), typically represented by the battery in Fig. 1.3. This emf is also known as *voltage* or *potential difference*. The voltage v_{ab} between two points a and b in an electric circuit is the energy (or work) needed to move a unit charge from a to b; mathematically,

$$v_{ab} \triangleq \frac{dw}{dq} \tag{1.3}$$

where w is energy in joules (J) and q is charge in coulombs (C). The voltage v_{ab} or simply v is measured in volts (V), named in honor of the Italian physicist Alessandro Antonio Volta (1745–1827), who invented the first voltaic battery. From Eq. (1.3), it is evident that

$$1 \text{ volt} = 1 \text{ joule/coulomb} = 1 \text{ newton-meter/coulomb}$$

Thus,

> **Voltage** (or **potential difference**) is the energy required to move a unit charge through an element, measured in volts (V).

Figure 1.6 shows the voltage across an element (represented by a rectangular block) connected to points a and b. The plus (+) and minus (−) signs are used to define reference direction or voltage polarity. The v_{ab} can be interpreted in two ways: (1) Point a is at a potential of v_{ab}

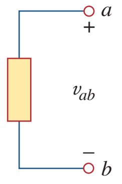


Figure 1.6
Polarity of voltage v_{ab}.