**Table No**

1.1

1.2

1.3

1.4

2.1

3.1

4.1

4.2

6.1

6.2

7.1

**8.1**

**8.2**

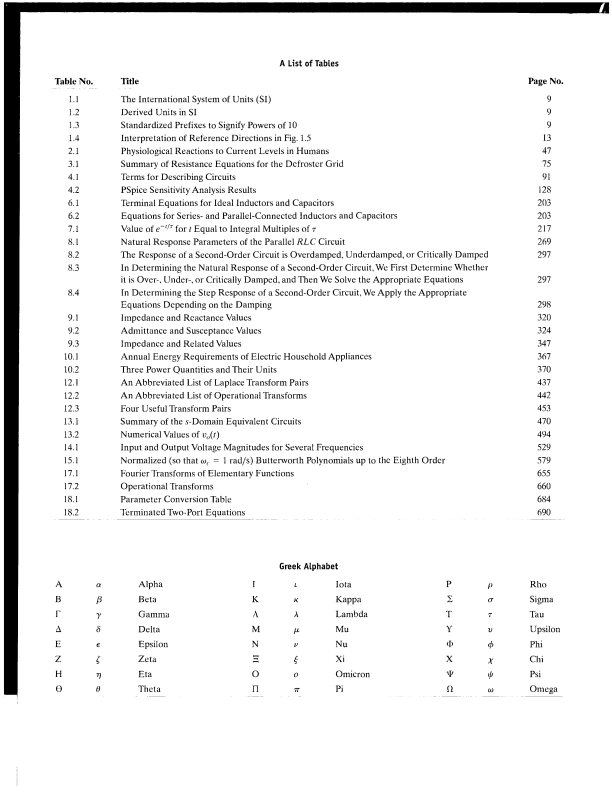
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**Greek Alphabet**

*\*

B **r** A E

Z

H O

***a***

/3

*y*

**s** e

***t*** *V 0*

Alpha Beta

Gamma Delta

Epsilon Zeta

Eta

Theta

**I**

K A M N 2

0

**n**

**i**

**K** A *V* ***V***

*$*

*o*

**77**

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Kappa

Lambda Mu

Nu

Xi

Omicron Pi

P

2

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X \*

XI

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**T**

***V***

***4>*** *X*

</'

***CO***

Rho

Sigma Tau

Up si Ion Phi

Chi

Psi

Omega

*fit) (t>* 0") ***m***

</(/)

***t***

***-at***

***C***

sin *cot*

cos *lot*

*ft>~"1*

**it**

<?-"fsin *cot* ***-at***

**An Abbreviated List of Laplace Type**

(impulse)

(step)

(ramp)

(exponential)

(sine)

(cosine)

(damped ramp)

(damped sine)

(damped cosine)

**Transform Pairs**

***F{s)***

**1**

**]**

*s*

**1**

*i*

1

.v + *a*

***CO***

***2* i 2**

,v *+io*

*S" + IO ~*

**1**

**(.v + a)2**

***CO***

***(s + a)2 +*** *io2*

*s* ***+ a***

**(s + *a)2 +*** *io2*

An Abbreviated List of Operational Transforms

/(/) *F(s)*

*Kf(t) KF(s)*

*ft(t) +* / 2 (0 *- h(t)* + • • • F,(.v) + F2(.v) *-* F3(.v) +

*dfiO dt*

*sF(s) -* /(0-) *s2F(s)* - s/(0") -

**71- 1** rf/(0 , ,rf/(0') ,rff 0") rf,,\_1/(0") —f^- v" F(.v) - .v"' /(()-) - .v"-2 , ; - j"' - 3 y \ ; ^-V^ *F(s)*

*f(x) dx* /o *s*

/ (/ - «)«(r - fl),A>0 t>-"vF(,v)

^"7( 0 F(Jf + a)

/(«/), A> 0 -F( -

**//(/)**

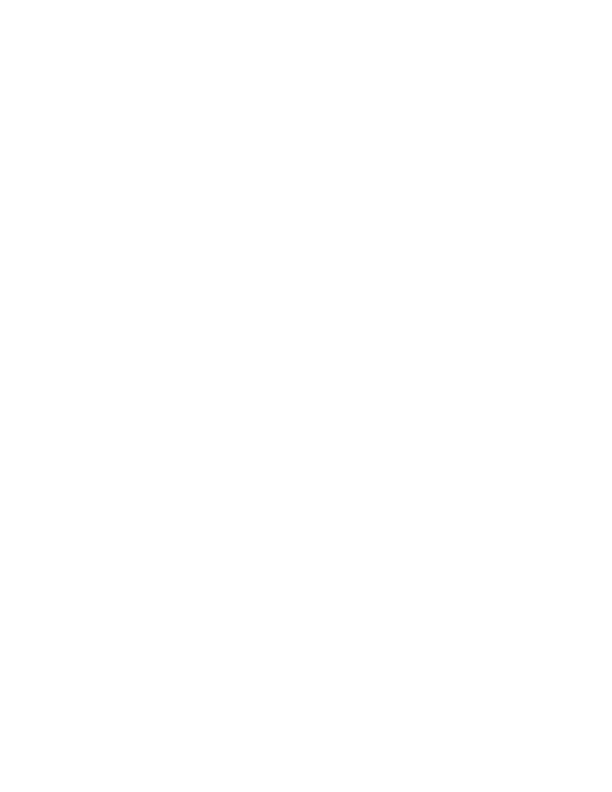
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***m*** *t*

*ds"*

F(«) rf/<

**ELECTRIC CIRCUITS** NINTH EDITION



**ELECTRIC CIRCUITS** NINTH EDITION

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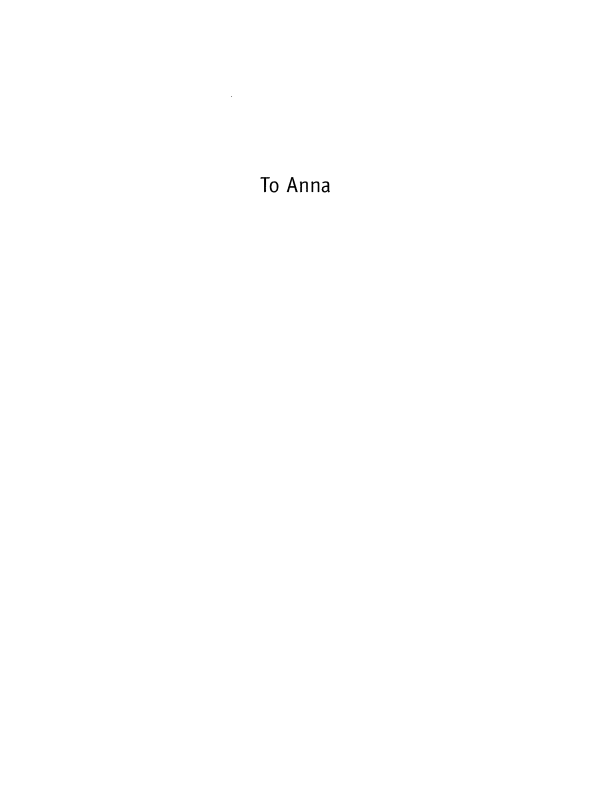
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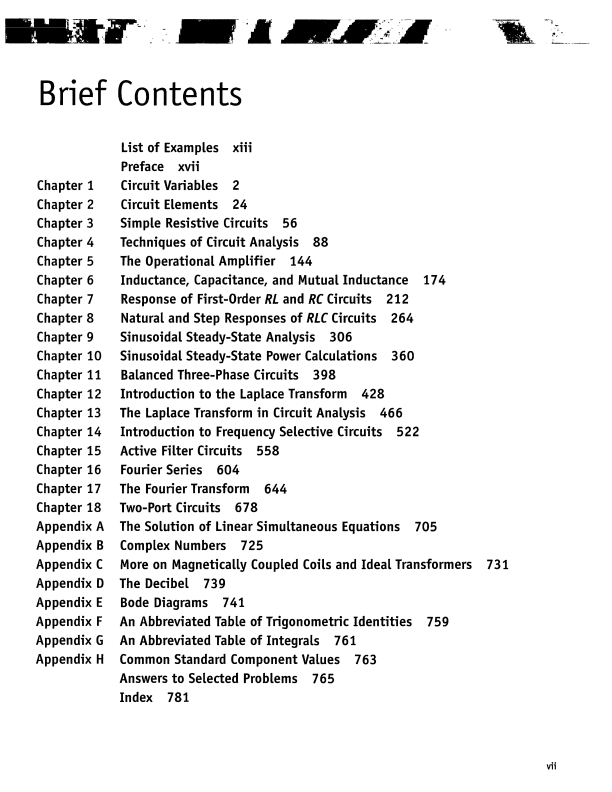
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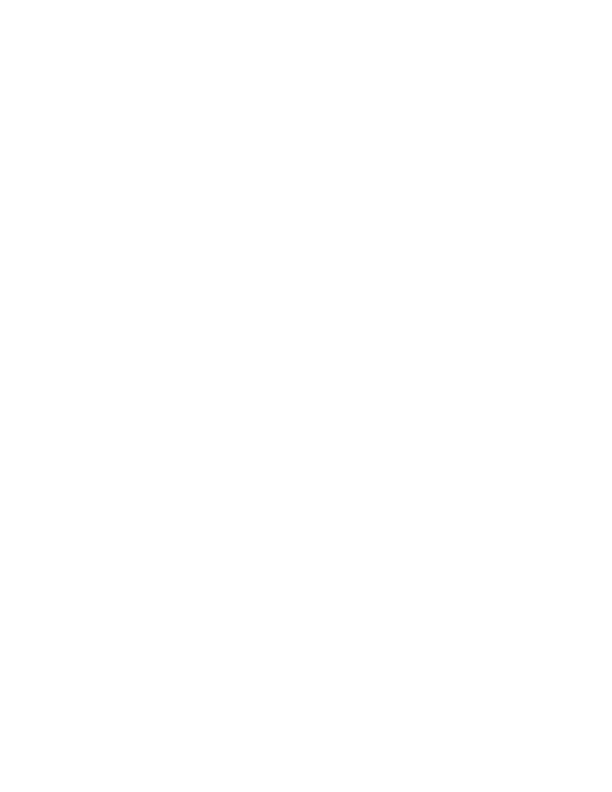
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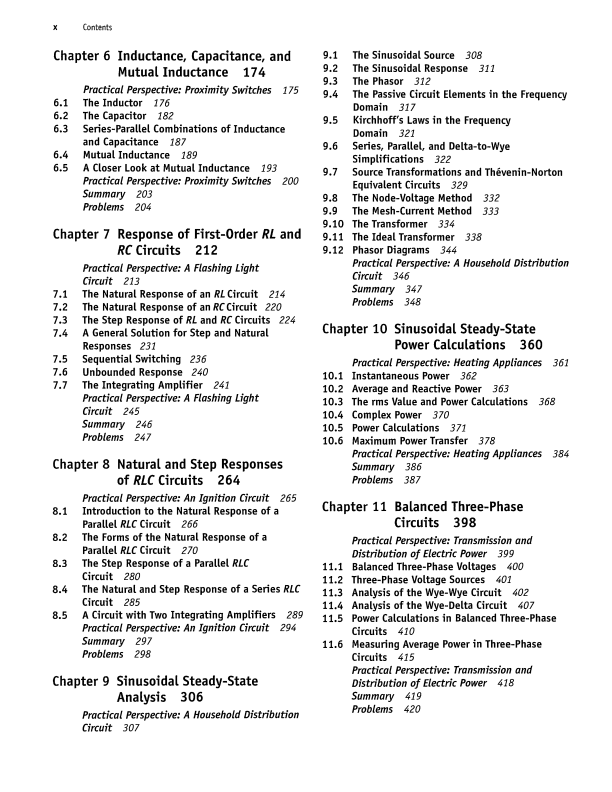
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Preface

The ninth edition of *Electric Circuits* represents a planned revision designed

to incrementally improve this introductory circuits text used by more than

700,000 students worldwide during the past 28 years. While the book has

evolved over the years to meet the changing learning styles of students, the

fundamental goals of the text remain unchanged. These goals are:

• To build an understanding of concepts and ideas explicitly in terms of

previous learning. Students are constantly challenged by the need to

layer new concepts on top of previous concepts they may still be

struggling to master. This text provides an important focus on helping

students understand how new concepts are related to and rely upon

concepts previously presented.

• To emphasize the relationship between conceptual understanding

and problem-solving approaches. Developing problem-solving skills

continues to be the central challenge in a first-year circuits course. In

this text we include numerous Examples that present problem-

solving techniques followed by Assessment Problems that enable

students to test their mastery of the material and techniques intro-

duced. The problem-solving process we illustrate is based on con-

cepts rather than the use of rote procedures. This encourages

students to think about a problem before attempting to solve it.

• To provide students with a strong foundation of engineering prac-

tices. There are limited opportunities in a first-year circuit analysis

course to introduce students to realistic engineering experiences. We

continue to take advantage of the opportunities that do exist by

including problems and examples that use realistic component values

and represent realizable circuits. We include many problems related

to the Practical Perspective problems that begin each chapter. We

also include problems intended to stimulate the students' interest in

engineering, where the problems require the type of insight typical of

a practicing engineer.

**WHY THIS EDITION?**

The ninth edition revision of *Electric Circuits* began with a thorough

review of the text by instructors who currently use *Electric Circuits* and

those who use other texts. This review provided a clear picture of what mat-

ters most to instructors and their students and led to the following changes:

• Problem solving is fundamental to the study of circuit analysis.

Having a wealth of new problems to assign and work is a key to suc-

cess in any circuits course. Therefore, existing end-of-chapter prob-

lems were revised, and new end-of-chapter problems were added.

The result is a text with approximately 75% new or revised problems

compared to the previous edition.

• Both students and instructors want to know how the generalized

techniques presented in a first-year circuit analysis course relate to

problems faced by practicing engineers. The Practical Perspective

problems provide this connection between circuit analysis and the

real world. We have expanded the use of the Practical Perspectives so

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that they now appear at the start of every chapter. Each Practical Perspective problem is solved, at least in part, at the end of the chap ter, and additional end-of-chapter problems can be assigned to allow

students to explore the Practical Perspective topic further. • Examples embedded in the text that illustrate the application of con cepts just presented are an important tool to improve student under standing. The ninth edition adds new examples and now all chapters except Chapter 12 have a minimum of four examples. Chapter 12, which presents an introduction to Laplace transform techniques, is comprised of a collection of examples, but does not follow the format of concept-example employed by the other chapters.

• Previous editions of *Electric Circuits* contained many end-of-chapter problems with circuits comprised of components with standard val ues. These circuits could actually be constructed and tested in a labo ratory. New to the ninth edition is Appendix H, which lists standard values for resistors, inductors, and capacitors. Also new are end-of chapter problems for most chapters that ask students to use compo nents from Appendix H to construct circuits that meet particular requirements. The use of standard components is another effort to tie circuit analysis concepts to real-world circuits.

• Previous editions of *Electric Circuits* have been published with an optional separate paperback manual presenting an introduction to PSpice and its use in simulating circuits a student encounters in their study of linear circuits. With the ninth edition, students and instruc

tors can choose from two circuit-simulation manuals—PSpice, or Multisim. Each manual presents the simulation material in the same order as the material is presented in the text. These manuals continue to include examples of circuits to be simulated that are drawn directly from the text. The text continues to indicate end-of-chapter problems that are good candidates for simulation using either PSpice or Multisim.

• Students who could benefit from additional examples and practice problems can use the Student Workbook. This workbook has exam ples and problems covering the following material: balancing power, simple resistive circuits, node voltage method, mesh current method, Thevenin and Norton equivalents, op amp circuits, first-order cir cuits, second-order circuits, AC steady-state analysis, and Laplace transform circuit analysis.

• Instructors and students benefit greatly from thoughtful methods of assessing student learning. The ninth edition makes PowerPoint pre sentations available to instructors that include embedded assessment questions. During a lecture, the instructor can present material using PowerPoint, pose a question to the students concerning that material, and allow students to respond to the question. Using a Classroom Response System, results from student responses are immediately available to the instructor, providing real-time information about the students' comprehension of the material. This immediate feedback allows the instructor go back and revisit material the students did not comprehend, or to continue presenting new material if comprehen

sion is satisfactory.

• Every new copy of the book now comes with access to Video Solutions and a Pearson etext. Video solutions are complete, step-by step solution walkthroughs of representative homework problems. The Pearson etext is a complete on-line version of the book that includes highlighting, note-taking and search capabilities.

**HALLMARK FEATURES**

**Chapter Problems**

Users of *Electric Circuits* have consistently rated the Chapter Problems as one of the book's most attractive features. In the ninth edition, there are over 1300 problems with approximately 75% that are new or revised from the previous edition. Problems are organized at the end of each chapter by section.

**Practical Perspectives**

The ninth edition continues the use of Practical Perspectives introduced with the chapter openers. They offer examples of real-world circuits, taken from real-world devices. Every chapter begins with a brief description of a practical application of the material that follows. Once the chapter mate

rial is presented, the chapter concludes with a quantitative analysis of the Practical Perspective application. A group of end-of-chapter problems directly relates to the Practical Perspective application. Solving some of these problems enables you to understand how to apply the chapter con

tents to the solution of a real-world problem.

**Assessment Problems**

Each chapter begins with a set of chapter objectives. At key points in the chapter, you are asked to stop and assess your mastery of a particular objective by solving one or more assessment problems. The answers to all of the assessment problems are given at the conclusion of each problem, so you can check your work. If you are able to solve the assessment problems for a given objective, you have mastered that objective. If you need more practice, several end-of-chapter problems that relate to the objective are suggested at the conclusion of the assessment problems.

**Examples**

Every chapter includes many examples that illustrate the concepts presented in the text in the form of a numeric example. There are nearly 150 examples in this text. The examples are intended to illus trate the application of a particular concept, and also to encourage good problem-solving skills.

**Fundamental Equations and C**o**ncepts**

Throughout the text, you will see fundamental equations and concepts set apart from the main text. This is done to help you focus on some of the key principles in electric circuits and to help you navigate through the important topics.

**Integrati**o**n** o**f C**o**mputer T**oo**ls**

Computer tools can assist students in the learning process by providing a visual representation of a circuit's behavior, validating a calculated solu tion, reducing the computational burden of more complex circuits, and iterating toward a desired solution using parameter variation. This compu tational support is often invaluable in the design process. The ninth edition includes the support of PSpice® and Multisim®, both popular computer tools for circuit simulation and analysis. Chapter problems suited for exploration with PSpice and Multisim are marked accordingly.

**Design Emphasis**

The ninth edition continues to support the emphasis on the design of cir cuits in many ways. First, many of the Practical Perspective discussions focus on the design aspects of the circuits. The accompanying Chapter Problems continue the discussion of the design issues in these practical examples. Second, design-oriented Chapter Problems have been labeled explicitly, enabling students and instructors to identify those problems with a design focus. Third, the identification of problems suited to explo ration with PSpice or Multisim suggests design opportunities using these software tools. Fourth, new problems have been added to most chapters that focus on the use of realistic component values in achieving a desired circuit design. Once such a problem has been analyzed, the student can proceed to a laboratory to build and test the circuit, comparing the analy sis with the measured performance of the actual circuit.

**Accuracy**

All text and problems in the ninth edition have undergone our strict hall mark accuracy checking process, to ensure the most error-free book possible.

**RESOURCES FOR STUDENTS**

**Companion** Website. The Companion Website, located at www. pearsonhighered.com/nilsson, includes opportunities for practice and review including:

• **Video Solutions** - Complete, step-by-step solution walkthroughs of representative homework problems for each chapter.

• **Pearson etext** - A complete on-line version of the book that includes highlighting, note-taking and search capabilities.

• **On-Line Study Guide** - Chapter-by-Chapter notes that highlight key concepts of electric circuits

An access code to the Companion Website is included with the purchase of every new copy of Nilsson/Riedel, Electric Circuits 9e and can be redeemed at www.pearsonhighered.com/nilsson. Access can also be pur chased directly from the site.

**Student Study** Pack. This resource teaches students techniques for solv ing problems presented in the text. Organized by concepts, this is a valu able problem-solving resource for all levels of students.

**Introduction to Multisim and Introduction to PSpice Manuals—**Updated for the ninth edition, these manuals are excellent resources for those wish ing to integrate PSpice or Multisim into their classes.

**RESOURCES FOR INSTRUCTORS**

All instructor resources are available for download at www.pearsonhigh ered.com. If you are in need of a login and password for this site, please contact your local Pearson representative.

**Instructor Solutions Manual—**Fully worked-out solutions to end-of chapter problems

**PowerPoint lecture images—**All figures from the text are available in PowerPoint for vour lecture needs.

**Custom Solutions—**New options for textbook customization are now available for Electric Circuits, Ninth Edition. Please contact your local Pearson representative for details.

**PREREQUISITES**

In writing the first 12 chapters of the text, we have assumed that the reader has taken a course in elementary differential and integral calculus. We have also assumed that the reader has had an introductory physics course, at either the high school or university level, that introduces the concepts of energy, power, electric charge, electric current, electric poten

tial, and electromagnetic fields. In writing the final six chapters, we have assumed the student has had, or is enrolled in, an introductory course in differential equations.

**COURSE OPTIONS**

The text has been designed for use in a one-semester, two-semester, or a three-quarter sequence.

• *Single-semester course:* After covering Chapters 1-4 and Chapters 6-10 (omitting Sections 7.7 and 8.5) the instructor can choose from Chapter 5 (operational amplifiers), Chapter 11 (three-phase circuits). Chapters 13 and 14 (Laplace methods), and Chapter 18 (Two-Port Circuits) to develop the desired emphasis.

• *Two-semester sequence:* Assuming three lectures per week, the first nine chapters can be covered during the first semester, leaving Chapters 10-18 for the second semester.

• *Academic quarter schedule:* The book can be subdivided into three parts: Chapters 1-6, Chapters 7-12, and Chapters 13-18.

The introduction to operational amplifier circuits in Chapter 5 can be omitted without interfering with the reading of subsequent chapters. For example, if Chapter 5 is omitted, the instructor can simply skip Section 7.7, Section 8.5, Chapter 15, and those assessment problems and end-of

chapter problems in the chapters following Chapter 5 that pertain to oper ational amplifiers.

There are several appendixes at the end of the book to help readers make effective use of their mathematical background. Appendix A reviews Cramer's method of solving simultaneous linear equations and simple matrix algebra; complex numbers are reviewed in Appendix B; Appendix C contains additional material on magnetically coupled coils and ideal transformers; Appendix D contains a brief discussion of the deci

bel; Appendix E is dedicated to Bode diagrams; Appendix F is devoted to an abbreviated table of trigonometric identities that are useful in circuit analysis; and an abbreviated table of useful integrals is given in Appendix G. A new Appendix H provides tables of common standard component values for resistors, inductors, and capacitors, to be used in solving many new end-of-chapter problems. Selected Answers provides answers to selected end-of-chapter problems.

**ACKNOWLEDGMENTS**

There were many hard-working people behind the scenes at our publisher who deserve our thanks and gratitude for their efforts on behalf of the ninth edition. At Pearson, we would like to thank Andrew Gilfillan, Rose Kernan, Lisa McDowell, Kristine Carney, Tim Galligan, and

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We are deeply indebted to the many instructors and students who have offered positive feedback and suggestions for improvement. We are delighted whenever we receive email from instructors and students who use the book, even when they are pointing out an error we failed to catch in the review process. We have been contacted by people who use our text from all over the world, and even from someone who went to kinder

garten with one of us! We use as many of your suggestions as possible to continue to improve the content, the pedagogy, and the presentation in this text. We are privileged to have the opportunity to impact the educa tional experience of the many thousands of future engineers who will turn the pages of this text.

James W. Nilsson

Susan A. Riedel

**ELECTRIC CIRCUITS** NINTH EDITION

**CHAPTER CONTENTS**

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1.5 The Ideal Basic Circuit Element p. 12 1.6 Power and Energy p. 14

**/"CHAPTER OBJECTIVES**

1 Understand and be able to use SI units and the standard prefixes for powers of 10.

2 Know and be able to use the definitions of voltage and current.

3 Know and be able to use the definitions of power and energy.

4 Be able to use the passive sign convention to calculate the power for an ideal basic circuit element given its voltage and current.

2

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Circuit Variables

**Electrical engineering** is an exciting and challenging profession for anyone who has a genuine interest in, and aptitude **for,** applied science and mathematics. Over the past century and a half, electrical engineers have played a dominant **role in** the development of systems that have changed the way people live and work. Satellite communication links, telephones, digital com

puters, televisions, diagnostic and surgical medical equipment, assembly-line robots, and electrical power tools are representa tive components of systems that define a modern technological society. As an electrical engineer, you can participate in this ongo ing technological revolution by improving and refining these existing systems and by discovering and developing new systems to meet the needs of our ever-changing society.

As you embark on the study of circuit analysis, you need to gain a feel for where this study fits into the hierarchy of topics that comprise an introduction to electrical engineering. Hence we begin by presenting an overview of electrical engineering, some ideas about an engineering point of view as it relates to circuit analysis, and a review of the international system of units.

We then describe generally what circuit analysis entails. Next, we introduce the concepts of voltage and current. We follow these concepts with discussion of an ideal basic element and the need **for** a polarity reference system. We conclude the chapter by describing how current and voltage relate to power and energy.

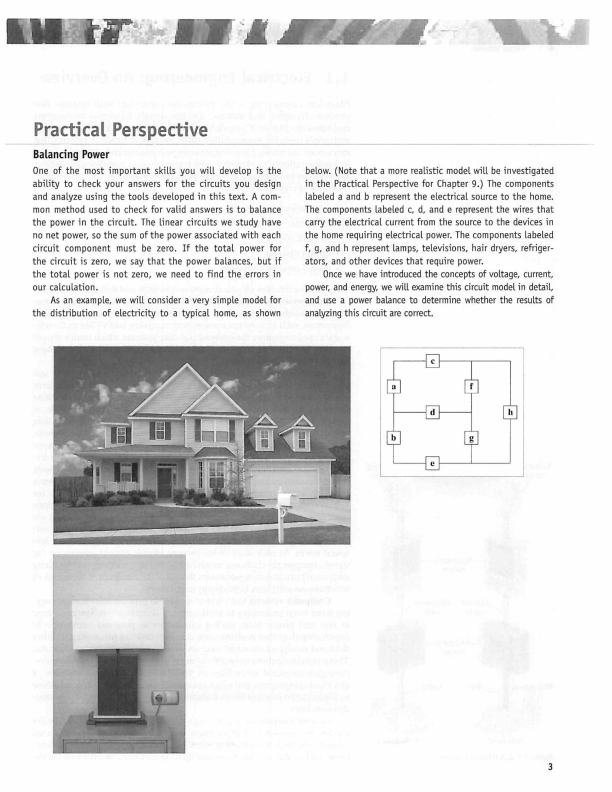
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**Practical Perspective**

**Balancing Power**

One of the most important skills you will develop is the ability to check your answers for the circuits you design and analyze using the tools developed in this text. A com mon method used to check for valid answers is to balance the power in the circuit. The linear circuits we study have no net power, so the sum of the power associated with each circuit component must be zero. If the total power for the circuit is zero, we say that the power balances, but if the total power is not zero, we need to find the errors in our calculation.

As an example, we will consider a very simple model for the distribution of electricity to a typical home, as shown

below. (Note that a more realistic model will be investigated in the Practical Perspective for Chapter 9.) The components labeled a and b represent the electrical source to the home. The components labeled c, d, and e represent the wires that carry the electrical current from the source to the devices in the home requiring electrical power. The components labeled f, g, and h represent lamps, televisions, hair dryers, refriger 

ators, and other devices that require power.

Once we have introduced the concepts of voltage, current, power, and energy, we will examine this circuit model in detail, and use a power balance to determine whether the results of analyzing this circuit are correct.

**c**

**;**

***\***

**t**

**)**

**d**

**f g**

**h**

Circuit Variables

Transmission

antenna

Microph

Telephone Telephone Figure 1.1 • A telephone system.

**1.1 Electrical Engineering: An Overview**

Electrical engineering is the profession concerned with systems that produce, transmit, and measure electric signals. Electrical engineering combines the physicist's models of natural phenomena with the mathe matician's tools for manipulating those models to produce systems that meet practical needs. Electrical systems pervade our lives; they are found in homes, schools, workplaces, and transportation vehicles everywhere. We begin by presenting a few examples from each of the five major class ifications of electrical systems:

• communication systems

• computer systems

• control systems

• power systems

• signal-processing systems

Then we describe how electrical engineers analyze and design such systems. Communication systems are electrical systems that generate, trans mit, and distribute information. Well-known examples include television equipment, such as cameras, transmitters, receivers, and VCRs; radio tele scopes, used to explore the universe; satellite systems, which return images of other planets and our own; radar systems, used to coordinate plane flights; and telephone systems.

Figure 1.1 depicts the major components of a modern telephone sys tem. Starting at the left of the figure, inside a telephone, a microphone turns sound waves into electric signals. These signals are carried to a switching center where they are combined with the signals from tens, hundreds, or thousands of other telephones. The combined signals leave the switching center; their form depends on the distance they must travel. In our example, they are sent through wires in underground coaxial cables to a microwave transmission station. Here, the signals are transformed into microwave fre quencies and broadcast from a transmission antenna through air and space, via a communications satellite, to a receiving antenna. The microwave receiving station translates the microwave signals into a form suitable for further transmission, perhaps as pulses of light to be sent through fiber-optic cable. On arrival at the second switching center, the combined signals are separated, and each is routed to the appropriate telephone, where an ear phone acts as a speaker to convert the received electric signals back into sound waves. At each stage of the process, electric circuits operate on the signals. Imagine the challenge involved in designing, building, and operating each circuit in a way that guarantees that all of the hundreds of thousands of simultaneous calls have high-quality connections.

Computer systems use electric signals to process information rang ing from word processing to mathematical computations. Systems range in size and power from pocket calculators to personal computers to supercomputers that perform such complex tasks as processing weather data and modeling chemical interactions of complex organic molecules. These systems include networks of microcircuits, or integrated circuits— postage-stampsized assemblies of hundreds, thousands, or millions of electrical components that often operate at speeds and power levels close to fundamental physical limits, including the speed of light and the thermo

dynamic laws.

Control systems use electric signals to regulate processes. Examples include the control of temperatures, pressures, and flow rates in an oil refinery; the fuel-air mixture in a fuel-injected automobile engine; mecha nisms such as the motors, doors, and lights in elevators; and the locks in the

1.1 Electrical Engineering: An Overview 5

Panama Canal. The autopilot and autolanding systems that help to fly and

land airplanes are also familiar control systems.

Power systems generate and distribute electric power. Electric power,

which is the foundation of our technology-based society, usually is gener

ated in large quantities by nuclear, hydroelectric, and thermal (coal-, oil-,

or gas-fired) generators. Power is distributed by a grid of conductors that

crisscross the country. A major challenge in designing and operating such

a system is to provide sufficient redundancy and control so that failure of

any piece of equipment does not leave a city, state, or region completely

without power.

Signal-processing systems act on electric signals that represent infor

mation. They transform the signals and the information contained in them

into a more suitable form. There are many different ways to process the

signals and their information. For example, image-processing systems

gather massive quantities of data from orbiting weather satellites, reduce

the amount of data to a manageable level, and transform the remaining

data into a video image for the evening news broadcast. A computerized

tomography (CT) scan is another example of an image-processing system.

It takes signals generated by a special X-ray machine and transforms them

into an image such as the one in Fig. 1.2. Although the original X-ray sig

nals are of little use to a physician, once they are processed into a recog

nizable image the information they contain can be used in the diagnosis of

disease and injury.

Considerable interaction takes place among the engineering disci

plines involved in designing and operating these five classes of systems.

Thus communications engineers use digital computers to control the flow

of information. Computers contain control systems, and control systems

contain computers. Power systems require extensive communications sys

tems to coordinate safely and reliably the operation of components, which

may be spread across a continent. A signal-processing system may involve

a communications link, a computer, and a control system.

A good example of the interaction among systems is a commercial

airplane, such as the one shown in Fig. 1.3. A sophisticated communica tions system enables the pilot and the air traffic controller to monitor the plane's location, permitting the air traffic controller to design a safe flight path for all of the nearby aircraft and enabling the pilot to keep the plane on its designated path. On the newest commercial airplanes, an onboard computer system is used for managing engine functions, implementing the navigation and flight control systems, and generating video informa tion screens in the cockpit. A complex control system uses cockpit com mands to adjust the position and speed of the airplane, producing the appropriate signals to the engines and the control surfaces (such as the wing flaps, ailerons, and rudder) to ensure the plane remains safely air borne and on the desired flight path. The plane must have its own power system to stay aloft and to provide and distribute the electric power needed to keep the cabin lights on, make the coffee, and show the movie. Signal-processing systems reduce the noise in air traffic communications and transform information about the plane's location into the more meaningful form of a video display in the cockpit. Engineering challenges abound in the design of each of these systems and their integration into a coherent whole. For example, these systems must operate in widely vary ing and unpredictable environmental conditions. Perhaps the most important engineering challenge is to guarantee that sufficient redun dancy is incorporated in the designs to ensure that passengers arrive safely and on time at their desired destinations.

Although electrical engineers may be interested primarily in one area, they must also be knowledgeable in other areas that interact with this area of interest. This interaction is part of what makes electrical

Figure 1.2 A A CT scan of an adult head. Figure 1.3 A An airplane.

engineering a challenging and exciting profession. The emphasis in engi neering is on making things work, so an engineer is free to acquire and use any technique, from any field, that helps to get the job done.

**Circuit Theory**

In a field as diverse as electrical engineering, you might well ask whether all of its branches have anything in common. The answer is yes—electric circuits. An **electric circuit** is a mathematical model that approximates the behavior of an actual electrical system. As such, it provides an impor

tant foundation for learning—in your later courses and as a practicing engineer—the details of how to design and operate systems such as those just described. The models, the mathematical techniques, and the language of circuit theory will form the intellectual framework for your future engi

neering endeavors.

Note that the term *electric circuit* is commonly used to refer to an actual electrical system as well as to the model that represents it. In this text, when we talk about an electric circuit, we always mean a model, unless otherwise stated. It is the modeling aspect of circuit theory that has broad applications across engineering disciplines.

Circuit theory is a special case of electromagnetic field theory: the study of static and moving electric charges. Although generalized field theory might seem to be an appropriate starting point for investigating electric sig nals, its application is not only cumbersome but also requires the use of advanced mathematics. Consequently, a course in electromagnetic field theory is not a prerequisite to understanding the material in this book. We do, however, assume that you have had an introductory physics course in which electrical and magnetic phenomena were discussed.

Three basic assumptions permit us to use circuit theory, rather than electromagnetic field theory, to study a physical system represented by an electric circuit. These assumptions are as follows:

1. *Electrical effects happen instantaneously throughout a system.* We can make this assumption because we know that electric signals travel at or near the speed of light. Thus, if the system is physically small, electric signals move through it so quickly that we can con

sider them to affect every point in the system simultaneously. A sys tem that is small enough so that we can make this assumption is called a **lumped-parameter system.**

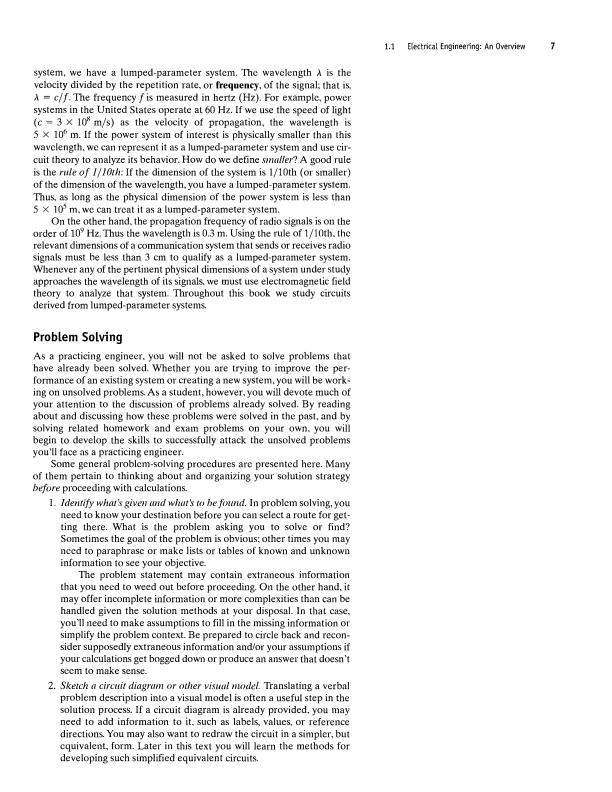
*2. The net charge on every component in the system is always zero.* Thus no component can collect a net excess of charge, although some components, as you will learn later, can hold equal but oppo site separated charges.

3. *There is no magnetic coupling between the components in a system.* As we demonstrate later, magnetic coupling can occur *within* a component.

That's it; there are no other assumptions. Using circuit theory provides simple solutions (of sufficient accuracy) to problems that would become hopelessly complicated if we were to use electromagnetic field theory. These benefits are so great that engineers sometimes specifically design electrical systems to ensure that these assumptions are met. The impor

tance of assumptions 2 and 3 becomes apparent after we introduce the basic circuit elements and the rules for analyzing interconnected elements. However, we need to take a closer look at assumption l.The question

is, "How small does a physical system have to be to qualify as a lumped parameter system?" We can get a quantitative handle on the question by noting that electric signals propagate by wave phenomena. If the wave length of the signal is large compared to the physical dimensions of the

system, we have a lumped-parameter system. The wavelength A is the velocity divided by the repetition rate, or **frequency,** of the signal; that is, A = *c/f.* The frequency /is measured in hertz (Hz). For example, power systems in the United States operate at 60 Hz. If we use the speed of light *(c* = 3 X 108 m/s) as the velocity of propagation, the wavelength is 5 X 106 m. If the power system of interest is physically smaller than this wavelength, we can represent it as a lumped-parameter system and use cir 

cuit theory to analyze its behavior. How do we define *smaller? A* good rule is the *rule of 1/lOth:* If the dimension of the system is l/10th (or smaller) of the dimension of the wavelength, you have a lumped-parameter system. Thus, as long as the physical dimension of the power system is less than 5 X 105 m, we can treat it as a lumped-parameter system.

On the other hand, the propagation frequency of radio signals is on the order of 109 Hz.Thus the wavelength is 0.3 m. Using the rule of l/10th, the relevant dimensions of a communication system that sends or receives radio signals must be less than 3 cm to qualify as a lumped-parameter system. Whenever any of the pertinent physical dimensions of a system under study approaches the wavelength of its signals, we must use electromagnetic field theory to analyze that system. Throughout this book we study circuits derived from lumped-parameter systems.

**Problem Solving**

As a practicing engineer, you will not be asked to solve problems that have already been solved. Whether you are trying to improve the per formance of an existing system or creating a new system, you will be work ing on unsolved problems. As a student, however, you will devote much of your attention to the discussion of problems already solved. By reading about and discussing how these problems were solved in the past, and by solving related homework and exam problems on your own, you will begin to develop the skills to successfully attack the unsolved problems you'll face as a practicing engineer.

Some general problem-solving procedures are presented here. Many of them pertain to thinking about and organizing your solution strategy *before* proceeding with calculations.

1. *Identify what's given and what's to be found.* In problem solving, you need to know your destination before you can select a route for get ting there. What is the problem asking you to solve or find? Sometimes the goal of the problem is obvious; other times you may need to paraphrase or make lists or tables of known and unknown information to see your objective.

The problem statement may contain extraneous information that you need to weed out before proceeding. On the other hand, it may offer incomplete information or more complexities than can be handled given the solution methods at your disposal. In that case, you'll need to make assumptions to fill in the missing information or simplify the problem context. Be prepared to circle back and recon

sider supposedly extraneous information and/or your assumptions if your calculations get bogged down or produce an answer that doesn't seem to make sense.

2. *Sketch a circuit diagram or other visual model.* Translating a verbal problem description into a visual model is often a useful step in the solution process. If a circuit diagram is already provided, you may need to add information to it, such as labels, values, or reference directions. You may also want to redraw the circuit in a simpler, but equivalent, form. Later in this text you will learn the methods for developing such simplified equivalent circuits.

3. *Think of several solution methods and decide on a way of choosing among them.* This course will help you build a collection of analyt ical tools, several of which may work on a given problem. But one method may produce fewer equations to be solved than another, or it may require only algebra instead of calculus to reach a solu tion. Such efficiencies, if you can anticipate them, can streamline your calculations considerably. Having an alternative method in mind also gives you a path to pursue if your first solution attempt bogs down.

4. *Calculate a solution.* Your planning up to this point should have helped you identify a good analytical method and the correct equa tions for the problem. Now comes the solution of those equations. Paper-and-pencil, calculator, and computer methods are all avail able for performing the actual calculations of circuit analysis. Efficiency and your instructor's preferences will dictate which tools you should use.

5. *Use your creativity.* If you suspect that your answer is off base or if the calculations seem to go on and on without moving you toward a solu tion, you should pause and consider alternatives. You may need to revisit your assumptions or select a different solution method. Or, you may need to take a less-conventional problem-solving approach, such as working backward from a solution. This text provides answers to all of the Assessment Problems and many of the Chapter Problems so that you may work backward when you get stuck. In the real world, you won't be given answers in advance, but you may have a desired problem outcome in mind from which you can work backward. Other creative approaches include allowing yourself to see parallels with other types of problems you've successfully solved, following your intuition or hunches about how to proceed, and simply setting the problem aside temporarily and coming back to it later.

6. *Test your solution.* Ask yourself whether the solution you've obtained makes sense. Does the magnitude of the answer seem rea sonable? Is the solution physically realizable? You may want to go further and rework the problem via an alternative method. Doing so will not only test the validity of your original answer, but will also help you develop your intuition about the most efficient solution methods for various kinds of problems. In the real world, safety critical designs are always checked by several independent means. Getting into the habit of checking your answers will benefit you as a student and as a practicing engineer.

These problem-solving steps cannot be used as a recipe to solve every prob lem in this or any other course. You may need to skip, change the order of, or elaborate on certain steps to solve a particular problem. Use these steps as a guideline to develop a problem-solving style that works for you.

**1.2 The International System of Units**

Engineers compare theoretical results to experimental results and com pare competing engineering designs using quantitative measures. Modern engineering is a multidisciplinary profession in which teams of engineers work together on projects, and they can communicate their results in a meaningful way only if they all use the same units of measure. The International System of Units (abbreviated SI) is used by all the major engineering societies and most engineers throughout the world; hence we use it in this book.

1.2 The International System of Units 9

TABLE 1.1 The International System of Units (SI)

**Quantity**

Length

Mass

Time

Electric current

Thermodynamic temperature Amount of substance

Luminous intensity

**Basic Unit** meter

kilogram

second

ampere

degree kelvin mole

candela

**Symbol** m

kg

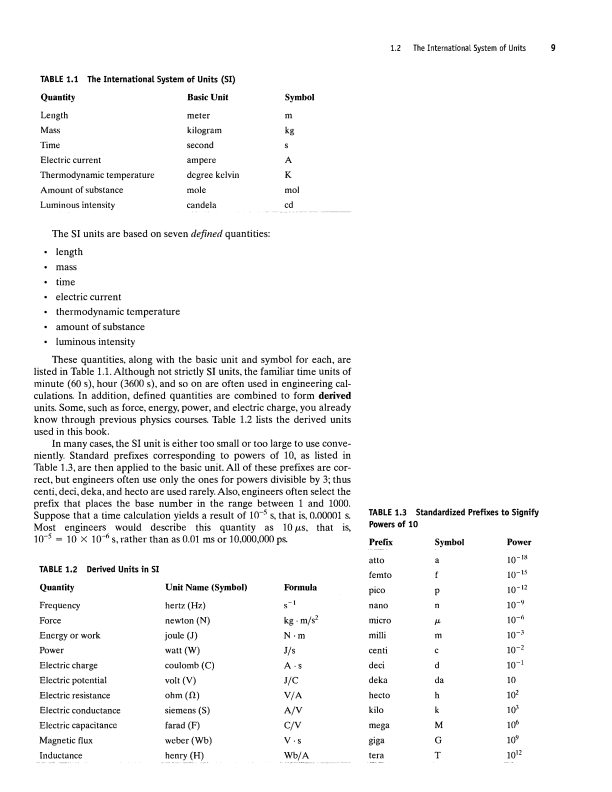
s

A

K

mol

cd

The SI units are based on seven *defined* quantities: 

• length

• mass

• **time**

• electric current

• thermodynamic temperature

• amount of substance

• luminous intensity

These quantities, along with the basic unit and symbol for each, are listed in Table 1.1. Although not strictly SI units, the familiar time units of minute (60 s), hour (3600 s), and so on are often used in engineering cal culations. In addition, defined quantities are combined to form **derived** units. Some, such as force, energy, power, and electric charge, you already know through previous physics courses. Table 1.2 lists the derived units used in this book.

In many cases, the SI unit is either too small or too large to use conve niently. Standard prefixes corresponding to powers of 10, as listed in Table 1.3, are then applied to the basic unit. All of these prefixes are cor rect, but engineers often use only the ones for powers divisible by 3; thus centi, deci, deka, and hecto are used rarely. Also, engineers often select the prefix that places the base number in the range between 1 and 1000. Suppose that a time calculation yields a result of 10~5 s, that is, 0.00001 s. Most engineers would describe this quantity as 10/xs, that is,

TABLE 1.3 Standardized Prefixes to Signify Powers of 10

10"5 = 10 X 10"6 s, rather than as 0.01 ms or 10,000,000 ps. TABLE 1.2 Derived Units in SI

**Prefix**

atto

femto

**Symbol** a

**f**

**Power 1 0 - 1 8 io-15**

**Quantity**

Frequency

Force

Energy or work Power

Electric charge

Electric potential Electric resistance Electric conductance Electric capacitance Magnetic flux

Inductance

**Unit Name (Symbol)** hertz (Hz)

newton (N)

joule (J)

watt (W)

coulomb (C)

volt (V)

ohm (H)

Siemens (S)

farad (F)

weber (Wb)

henry (H)

**Formula** s- 1

kg • m/s2  N m

J/s

A -s

J/C

V/A

A/V

C/V

V -s

Wb/A

pico nano micro milli centi deci

deka hecto kilo

mega giga

tera

**P**

n

**M** m **c**

d

da **h**

**k**

**M G T**

10"12  **io-9** 10- 6  **io-3  io-2  io-1** in

1U2

in3

106

109

1012

10 Circuit Variables

Example 1.1 illustrates a method for converting from one set of units

to another and also uses power-of-ten prefixes.

**Example 1.1 Using SI U**n**its a**n**d Prefixes for Powers of 10**

If a signal can travel in a cable at 80% of the speed of light, what length of cable, in inches, represents 1 ns?

**Solution**

First, note that 1 ns = 10- 9 s. Also, recall that the speed of Light *c =* 3 X 108m/s. Then, 80% of the speed of light is 0.8c = (0.8)(3 x 108) = 2.4 x 108m/s. Using a product of ratios, we can convert 80% of the speed of light from meters-per

second to inches-per-nanosecond. The result is the distance in inches traveled in 1 ns:

Therefore, a signal traveling at 80% of the speed of light will cover 9.45 inches of cable in 1 nanosecond.

2.4 X 108 meters 1 second 100 centimeters 1 inch

1 second 10y nanoseconds 1 meter 2.54 centimeters

(2.4 X 108)(100)

(109)(2.54) = 9.45 inches/nanosecond

**I/ASSESSMENT PROBLEMS**

**Objective 1—Understand and be able to use SI units and the standard prefixes for powers of 10**

**1.1** Assume a telephone signal travels through a cable at two-thirds the speed of light. How long does it take the signal to get from New York City to Miami if the distance is approximately 1100 miles?

**Answer:** 8.85 ms.

*NOTE: Also try Chapter Problems 1.2,1.3, and 1.4.*

**1.2** How many dollars per millisecond would the federal government have to collect to retire a deficit of $100 billion in one year?

**Answer:** $3.17/ms.

**1.3 Circuit Analysis: An Overview**

Before becoming involved in the details of circuit analysis, we need to take a broad look at engineering design, specifically the design of electric circuits. The purpose of this overview is to provide you with a perspective on where circuit analysis fits within the whole of circuit design. Even though this book focuses on circuit analysis, we try to provide opportuni

ties for circuit design where appropriate.

All engineering designs begin with a need, as shown in Fig. 1.4. This need may come from the desire to improve on an existing design, or it may be something brand-new. A careful assessment of the need results in design specifications, which are measurable characteristics of a proposed design. Once a design is proposed, the design specifications allow us to assess whether or not the design actually meets the need.

A concept for the design comes next. The concept derives from a com plete understanding of the design specifications coupled with an insight into

1.4 Voltage and Current 11

the need, which comes from education and experience. The concept may be

realized as a sketch, as a written description, or in some other form. Often the next step is to translate the concept into a mathematical model. A com monly used mathematical model for electrical systems is a **circuit model.**

The elements that comprise the circuit model are called **ideal circuit components.** An ideal circuit component is a mathematical model of an actual electrical component, like a battery or a light bulb. It is important for the ideal circuit component used in a circuit model to represent the behavior of the actual electrical component to an acceptable degree of accuracy. The tools of **circuit analysis,** the focus of this book, are then applied to the circuit. Circuit analysis is based on mathematical techniques and is used to predict the behavior of the circuit model and its ideal circuit components. A comparison between the desired behavior, from the design specifications, and the predicted behavior, from circuit analysis, may lead to refinements in the circuit model and its ideal circuit elements. Once the desired and predicted behavior are in agreement, a physical prototype can be constructed.

The **physical prototype** is an actual electrical system, constructed from actual electrical components. Measurement techniques are used to deter mine the actual, quantitative behavior of the physical system. This actual behavior is compared with the desired behavior from the design specifica

jsjeed

Design

physic<iikConcePl

in\*?1 Circi'1.^

analp

rcuit ;r which

tions and the predicted behavior from circuit analysis. The comparisons may result in refinements to the physical prototype, the circuit model, or both. Eventually, this iterative process, in which models, components, and systems are continually refined, may produce a design that accurately matches the design specifications and thus meets the need.

From this description, it is clear that circuit analysis plays a very important role in the design process. Because circuit analysis is applied to circuit models, practicing engineers try to use mature circuit models so that the resulting designs will meet the design specifications in the first iteration. In this book, we use models that have been tested for between 20 and 100 years; you can assume that they are mature. The ability to model actual electrical systems with ideal circuit elements makes circuit theory extremely useful to engineers.

Saying that the interconnection of ideal circuit elements can be used to quantitatively predict the behavior of a system implies that we can describe the interconnection with mathematical equations. For the mathe matical equations to be useful, we must write them in terms of measurable quantities. In the case of circuits, these quantities are voltage and current, which we discuss in Section 1.4. The study of circuit analysis involves understanding the behavior of each ideal circuit element in terms of its voltage and current and understanding the constraints imposed on the voltage and current as a result of interconnecting the ideal elements.

**1.4 Voltage and Current**

The concept of electric charge is the basis for describing all electrical phe nomena. Let's review some important characteristics of electric charge.

• The charge is bipolar, meaning that electrical effects are described in terms of positive and negative charges.

• The electric charge exists in discrete quantities, which are integral multiples of the electronic charge, 1.6022 X 10-19 C.

• Electrical effects are attributed to both the separation of charge and charges in motion.

In circuit theory, the separation of charge creates an electric force (volt age), and the motion of charge creates an electric fluid (current).

**Figure 1.4 •** A conceptual model for electrical engi neering design.

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The concepts of voltage and current are useful from an engineering

point of view because they can be expressed quantitatively. Whenever

positive and negative charges are separated, energy is expended. **Voltage**

is the energy per unit charge created by the separation. We express this

ratio in differential form as

Definition of voltage • *v* = ***dw***

***dq* ' (1.1)**

where

*v* = the voltage in volts,

*w =* the energy in joules,

*q =* the charge in coulombs.

The electrical effects caused by charges in motion depend on the rate

of charge flow. The rate of charge flow is known as the **electric current,**

which is expressed as

**Definition of current • *i* = *dq***

***~di'* (1.2)**

where

*i* = the current in amperes,

*q* = the charge in coulombs,

*t =* the time in seconds.

Equations 1.1 and 1.2 are definitions for the magnitude of voltage and

current, respectively. The bipolar nature of electric charge requires that we

assign polarity references to these variables. We will do so in Section 1.5.

Although current is made up of discrete, moving electrons, we do not

need to consider them individually because of the enormous number of

them. Rather, we can think of electrons and their corresponding charge as

one smoothly flowing entity. Thus, *i* is treated as a continuous variable.

One advantage of using circuit models is that we can model a compo

nent strictly in terms of the voltage and current at its terminals. Thus two

physically different components could have the same relationship

between the terminal voltage and terminal current. If they do, for pur

poses of circuit analysis, they are identical. Once we know how a compo

nent behaves at its terminals, we can analyze its behavior in a circuit.

However, when developing circuit models, we are interested in a compo

nent's internal behavior. We might want to know, for example, whether

charge conduction is taking place because of free electrons moving

through the crystal lattice structure of a metal or whether it is because of

electrons moving within the covalent bonds of a semiconductor material.

However, these concerns are beyond the realm of circuit theory. In this

book we use circuit models that have already been developed; we do not

discuss how component models are developed.

**1.5 The Ideal Basic Circuit Element**

**An ideal basic circuit element** has three attributes: (1) it has only two ter

minals, which are points of connection to other circuit components; (2) it is

described mathematically in terms of current and/or voltage; and (3) it

cannot be subdivided into other elements. We use the word *ideal* to imply

1.5 The Ideal Basic Circuit Element 13

thai a basic circuit element does not exist as a realizable physical compo

nent. However, as we discussed in Section 1.3, ideal elements can be con

nected in order to model actual devices and systems. We use the word

*basic* to imply that ihe circuit element cannot be further reduced or sub

divided into other elements. Thus the basic circuit elements form the build ing blocks for constructing circuit models, but they themselves cannot be modeled with any other type of element.

Figure 1.5 is a representation of an ideal basic circuit element. The box is blank because we are making no commitment at this time as to the type of circuit element it is. In Fig. 1.5, the voltage across the terminals of the box is denoted by *v,* and the current in the circuit element is denoted by /. The polarity reference for the voltage is indicated by the plus and minus signs, and the reference direction for the current is shown by the arrow placed alongside the current. The interpretation of these references given positive or negative numerical values of *v* and *i* is summarized in Table 1.4. Note that algebraically the notion of positive charge flowing in one direction is equivalent to the notion of negative charge flowing in the opposite direction.

The assignments of the reference polarity for voltage and the refer ence direction for current are entirely arbitrary. However, once you have assigned the references, you must write all subsequent equations to agree with the chosen references. The most widely used sign convention applied to these references is called the passive sign convention, which we use throughout this book. The passive sign convention can be stated as follows:

Whenever the reference direction for the current in an element is in the direction of the reference voltage drop across the element (as in Fig. 1.5), use a positive sign in any expression that relates the voltage to the current. Otherwise, use a negative sign.

We apply this sign convention in all the analyses that follow. Our pur pose for introducing it even before we have introduced the different types of basic circuit elements is to impress on you the fact that the selec tion of polarity references along with the adoption of the passive sign convention is *not* a function of the basic elements nor the type of inter connections made with the basic elements. We present the application and interpretation of the passive sign convention in power calculations in Section 1.6.

Example 1.2 illustrates one use of the equation defining current. TABLE 1.4 Interpretation of Reference Directions in Fig. 1.5

Figure 1.5 • An ideal basic circuit element. *<* Passive sign convention

Positive Value

*v* voltage drop from terminal 1 to terminal 2 ***or***

voltage rise from terminal 2 to terminal 1

*i* positive charge flowing from terminal 1 to terminal 2 ***or***

negative charge flowing from terminal 2 to terminal 1

Negative Value

voltage rise from terminal 1 to terminal 2 ***or***

voltage drop from terminal 2 to terminal 1 positive charge flowing from terminal 2 to terminal 1 ***or***

negative charge flowing from terminal 1 to terminal 2

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Example 1.2 Relating Current and Charge

No charge exists at the upper terminal of the ele ment in Fig. 1.5 for *t* < 0. At *t* = 0, a 5 A current begins to flow into the upper terminal.

a) Derive the expression for the charge accumulat ing at the upper terminal of the element for *t >* 0.

b) If the current is stopped after 10 seconds, how much charge has accumulated at the upper terminal?

**^/ASSESSMENT PROBLEMS**

**Solution**

a) From the definition of current given in Eq. 1.2, the expression for charge accumulation due to current flow is

*q(t)* = *I t(x)dx.*

Therefore,

*q(t) =* / *5dx = 5x* = 5? - 5(0) = *5t C* for *t >* 0.

b) The total charge that accumulates at the upper terminal in 10 seconds due to a 5 A current is ¢(10) = 5(10) = 50 C.

Objective 2—Know and be able to use the definitions of voltage and current

1.3 The current at the terminals of the element in Fig. 1.5 is

1.4 The expression for the charge entering the upper terminal of Fig. 1.5 is

*i =* 0,

/ = 20e -SOOOf

t < 0;

A, *t* > 0. *q* = — *a a*

Calculate the total charge (in microcoulombs) entering the element at its upper terminal.

**Answer:** 4000 */xC.*

*NOTE: Also try Chapter Problem 1.10.*

Find the maximum value of the current enter ing the terminal if *a =* 0.03679 s\_l.

Answer: 10 A.

**1.6 Power and Energy**

Power and energy calculations also are important in circuit analysis. One reason is that although voltage and current are useful variables in the analy sis and design of electrically based systems, the useful output of the system often is nonelectrical, and this output is conveniently expressed in terms of power or energy. Another reason is that all practical devices have limita tions on the amount of power that they can handle. In the design process, therefore, voltage and current calculations by themselves are not sufficient.

We now relate power and energy to voltage and current and at the same time use the power calculation to illustrate the passive sign conven tion. Recall from basic physics that power is the time rate of expending or

1.6 Power and Energy 15

absorbing energy. (A water pump rated 75 kW can deliver more liters per

second than one rated 7.5 kW.) Mathematically, energy per unit time is

expressed in the form of a derivative, or

***dw* (1.3) -+X Definition of power**

where

*p -* the power in watts,

*w* = the energy in joules,

*i* = the time in seconds.

Thus 1 W is equivalent to 1 J/s.

The power associated with the flow of charge follows directly from

the definition of voltage and current in Eqs. 1.1 and 1.2, or

\_ *dw \_ fdw\/dq*

***dt \dg )\dt)'***

so

***p* = *vi* (1.4) ^ Power equation**

where

*p* = the power in watts,

*v —* the voltage in volts,

*i =* the current in amperes.

Equation 1.4 shows that the **power** associated with a basic circuit element

is simply the product of the current in the element and the voltage across

the element. Therefore, power is a quantity associated with a pair of ter

minals, and we have to be able to tell from our calculation whether power

is being delivered to the pair of terminals or extracted from it. This infor

mation comes from the correct application and interpretation of the pas

sive sign convention.

If we use the passive sign convention, Eq. 1.4 is correct if the reference

direction for the current is in the direction of the reference voltage drop

across the terminals. Otherwise, Eq. 1.4 must be written with a minus sign. In other words, if the current reference is in the direction of a reference voltage rise across the terminals, the expression for the power is

***p* = *-vi* (1.5)**

The algebraic sign of power is based on charge movement through

**(a)/'** (b)/» «<--. .

***m 1***

**• Z**

**= *—vi***

**• i**

• z

voltage drops and rises. As positive charges move through a drop in volt age, they lose energy, and as they move through a rise in voltage, they gain energy. Figure 1.6 summarizes the relationship between the polarity refer ences for voltage and current and the expression for power.

**(c)p = -vi (<1)P *vi***

**Figure 1.6 •** Polarity references and the expression for power.

16 Circuit Variables

We can now state the rule for interpreting the algebraic sign of power:

If the power is positive (that is, if *p* > 0), power is being delivered to

**Interpreting algebraic sign of power •**

the circuit inside the box. If the power is negative (that is, if *p <* 0), power is being extracted from the circuit inside the box.

For example, suppose that we have selected the polarity references shown in Fig. 1.6(b). Assume further that our calculations for the current and voltage yield the following numerical results:

*i* = 4 A and *v* = -10 V.

Then the power associated with the terminal pair 1,2 is

*p =* -(-10)(4) = 40 W.

Thus the circuit inside the box is absorbing 40 W.

To take this analysis one step further, assume that a colleague is solv ing the same problem but has chosen the reference polarities shown in Fig. 1.6(c). The resulting numerical values are

-4 A. 10 V, and *P* 40 W.

Note that interpreting these results in terms of this reference system gives the same conclusions that we previously obtained—namely, that the cir cuit inside the box is absorbing 40 W. In fact, any of the reference systems in Fig. 1.6 yields this same result.

Example 1.3 illustrates the relationship between voltage, current, power, and energy for an ideal basic circuit element and the use of the pas sive sign convention.

Example 1.3 **Relating Voltage, Cu**rr**e**n**t, Powe**r**, a**n**d Ene**r**gy**

Assume that the voltage at the terminals of the ele ment in Fig. 1.5, whose current was defined in Assessment Problem 1.3, is

b) From the definition of power given in Eq. 1.3. the expression for energy is

***v* = 0**

***v =* iot>-S(MM)f kV ,**

t < 0; t > 0.

*w(t)* = *I p(x)dx*

*Jo*

To find the total energy delivered, integrate the expresssion for power from zero to infinity.

a) Calculate the power supplied to the element at 1 ms.

b) Calculate the total energy (in joules) delivered to the circuit element.

**Solution**

a) Since the current is entering the + terminal of the voltage drop defined for the element in Fig. 1.5, we use a u + " sign in the power equation.

*p = vL =* (10,000e"5o,M)')(2Oc^5()OOf) = 200,000<r10-()00'W. p(0.001) = 200,000e" 10(,00'(,)(,01) = 200,000e-10  = 200,000(45.4 X 10~6) = 0.908 W.

Therefore,

Wtotal 200.000e"1(WXK)x*dx =* 200,000c -10,000\*  10,000

-20<? - (-20 O = 0 + 20 = 20 J.

Thus, the total energy supplied to the circuit ele ment is 20 J.

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**I/'ASSESSMENT PROBLEMS**

**Objective 3—Know and use the definitions of *power* and *energy;* Objective 4—Be able to use the passive sign convention**

**1.5** Assume that a 20 V voltage drop occurs across an element from terminal 2 to terminal 1 and that a current of 4 A enters terminal 2.

a) Specify the values of ***v*** and /' for the polarity references shown in Fig. 1.6(a)-(d).

b) State whether the circuit inside the box is absorbing or delivering power.

c) How much power is the circuit absorbing?

**Answer:** (a) Circuit 1.6(a): ***v*** = -2 0 V, *i* = - 4 A; circuit 1.6(b): ***v*** *=* -2 0 V, *i* = 4 A;

circuit 1.6(c): *v* « 20 V, *i* - - 4 A;

circuit 1.6(d): *v* = 20 V, *i ~* 4 A;

(b) absorbing;

(c) 80 W.

1.6 The voltage and current at the terminals of the circuit element in Fig 1.5 are zero for *t <* 0. For f£0 , they are

***v*** = 80,000f<r500' V, *t* 2> 0;

*i = 15te-5QQt* A, *t* > 0.

a) Find the time when the power delivered to the circuit element is maximum.

b) Find the maximum value of power.

c) Find the total energy delivered to the cir cuit element.

**Answer:** (a) 2 ms; (b) 649.6 mW; (c) 2.4 mJ.

1.7 A high-voltage direct-current (dc) transmission line between Celilo, Oregon and Sylmar,

California is operating at 800 kV and carrying 1800 A, as shown. Calculate the power (in megawatts) at the Oregon end of the line and state the direction of power flow.

1.8 k A

Celilo,

Oregon 800 kV Sylmar,

California

**Answer:** 1440 MW, Celilo to Sylmar.

*NOTE: Also try Chapter Problems 1.14,1.18,1.25, and 1.26.*

**Practical Perspective**

**Balancing Power**

A model of the circuitry that distributes power to a typical home is shown in Fig. 1.7 with voltage polarities and current directions defined for all of the circuit components. The results of circuit analysis give the values for all of these voltages and currents, which are summarized in Table 1.4. To deter

mine whether or not the values given are correct, calculate the power asso ciated with each component. Use the passive sign convention in the power calculations, as shown below.

*Pa* = *vja =* (120)(-10) = -1200 W *Pc* = *vcic* = (10)(10) = 100 W *pe = vje* = (-10)(-9) = 90 W *pg* = *vgig* = (120)(4) = 480 W

*Pb* = -tfcjft *=* -(120)(9) = -1080 W *Pc=* -^=-(10)(1) = -10W *pf = -vfy =* -(-100)(5) = 500 W *Pi, ^ vhih =* (-220)(-5) = 1100 W

The power calculations show that components a, b, and d are supplying power, since the power values are negative, while components c, e, f, g, and h are absorbing power. Now check to see if the power balances by finding the total power supplied and the total power absorbed.

18 Circuit Variables

Supplied = *Pa* + *Pb + Pd =* -1200 - 1080 - 10 = -2290 W

Pabsorbed = *Pc* + *Pe* + *Pf* + *Pg* + *Ph*

= 100 + 90 + 500 + 480 + 1100 = 2270 W

^supplied + ^absorbed = "229 0 + 227 0 = -2 0 W

Something is wrong—if the values for voltage and current in this circuit are

correct, the total power should be zero! There is an error in the data and we

can find it from the calculated powers if the error exists in the sign of a sin

gle component. Note that if we divide the total power by 2, we get -1 0 W,

which is the power calculated for component d. If the power for component

d was +10 W, the total power would be 0. Circuit analysis techniques from

upcoming chapters can be used to show that the current through component

d shouLd be - 1 A, not +1 A given in Table 1.4.

+ **AC TABLE 1.4 Volatage and current**

**values for the circuit in Fig. 1.7.**

**+**

***v»*** a

c

**—\*-** »c

**—**

**+ 1**

**Component** a

b

c

d

e

f

***v(Y)*** 120

120

**10**

**10**

**-10**

-100

i(A) **-10 9**

**10**

**1**

**-9**

**5**

***+*** "h

**H.**

b **fa**

- y«j + d

**—*\*-***

**'a**

***+ ve* —  'c**

**+** i>g

**• i'-r**

«h h

**+**

**?'•**

**C**

**J**

g h

120

-220

**4**

**-5**

**Figure 1.7 •** Circuit model for power distribution in a home, with voltages and currents defined.

Note: Assess your understanding of the Practical Perspective by trying Chapter

Problems 1.31 and 1.32.

**Summary**

The International System of Units (SI) enables engineers to communicate in a meaningful way about quantitative results. Table 1.1 summarizes the base SI units; Table 1.2 presents some useful derived SI units. (See pages 8 and 9.) Circuit analysis is based on the variables of voltage and current. (See page **11.)**

**Voltage** is the energy per unit charge created by charge separation and has the SI unit of volt *(v* = *dw/dq).* (See page 12.)

**Current** is the rate of charge flow and has the SI unit of ampere *(i = dq/dt).* (See page 12.)

The **ideal basic circuit element** is a two-terminal compo nent that cannot be subdivided; it can be described mathematically in terms of its terminal voltage and cur rent. (See page 12.)

The **passive sign convention** uses a positive sign in the expression that relates the voltage and current at the terminals of an element when the reference direction for the current through the element is in the direction of the reference voltage drop across the element. (See page 13.)

**Power** is energy per unit of time and is equal to the product of the terminal voltage and current; it has the SI unit of watt *(p = dw/dt = vi).* (See page 15.)

The algebraic sign of power is interpreted as follows: • If *p* > 0, power is being delivered to the circuit or circuit component.

• If *p <* 0, power is being extracted from the circuit or circuit component. (See page 16.)

Problems **19**

**Problems**

**Section 1.2**

**1.1** Some species of bamboo can grow 250 mm/day. Assume individual cells in the plant are 10 */xm* long. a) How long, on average, does it take a bamboo stalk to grow 1 cell length?

b) How many cell lengths are added in one week, on average?

**1.2** One liter (L) of paint covers approximately 10 m2  of wall. How thick is the layer before it dries? *(Hint.* 1 L = 1 X 106 mm3.)

**1.3** There are approximately 260 million passenger vehicles registered in the United States. Assume that the battery in the average vehicle stores 540 watt-hours (Wh) of energy. Estimate (in gigawatt-hours) the total energy stored in U.S. pas

senger vehicles.

**1.4** The 16 giga-byte (GB = 23{) bytes) flash memory chip for an MP3 player is 11 mm by 15 mm by 1 mm. This memory chip holds 20,000 photos.

a) How many photos fit into a cube whose sides are 1 mm?

b) How many bytes of memory are stored in a cube whose sides are 200 */j,m?*

**1.5** A hand-held video player displays 480 x 320 picture elements (pixels) in each frame of the video. Each pixel requires 2 bytes of memory. Videos are dis played at a rate of 30 frames per second. How many hours of video will fit in a 32 gigabyte memory?

**1.6** The line described in Assessment Problem 1.7 is 845 mi in length. The line contains four conductors, each weighing 2526 lb per 1000 ft. How many kilo grams of conductor are in the line?

**Section 1.4**

**1.7** How much energy is imparted to an electron as it flows through a 6 V battery from the positive to the negative terminal? Express your answer in attojoules.

1.8 In electronic circuits it is not unusual to encounter currents in the microampere range. Assume a 35 juA current, due to the flow of electrons. What is the average number of electrons per second that flow past a fixed reference cross section that is per

pendicular to the direction of flow?

1.9 A current of 1600 A exists in a rectangular (0.4-by 16 cm) bus bar. The current is due to free electrons moving through the wire at an average velocity of *v* meters/second. If the concentration of free elec trons is 1029 electrons per cubic meter and if they are uniformly dispersed throughout the wire, then what is the average velocity of an electron?

**1.10** The current entering the upper terminal of Fig. 1.5 is *i =* 20 cos 50()0f A.

Assume the charge at the upper terminal is zero at the instant the current is passing through its maxi mum value. Find the expression for *q(t).*

**Sections 1.5-1.6**

**1.11** When a car has a dead battery, it can often be started by connecting the battery from another car across its terminals. The positive terminals are connected together as are the negative terminals. The connec

tion is illustrated in Fig. Pl.ll. Assume the current *i* in Fig. Pl.ll is measured and found to be 30 A.

a) Which car has the dead battery?

b) If this connection is maintained for 1 min, how much energy is transferred to the dead battery?

Figure **Pl.ll**

A -— /' B

**1.12** One 12 V battery supplies 100 mA to a boom box. How much energy does the battery supply in 4 h?

**1.13** The manufacturer of a 1.5 V D flashlight battery says that the battery will deliver 9 mA for 40 con tinuous hours. During that time the voltage will drop from 1.5 V to 1.0 V. Assume the drop in volt age is linear with time. How much energy does the battery deliver in this 40 h interval?

**1.14** Two electric circuits, represented by boxes A and B, are connected as shown in Fig. PI.14.The reference direction for the current *i* in the interconnection and the reference polarity for the voltage *v* across the interconnection are as shown in the figure. For each

20 Circuit Variables

of the following sets of numerical values, calculate the power in the interconnection and state whether the power is flowing from A to B or vice versa. a) *i =* 10 A, *v =* 125 V

b) / = 5 A, *v =* -240 V

c) *i* = -12 A, *v* = 480 V

d) / = -25 A, *v =* -660 V

Figure P1.14

***i***

Figure P1.19

/(A)

7 8 9 10 f(s)

A

***+***

***V*** B

«(V) 5

**1.15** The references for the voltage and current at the terminal of a circuit element are as shown in Fig. 1.6(d).The numerical values for *v* and *i* are 40 V and-1 0 A.

a) Calculate the power at the terminals and state whether the power is being absorbed or deliv ered by the element in the box.

b) Given that the current is due to electron flow,

**J I L**

1 2 3 4 5 6 7 8 9 10 / (s)

**-5**

(b)

state whether the electrons are entering or leav ing terminal 2.

c) Do the electrons gain or lose energy as they pass through the element in the box?

**1.16** Repeat Problem **1.15** with a voltage of -6 0 V.

**1.17** The voltage and current at the terminals of the cir PSPICE cuit element in Fig. 1.5 are zero for *t <* 0. For \* > 0 MULTISIM theyar e

75<T1000' V, ***v* 75**

/ = 50e -1000/ mA.

a) Find the maximum value of the power delivered to the circuit.

b) Find the total energy delivered to the element.

**1.18** The voltage and current at the terminals of the cir cuit element in Fig. 1.5 are zero for *t <* 0. For *t >* 0 they are

*v =* 50<r]600' - 50e~400' V,

*i =*5e-i60O/ \_ 5e-4oo, m A

a) Find the power at *t =* 625 /xs.

b) How much energy is delivered to the circuit ele ment between 0 and 625 /xs?

c) Find the total energy delivered to the element. **1.19** The voltage and current at the terminals of the cir

**1.20** The voltage and current at the terminals of the cir PSPICE cu it element in Fig. 1.5 are zero for *t < 0.* For *t* > 0 **MULTISIM j i**

they are

*v* = 400e"100' sin 200r V,

*i =* 5C-1<» si n 200f A.

a) Find the power absorbed by the element at *t -* 10 ms.

b) Find the total energy absorbed by the element.

**1.21** The voltage and current at the terminals of the cir PSPICE cuit element in Fig. 1.5 are zero for *t <* 0. For *t ^* 0 HULns,M theyare

*v* = (16,000; + 20)e~8TO V,

*i* = (128\* + 0.16)e"800' A.

a) At what instant of time is maximum power delivered to the element?

b) Find the maximum power in watts.

c) Find the total energy delivered to the element in millijoules.

**1.22** The voltage and current at the terminals of the cir PSPICE cuit element in Fig. 1.5 are zero for *t <* 0. For *t >* 0 MumsiM theyare

*v =* (10,000\* + *5)e~4m* V,

**\* > 0;**

cuit element in Fig. 1.5 are shown in Fig. PI. 19.

*i =* (40; + 0.05)<T400' A,

**\* > 0.**

a) Sketch the power versus \* plot for 0 < \* ^ 10 s. b) Calculate the energy delivered to the circuit ele ment at \* *=* 1, 6, and 10 s.

a) Find the time (in milliseconds) when the power delivered to the circuit element is maximum.

b) Find the maximum value of *p* in milliwatts. c) Find the total energy delivered to the circuit ele ment in millijoules.

1.23 The voltage and current at the terminals of the ele PSPICE ment in Fig. 1.5 are

**MUITISIM**

*v =* 250 cos 800TT/ V, *i =* 8 sin 800TT/ A.

a) Find the maximum value of the power being delivered to the element.

b) Find the maximum value of the power being extracted from the element.

c) Find the average value of *p* in the interval 0 < / < 2.5 ms.

Problems 21

a) At what instant of time is the power being deliv ered to the circuit element maximum?

b) What is the power at the time found in part (a)? c) At what instant of time is the power being extracted from the circuit element maximum? d) What is the power at the time found in part (c)? e) Calculate the net energy delivered to the circuit at 0,10,20,30 and 40 s.

1.26 The numerical values for the currents and voltages in the circuit in Fig. P1.26 are given in Table P1.26. Find the total power developed in the circuit.

Figure P1.26

d) Find the average value of *p* in the interval 0 < *t* < 15.625 ms.

1.24 The voltage and current at the terminals of an auto PSPICE mobile battery during a charge cycle are shown in **MULTISIM Fig p 124 .**

a) Calculate the total charge transferred to the battery.

***I.* t**

**<b**

*\*-*

**|4**

**+ »•** a

*+*

b

-

**\_ J<e «,J**

b) Calculate the total energy transferred to the battery.

**C**

TABLE P1.26

d

**- Vd +**

*vc* e  *+*

***k***

f

z(ks)

Element a

b

c

d

e

I'

Voltage (kV)

150

150

100

250

300

-300

Current (raA) 0.6

-1.4

-0.8

-0.8

-2.0

1.2

1.27 The numerical values of the voltages and currents in the interconnection seen in Fig. PI.27 are given in Table PI.27. Does the interconnection satisfy the power check?

Figure PI.27

***vd +***

***A***

/(ks)

1.25 The voltage and current at the terminals of the circuit PSPICE element in Fig. 1.5 are zero for *t <* 0 and *t >* 40 s. In LTISIM the interval between 0 and 40 s the expressions are

*v* = /(1 - 0.025r)V, 0 < *t <* 40 s;

/ = 4 - 0.2/ A, 0 < / < 40 s.

*-* k *va u*

+

+

yb b *\ib* ***vc* n**

***id***

*+ ve -* ***+ v(***

+

**'ft «\_**

fct l **1 *Vb  +***

22 Circuit Variables

**TABLE PI.27**

**Element**

**a**

**b**

**c**

**d**

**e**

**f**

**g**

**h**

**Voltage (V)** 990

600

300

105

-120

165

585

-585

**Current (mA)** -22.5

**-30**

60

52.5

**30**

82.5

52.5

82.5

1.29 a) The circuit shown in Fig. PI.29 identifies volt age polarities and current directions to be used in calculating power for each component. Using only the voltage polarities and current directions, predict which components supply power and which components absorb power, using the passive sign convention.

b) The numerical values of the currents and volt ages for each element are given in Table PI.29. How much total power is absorbed and how much is delivered in this circuit?

c) Based on the computations in part (b), identify the components that supply power and those that absorb power. Why are these answers dif

1.28 Assume you are an engineer in charge of a project and one of your subordinate engineers reports that the interconnection in Fig. PI .28 does not pass the power check. The data for the interconnection are

ferent from the ones in part (a)?

Figure P1.29

***vb +***

given in Table PI.28.

a

***b***

"

a) Is the subordinate correct? Explain your answer.

—

***k***

**+**

**+**

b) If the subordinate is correct, can you find the error in the data?

Figure P1.28

c **I'c**

**d**

***lg***

**g**

**. A ' d \***

***V<i*** —

**M**

**'h**

**h**

**e uc  —**

**., t**

**f U** +

+ **\l**

-

**d t\*.**

**»b b**

**ig**

**g**

**+**

-**i a a**

**» a**

**U e**

+

+

***>\-***

+ **»e  c**

**'c**

\*-

h

-

**<H** f ***v,***

**»,, +**

TABLE P1.29 Element

a

b

c

d

**+ »h -**

Voltage (V) 5

1

7

**- 9**

Current (mA) 2

3

- 2

1

e

***- v., + vh +***

I'

g

**TABLE P1.28**

h

**- 2 0 20**

**- 3**

-12

5

2

-2 - 3

**Element a**

**b**

**c**

**d**

**e**

**r**

g

**h**

**Voltage (V)** 46.16

14.16

-32.0

22.0

33.6

66.0

2.56

-0.4

Current (A) 6.0

4.72

-6.4

1.28

1.68

-0.4

1.28

0.4

1.30 One method of checking calculations involving interconnected circuit elements is to see that the total power delivered equals the total power absorbed (conservation-of-energy principle). With this thought in mind, check the interconnection in Fig. PI.30 and state whether it satisfies this power check. The current and voltage values for each ele

ment are given in Table PI.30.

Problems 23

1.31 Show that the power balances for the circuit shown in Fig. 1.7, using the voltage and current values given in Table 1.4, with the value of the current for component d changed to —1 A.

1.32 Suppose there is no power lost in the wires used to distribute power in a typical home.

a) Create a new model for the power distribution circuit by modifying the circuit shown in Fig 1.7. Use the same names, voltage polarities, and cur rent directions for the components that remain in this modified model.

b) The following voltages and currents are calcu lated for the components:

**"a = *vb = V( = Vo = vh* =**

120 V

120 V

-120 V 120 V

-240 V

*i, =* -1 0 A /b = 10 A /f = 3 A

*k* = - 7 A

If the power in this modified model balances, what is the value of the current in component g?

**CHAPTER CONTENTS**

**2.1 Voltage and Current Sources p. 26 2.2 Electrical Resistance (Ohm's Law) p. 30 2.3 Construction of a Circuit Model p. 34 2.4 Kirchhoff's Laws p. 37**

**2.5 Analysis of a Circuit Containing Dependent Sources** p. 42

Understand the symbols for and the behavior of the following ideal basic circuit elements: independent voltage and current sources, dependent voltage and current sources, and resistors.

Be able to state Ohm's law, Kirchhoffs current law, and Kirchhoff's voltage law, and be able to use these laws to analyze simple circuits.

Know how to calculate the power for each element in a simple circuit and be able to determine whether or not the power balances for the whole circuit.

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Circuit Elements

**There are five ideal basic ci**r**cuit elements:** voltage sources, current sources, resistors, inductors, and capacitors. In this chap ter we discuss the characteristics of voltage sources, current sources, and resistors. Although this may seem like a small num ber of elements with which to begin analyzing circuits, many prac tical systems can be modeled with just sources and resistors. They are also a useful starting point because of their relative simplicity; the mathematical relationships between voltage and current in sources and resistors are algebraic. "Thus you will be able to begin learning the basic techniques of circuit analysis with only alge braic manipulations.

We will postpone introducing inductors and capacitors until Chapter 6, because their use requires that you solve integral and differential equations. However, the basic analytical techniques for solving circuits with inductors and capacitors are the same as those introduced in this chapter. So, by the time you need to begin manipulating more difficult equations, you should be very familiar with the methods of writing them.

**Practical Perspective**

**Electrical Safety**

"Danger—High Voltage." This commonly seen warning is mis leading. All forms of energy, including electrical energy, can be hazardous. But it's not only the voltage that harms. The static electricity shock you receive when you walk across a carpet and touch a doorknob is annoying but does not injure. Yet that spark is caused by a voltage hundreds or thousands

of times larger than the voltages that can cause harm. The electrical energy that can actually cause injury is due to electrical current and how it flows through the body. Why, then, does the sign warn of high voltage? Because of the way electrical power is produced and distributed, it is easier to determine voltages than currents. Also, most electrical sources produce constant, specified voltages. So the signs warn about what is easy to measure. Determining whether and under what conditions a source can supply potentially dangerous currents is more difficult, as this requires an under standing of electrical engineering.

Before we can examine this aspect of electrical safety, we have to learn how voltages and currents are produced and the relationship between them. The electrical behavior of objects,

such as the human body, is quite complex and often beyond complete comprehension. To allow us to predict and control electrical phenomena, we use simplifying models in which sim ple mathematical relationships between voltage and current approximate the actual relationships in real objects. Such mod els and analytical methods form the core of the electrical engi

neering techniques that will allow us to understand all electrical phenomena, including those relating to electrical safety. At the end of this chapter, we will use a simple electric circuit model to describe how and why people are injured by electric currents. Even though we may never develop a com plete and accurate explanation of the electrical behavior of the human body, we can obtain a close approximation using simple circuit models to assess and improve the safety of electrical systems and devices. Developing models that pro vide an understanding that is imperfect but adequate for solv ing practical problems lies at the heart of engineering. Much of the art of electrical engineering, which you will learn with experience, is in knowing when and how to solve difficult problems by using simplifying models.

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**26 Circuit Elements**

**<P <D**

(a) **(b)**

**Figure 2.1 • The circuit symbols for (a) an ideal** inde pendent voltage source and (b) an ideal independent **current source.**

**2,1 Voltage and Current Sources** Before discussing ideal voltage and current sources, we need to consider the general nature of electrical sources. An **electrical source** is a device that is capable of converting nonelectric energy to electric energy and vice versa. A discharging battery converts chemical energy to electric energy, whereas a battery being charged converts electric energy to chemical energy. A dynamo is a machine that converts mechanical energy to electric energy and vice versa. If operating in the mechanical-to-elec tric mode, it is called a generator. If transforming from electric to mechanical energy, it is referred to as a motor. The important thing to remember about these sources is that they can either deliver or absorb electric power, generally maintaining either voltage or current. This behavior is of particular interest for circuit analysis and led to the cre ation of the ideal voltage source and the ideal current source as basic cir cuit elements. The challenge is to model practical sources in terms of the ideal basic circuit elements.

An **ideal voltage source** is a circuit element that maintains a pre scribed voltage across its terminals regardless of the current flowing in those terminals. Similarly, an **ideal current source** is a circuit element that maintains a prescribed current through its terminals regardless of the voltage across those terminals. These circuit elements do not exist as practical devices—they are idealized models of actual voltage and cur rent sources.

Using an ideal model for current and voltage sources places an important restriction on how we may describe them mathematically. Because an ideal voltage source provides a steady voltage, even if the current in the element changes, it is impossible to specify the current in an ideal voltage source as a function of its voltage. Likewise, if the only information you have about an ideal current source is the value of cur

rent supplied, it is impossible to determine the voltage across that cur rent source. We have sacrificed our ability to relate voltage and current in a practical source for the simplicity of using ideal sources in circuit analysis.

Ideal voltage and current sources can be further described as either independent sources or dependent sources. An **independent source** estab lishes a voltage or current in a circuit without relying on voltages or cur rents elsewhere in the circuit. The value of the voltage or current supplied is specified by the value of the independent source alone. In contrast, a **dependent source** establishes a voltage or current whose value depends on the value of a voltage or current elsewhere in the circuit. You cannot spec ify the value of a dependent source unless you know the value of the volt age or current on which it depends.

The circuit symbols for the ideal independent sources are shown in Fig. 2.1. Note that a circle is used to represent an independent source. To completely specify an ideal independent voltage source in a circuit, you must include the value of the supplied voltage and the reference polarity, as shown in Fig. 2.1(a). Similarly, to completely specify an ideal independ

ent current source, you must include the value of the supplied current and its reference direction, as shown in Fig. 2.1(b).

The circuit symbols for the ideal dependent sources are shown in Fig. 2.2. A diamond is used to represent a dependent source. Both the

2.1 Voltage and Current Sources 27

dependent current source and the dependent voltage source may be con

trolled by either a voltage or a current elsewhere in the circuit, so there

are a total of four variations, as indicated by the symbols in Fig. 2.2. Dependent sources are sometimes called **controlled sources.** To completely specify an ideal dependent voltage-controlled voltage source, you must identify the controlling voltage, the equation that per mits you to compute the supplied voltage from the controlling voltage, and the reference polarity for the supplied voltage. In Fig. 2.2(a), the con

**0 *>>-4***

trolling voltage is named *vx,* the equation that determines the supplied (a) (c) voltage *vs* is

*vs = fivx*,

***Pix* 4 = i8/.v(f**

and the reference polarity for *vs* is as indicated. Note that /x is a multiply

ing constant that is dimensionless.

Similar requirements exist for completely specifying the other ideal

dependent sources. In Fig. 2.2(b), the controlling current is /v, the equation for the supplied voltage *vs* is

*vs = pix*,

the reference polarity is as shown, and the multiplying constant p has the dimension volts per ampere. In Fig. 2.2(c), the controlling voltage is *vx,* the equation for the supplied current *is* is

*is = avx*,

the reference direction is as shown, and the multiplying constant *a* has the dimension amperes per volt. In Fig. 2.2(d), the controlling current is /v, the equation for the supplied current *is* is

the reference direction is as shown, and the multiplying constant /3 is dimensionless.

Finally, in our discussion of ideal sources, we note that they are examples of active circuit elements. An **active element** is one that models a device capable of generating electric energy. **Passive elements** model physical devices that cannot generate electric energy. Resistors, induc

tors, and capacitors are examples of passive circuit elements. Examples 2.1 and 2.2 illustrate how the characteristics of ideal inde pendent and dependent sources limit the types of permissible intercon nections of the sources.

(b) (d)

Figure 2.2 • The circuit symbols for (a) an ideal dependent voltage-controlled voltage source, (b) an ideal dependent current-controlled voltage source, (c) an ideal dependent voltage-controlled current source, and (d) an ideal dependent current-controlled current source.

28 Circuit Elements

**Testing I**n**terco**nn**ectio**n**s of Ideal Sou**r**ces**

Using the definitions of the ideal independent volt age and current sources, state which interconnec tions in Fig. 2.3 are permissible and which violate the constraints imposed by the ideal sources.

**Solution**

Connection (a) is valid. Each source supplies volt age across the same pair of terminals, marked a,b. This requires that each source supply the same volt age with the same polarity, which they do.

Connection (b) is valid. Each source supplies current through the same pair of terminals, marked a,b. This requires that each source supply the same current in the same direction, which they do.

Connection (c) is not permissible. Each source supplies voltage across the same pair of terminals, marked a,b. This requires that each source supply the same voltage with the same polarity, which they do not.

Connection (d) is not permissible. Each source supplies current through the same pair of terminals, marked a,b. This requires that each source supply the same current in the same direction, which they do not.

Connection (e) is valid. The voltage source sup

plies voltage across the pair of terminals marked a,b. The current source supplies current through the same pair of terminals. Because an ideal voltage source supplies the same voltage regardless of the current, and an ideal current source supplies the same current regardless of the voltage, this is a per

missible connection.

5A **e**

iiov (\_)iov **CtJ 5 A**

b

(a) (b)

**a *S~\* b e**

2A

**10 V f H' )5V ( f )5 A**

**b**

(c) **(d)**

5A **e**

10 V

**Figure 2.3 •** The circuits for Example 2.1.

2.1 Voltage and Current Sources 29

**Example 2.2 Testi**n**g Inte**r**connections of Ideal Independent and Dependent Sou**r**ces**

Using the definitions of the ideal independent and

dependent sources, state which interconnections in

Fig. 2.4 are valid and which violate the constraints

imposed by the ideal sources.

**Solution**

Connection (a) is invalid. Both the independent

source and the dependent source supply voltage

across the same pair of terminals, labeled a,b. This

requires that each source supply the same voltage

with the same polarity. The independent source sup

plies 5 V, but the dependent source supplies 15 V.

Connection (b) is valid. The independent volt age source supplies voltage across the pair of termi nals marked a,b. The dependent current source supplies current through the same pair of terminals. Because an ideal voltage source supplies the same voltage regardless of current, and an ideal current source supplies the same current regardless of volt age, this is an allowable connection.

Connection (c) is valid. The independent cur rent source supplies current through the pair of ter minals marked a,b. The dependent voltage source supplies voltage across the same pair of terminals. Because an ideal current source supplies the same current regardless of voltage, and an ideal voltage source supplies the same voltage regardless of cur rent, this is an allowable connection.

Connection (d) is invalid. Both the independ ent source and the dependent source supply current through the same pair of terminals, labeled a,b.This requires that each source supply the same current in the same reference direction. The independent source supplies 2 A, but the dependent source sup plies 6 A in the opposite direction.

***vx = SV***

**— •**

**b**

**(b)**

***v,* = 4 *ix /A***

***L =* 2 A**

b

(c)

/v = 3 *ix*

***ix = 2* A**

**b**

**(d)**

**Figure 2,4 •** The circuits for Example 2.2.

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**^/ASSESSMENT PROBLEMS**

Objective 1—Understand ideal basic circuit elements

2,1 For the circuit shown,

a) What value of *vg* is required in order for the interconnection to be valid?

b) For this value of *vgH* find the power associ ated with the 8 A source.

**Answer:** (a) - 2 V;

(b) -16 W(16 W delivered).

*NOTE: Also try Chapter Problems 2.2 and 2.4.*

2.2 For the circuit shown,

a) What value of **a** is required in order for the interconnection to be valid?

b) For the value of a calculated in part (a), find the power associated with the 25 V source.

**Answer:** (a) 0.6 A/V;

(b) 375 W (375 W absorbed).

**15 A 25 V**

*R*

-^vw

**Figure 2.5 A** The circuit symbol for a resistor having a resistance /?.

**2.2 Electrical Resistance (Ohm's Law)**

**Resistance** is the capacity of materials to impede the flow of current or, more specifically, the flow of electric charge. The circuit element used to model this behavior is the **resistor.** Figure 2.5 shows the circuit symbol for the resistor, with *R* denoting the resistance value of the resistor.

Conceptually, we can understand resistance if we think about the moving electrons that make up electric current interacting with and being resisted by the atomic structure of the material through which they are moving. In the course of these interactions, some amount of electric energy is converted to thermal energy and dissipated in the form of heat. This effect may be undesirable. However, many useful electrical devices take advantage of resistance heating, including stoves, toasters, irons, and space heaters.

Most materials exhibit measurable resistance to current. The amount of resistance depends on the material. Metals such as copper and alu minum have small values of resistance, making them good choices for wiring used to conduct electric current. In fact, when represented in a cir cuit diagram, copper or aluminum wiring isn't usually modeled as a resis

**S** *V$R  v = iR*

*vkR*

*v = -iR*

tor; the resistance of the wire is so small compared to the resistance of other elements in the circuit that we can neglect the wiring resistance to simplify the diagram.

For purposes of circuit analysis, we must reference the current in the resistor to the terminal voltage. We can do so in two ways: either in

**Figure 2.6 A** Two possible reference choices for the current and voltage at the terminals of a resistor, and the resulting equations.

the direction of the voltage drop across the resistor or in the direction of the voltage rise across the resistor, as shown in Fig. 2.6. If we choose the former, the relationship between the voltage and current is

**Ohm's law •** *v = iR,* **(2.1)**

2.2 Electrical Resistance (Ohm's Law) 31

where

*v =* the voltage in volts,

*i* = the current in amperes,

*R -* the resistance in ohms.

If we choose the second method, we must write

***v = -iR,* (2.2)**

where *v,* /, and *R* are, as before, measured in volts, amperes, and ohms,

respectively. The algebraic signs used in Eqs. 2.1 and 2.2 are a direct conse

quence of the passive sign convention, which we introduced in Chapter 1.

Equations 2.1 and 2.2 are known as **Ohm's law** after Georg Simon

Ohm, a German physicist who established its validity early in the nine

teenth century. Ohm's law is the algebraic relationship between voltage

and current for a resistor. In SI units, resistance is measured in ohms. The *^}}* Greek letter omega (H) is the standard symbol for an ohm. The circuit

diagram symbol for an 8 **a** resistor is shown in Fig. 2.7. **figure 2.7 •** The circuit symbol for an S ft resistor. Ohm's law expresses the voltage as a function of the current. However,

expressing the current as a function of the voltage also is convenient. Thus,

from Eq. 2.1,

**' = *J***

or, from Eq. 2.2,

***v***

The reciprocal of the resistance is referred to as **conductance,** is sym

bolized by the letter G, and is measured in Siemens (S).Thus,

*G = ^* S. (2.5)

An 8 O resistor has a conductance value of 0.125 S. In much of the profes

sional literature, the unit used for conductance is the mho (ohm spelled back

ward), which is symbolized by an inverted omega (U). Therefore we may

also describe an 8 H resistor as having a conductance of 0.125 mho, (U).

We use ideal resistors in circuit analysis to model the behavior of

physical devices. Using the qualifier *ideal* reminds us that the resistor

model makes several simplifying assumptions about the behavior of

actual resistive devices. The most important of these simplifying assump

tions is that the resistance of the ideal resistor is constant and its value

does not vary over time. Most actual resistive devices do not have constant

resistance, and their resistance does vary over time. The ideal resistor

model can be used to represent a physical device whose resistance doesn't

vary much from some constant value over the time period of interest in

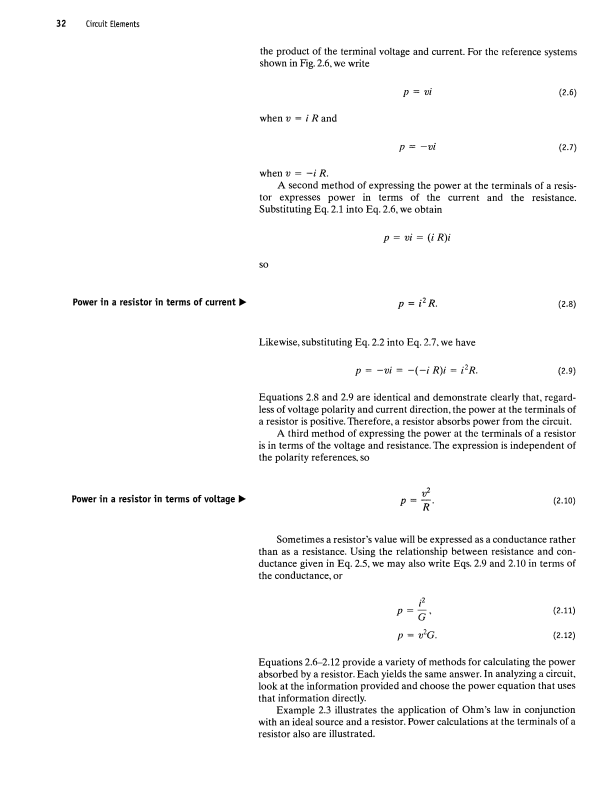
the circuit analysis. In this book we assume that the simplifying assump

tions about resistance devices are valid, and we thus use ideal resistors in

circuit analysis.

We may calculate the power at the terminals of a resistor in several

ways. The first approach is to use the defining equation and simply calculate

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the product of the terminal voltage and current. For the reference systems

shown in Fig. 2.6, we write

*p = vi* (2.6)

when *v = i R* and

*p = —vi* (2.7)

when ***v*** = *-i R.*

*A* second method of expressing the power at the terminals of a resis

tor expresses power in terms of the current and the resistance.

Substituting Eq. 2.1 into Eq. 2.6, we obtain

***p = vi = (i R)i***

so

**Power in** a **resistor in terms of current •** *p = i2 R.* (2.8)

Likewise, substituting Eq. 2.2 into Eq. 2.7, we have

***p* = *-vi = -(-iR)i = i2R.* (2.9)**

Equations 2.8 and 2.9 are identical and demonstrate clearly that, regard

less of voltage polarity and current direction, the power at the terminals of

a resistor is positive. Therefore, a resistor absorbs power from the circuit.

A third method of expressing the power at the terminals of a resistor

is in terms of the voltage and resistance. The expression is independent of

the polarity references, so

**Power in a resistor in terms of voltage •** *p =* —. (2.io)

Sometimes a resistor's value will be expressed as a conductance rather

than as a resistance. Using the relationship between resistance and con

ductance given in Eq. 2.5, we may also write Eqs. 2.9 and 2.10 in terms of

the conductance, or

***i2***

*p* = *V2G.* (2.12)

Equations 2.6-2.12 provide a variety of methods for calculating the power

absorbed by a resistor. Each yields the same answer. In analyzing a circuit,

look at the information provided and choose the power equation that uses

that information directly.

Example 2.3 illustrates the application of Ohm's law in conjunction

with an ideal source and a resistor. Power calculations at the terminals of a

resistor also are illustrated.

2.2 Electrical Resistance (Ohm's Law) **33**

**Calculati**n**g Voltage, Cu**rr**e**n**t, a**n**d Power for a Simple Resistive Circuit**

In each circuit in Fig. 2.8, either the value of *v* or *i* is not known.

**Ml A \*** 8 0 **50 V** T

0.2 S

(a) (b)

M i A *ik* 20*a* **50 V 25 0** . A

'ill

(c) (d)

**Figure 2.8 •** The circuits for Example 2.3.

The current *ih* in the resistor with a conductance of 0.2 S in Fig. 2.8(b) is in the direction of the voltage drop across the resistor. Thus

*ih =* (50)(0.2) = 10 A.

The voltage *vc* in Fig. 2.8(c) is a rise in the direc tion of the current in the resistor. Hence

*vc* = -(1)(20) = -2 0 V.

The current *id* in the 25 ft resistor in Fig. 2.8(d) is in the direction of the voltage rise across the resistor. Therefore

-50

25 = - 2 A.

*id*

b) The power dissipated in each of the four resistors is

a) Calculate the values of *v* and *i.*

b) Determine the power dissipated in each resistor.

(8)2

*Pm =*

(1)^(8) = 8 W,

**Solution**

*P0.2S =*

(50)2(0.2) = 500 W,

a) The voltage *va* in Fig. 2.8(a) is a drop in the direc tion of the current in the resistor. Therefore,

q.-(1)(8)- 8 V.

**^ASSESSMEN T PROBLEMS Objective 2—Be able to state and use Ohm's Law .. .**

*P20O,* = *Pisa* =

(-20)" 20

(50)2

25

= (1)2(20) = 20 W, (-2)2(25) = 100 W.

2.3 For the circuit shown,

a) If *vg* = 1 kV and *ig =* 5 mA, find the value of *R* and the power absorbed by the resistor.

b) If *ig -* 75 mA and the power delivered by the voltage source is 3 W, find *vg, R,* and the power absorbed by the resistor.

c) K *JR.* — 300 ft and the power absorbed by *R* is 480 mW, find *L* and *vg.*

**\*Q** *:R*

**Answer:** (a)200kQ,5W;

(b) 40 V, 533.33 ft, 3 W;

(c) 40 mA, 12 V

*NOTE: Also try Chapter Problems 2.5 and 2.7.*

2.4 For the circuit shown,

a) If *ig* = 0.5 A and *G =* 50 mS, find *vg* and the power delivered by the current source.

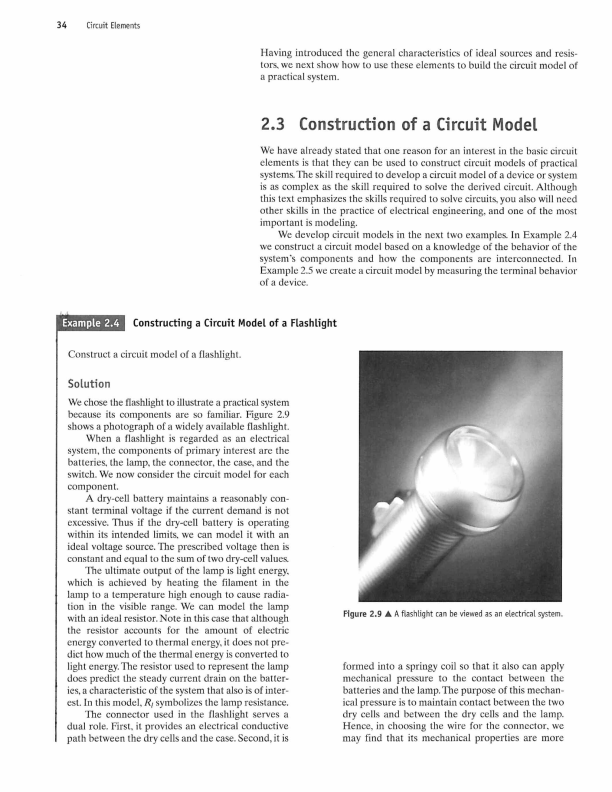
b) If *vg -* 15 V and the power delivered to the conductor is 9 W, find the conductance *G* and the source current L.

c) If *G =* 200 /xS and the power delivered to the conductance is 8 W, find *ig* and *vg.*

**Answer:** (a)10V,5 W;

(b)40mS,0.6 A;

(c) 40 mA, 200 V.

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Having introduced the general characteristics of ideal sources and resis

tors, we next show how to use these elements to build the circuit model of

a practical system.

**2.3 Construction of a Circuit Model**

We have already stated that one reason for an interest in the basic circuit

elements is that they can be used to construct circuit models of practical

systems. The skill required to develop a circuit model of a device or system

is as complex as the skill required to solve the derived circuit. Although

this text emphasizes the skills required to solve circuits, you also will need

other skills in the practice of electrical engineering, and one of the most

important is modeling.

We develop circuit models in the next two examples. In Example 2.4

we construct a circuit model based on a knowledge of the behavior of the

system's components and how the components are interconnected. In

Example 2.5 we create a circuit model by measuring the terminal behavior

of a device.

**Example 2.4 Constructing a Ci**r**cuit Model of a Flashlight**

Construct a circuit model of a flashlight.

**So**l**ution**

We chose the flashlight to illustrate a practical system

because its components are so familiar. Figure 2.9

shows a photograph of a widely available flashlight.

When a flashlight is regarded as an electrical

system, the components of primary interest are the

batteries, the lamp, the connector, the case, and the

switch. We now consider the circuit model for each

component.

A dry-cell battery maintains a reasonably con

stant terminal voltage if the current demand is not

excessive. Thus if the dry-cell battery is operating

within its intended limits, we can model it with an

ideal voltage source. The prescribed voltage then is

constant and equal to the sum of two dry-cell values.

The ultimate output of the lamp is light energy,

which is achieved by heating the filament in the

lamp to a temperature high enough to cause radia

tion in the visible range. We can model the lamp with an ideal resistor. Note in this case that although the resistor accounts for the amount of electric energy converted to thermal energy, it does not pre

dict how much of the thermal energy is converted to light energy. The resistor used to represent the lamp does predict the steady current drain on the batter ies, a characteristic of the system that also is of inter est. In this model, *R/* symbolizes the lamp resistance.

The connector used in the flashlight serves a dual role. First, it provides an electrical conductive path between the dry cells and the case. Second, it is

**Figure 2.9 •** A flashlight can be viewed as an electrical system.

formed into a springy coil so that it also can apply mechanical pressure to the contact between the batteries and the lamp. The purpose of this mechan ical pressure is to maintain contact between the two dry cells and between the dry cells and the lamp. Hence, in choosing the wire for the connector, we may find that its mechanical properties are more

2.3 Construction of a Circuit Model 35

important than its electrical properties for the

flashlight design. Electrically, we can model the connector with an ideal resistor, labeled *R{.* The case also serves both a mechanical and an electrical purpose. Mechanically, it contains all the other components and provides a grip for the person using it. Electrically, it provides a connection between other elements in the flashlight. If the case is metal, it conducts current between the batteries and the lamp. If it is plastic, a metal strip inside the case connects the coiled connector to the switch. Either way, an ideal resistor, which we denote *Rc,* models the electri cal connection provided by the case.

The final component is the switch. Electrically, the switch is a two-state device. It is either ON or OFF. An ideal switch offers no resistance to the cur rent when it is in the ON state, but it offers infinite resistance to current when it is in the OFF state. These two states represent the limiting values of a resistor; that is, the ON state corresponds to a resis

tor with a numerical value of zero, and the OFF state corresponds to a resistor with a numerical value of infinity. The two extreme values have the descrip tive names **short circuit *(R =* 0)** and **open circuit** *(R =* oo). Figure 2.10(a) and (b) show the graphical representation of a short circuit and an open circuit, respectively. The symbol shown in Fig. 2.10(c) rep resents the fact that a switch can be either a short circuit or an open circuit, depending on the position of its contacts.

We now construct the circuit model of the flashlight. Starting with the dry-cell batteries, the positive terminal of the first cell is connected to the negative terminal of the second cell, as shown in Fig. 2.11. The positive terminal of the second cell is connected to one terminal of the lamp. The other terminal of the lamp makes contact with one side of the switch, and the other side of the switch is con nected to the metal case.The metal case is then con

nected to the negative terminal of the first dry cell by means of the metal spring. Note that the ele ments form a closed path or circuit. You can see the closed path formed by the connected elements in Fig. 2.11. Figure 2.12 shows a circuit model for the flashlight.

(a)

(b)

OFF

ON

(c)

**Figure 2.10 •** Circuit symbols, (a) Short circuit, (b) Open circuit, (c) Switch.

Lamp

Filament

terminal

Sliding switch

Dry cell # 2

Case

Dry cell # 1

**Figure 2.11 •** The arrangement of flashlight components. **Figure 2.12 •** A circuit model for a flashlight.

We can make some general observations about modeling from our flashlight example: First, in developing a circuit model, the *electrical* behav ior of each physical component is of primary interest. In the flashlight model, three very different physical components—a lamp, a coiled wire, and a metal case—are all represented by the same circuit element (a resis tor), because the electrical phenomenon taking place in each is the same. Each is presenting resistance to the current flowing through the circuit.

Second, circuit models may need to account for undesired as well as desired electrical effects. For example, the heat resulting from the resist ance in the lamp produces the light, a desired effect. However, the heat

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resulting from the resistance in the case and coil represents an unwanted

or parasitic effect. It drains the dry cells and produces no useful output.

Such parasitic effects must be considered or the resulting model may not

adequately represent the system.

And finally, modeling requires approximation. Even for the basic sys

tem represented by the flashlight, we made simplifying assumptions in

developing the circuit model. For example, we assumed an ideal switch,

but in practical switches, contact resistance may be high enough to inter

fere with proper operation of the system. Our model does not predict this

behavior. We also assumed that the coiled connector exerts enough pres

sure to eliminate any contact resistance between the dry cells. Our model

does not predict the effect of inadequate pressure. Our use of an ideal

voltage source ignores any internal dissipation of energy in the dry cells,

which might be due to the parasitic heating just mentioned. We could

account for this by adding an ideal resistor between the source and the

lamp resistor. Our model assumes the internal loss to be negligible.

In modeling the flashlight as a circuit, we had a basic understanding of

and access to the internal components of the system. However, sometimes

we know only the terminal behavior of a device and must use this infor

mation in constructing the model. Example 2.5 explores such a modeling

problem.

**Example 2.5 Constructing a Ci**r**cuit Model Based o**n **Te**r**mi**n**al Measureme**n**ts**

The voltage and current are measured at the termi nals of the device illustrated in Fig. 2.13(a), and the values of *v,* and *it* are tabulated in Fig. 2.13(b). Construct a circuit model of the device inside the box.

**Solution**

Plotting the voltage as a function of the current yields the graph shown in Fig. 2.14(a). The equation of the line in this figure illustrates that the terminal

Device

**«k(V) - 4 0**

**- 2 0**

**0**

**20**

**40**

***it (A)* - 1 0**

**- 5**

**0**

**5**

**10**

voltage is directly proportional to the terminal cur rent, *v( -* 4/,. In terms of Ohm's law, the device inside the box behaves like a 4 *Cl* resistor. Therefore, the circuit model for the device inside the box is a 4 *CI* resistor, as seen in Fig. 2.14(b).

We come back to this technique of using termi nal characteristics to construct a circuit model after introducing Kirchhoff s laws and circuit analysis.

(a) (b)

**Figure 2.13 •** The (a) device and (b) data for Example 2.5. (a)

**:4 n**

(b)

**Figure 2.14 •** (a) The values of *v,* versus *i,* for the device in Fig. 2.13. (b) The circuit model for the device in Fig. 2.13.

*NOTE: Assess your understanding of this example by trying Chapter Problems 2.11 and 2.13.*

2.4 Kirchhoffs Laws

**2.4 Kirchhoff's Laws**

A circuit is said to be solved when the voltage across and the current in

every element have been determined. Ohm's law is an important equation

for deriving such solutions. However, Ohm's law may not be enough to

provide a complete solution. As we shall see in trying to solve the flash

light circuit from Example 2.4, we need to use two more important alge

braic relationships, known as Kirchhoff's laws, to solve most circuits.

We begin by redrawing the circuit as shown in Fig. 2.15, with the switch in the ON state. Note that we have also labeled the current and volt age variables associated with each resistor and the current associated with the voltage source. Labeling includes reference polarities, as always. For convenience, we attach the same subscript to the voltage and current labels as we do to the resistor labels. In Fig. 2.15, we also removed some of the terminal dots of Fig. 2.12 and have inserted nodes. Terminal dots are the start and end points of an individual circuit element. A **node** is a point where two or more circuit elements meet. It is necessary to identify nodes in order to use Kirchhoff's current law, as we will see in a moment. In Fig. 2.15, the nodes are labeled a, b, c, and d. Node d connects the battery and the lamp and in essence stretches all the way across the top of the dia

gram, though we label a single point for convenience. The dots on either side of the switch indicate its terminals, but only one is needed to repre sent a node, so only one is labeled node c.

For the circuit shown in Fig. 2.15, we can identify seven unknowns: /v, /j, *ic, if, V\, vc,* and *V{.* Recall that *vs* is a known voltage, as it represents the sum of the terminal voltages of the two dry cells, a constant voltage of 3 V. The problem is to find the seven unknown variables. From alge bra, you know that to find *n* unknown quantities you must solve *n* simul taneous independent equations. From our discussion of Ohm's law in Section 2.2, you know that three of the necessary equations are

(2.13)

**Figure 2.15 •** Circuit model of the flashlight with assigned voltage and current variables.

***vc = icRc,***

*Vi = iiRj.*

What about the other four equations?

(2.14) (2.15)

The interconnection of circuit elements imposes constraints on the

relationship between the terminal voltages and currents. These constraints

are referred to as Kirchhoff's laws, after Gustav Kirchhoff, who first stated

them in a paper published in 1848. The two laws that state the constraints

in mathematical form are known as Kirchhoff's current law and

Kirchhoff's voltage law.

We can now state **Kirchhoff's current law:**

The algebraic sum of all the currents at any node in a circuit

equals zero. **A Kirchhoff's current law (KCL)**

To use Kirchhoff's current law, an algebraic sign corresponding to a

reference direction must be assigned to every current at the node.

Assigning a positive sign to a current leaving a node requires assigning a

negative sign to a current entering a node. Conversely, giving a negative

sign to a current leaving a node requires giving a positive sign to a current

entering a node.

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Kirchhoffs voltage law (KVL) •

Applying Kirchhoffs current law to the four nodes in the circuit shown in Fig. 2.15, using the convention that currents leaving a node are considered positive, yields four equations:

node a *is - i{* = 0, (2.16)

node b /, + *ic* = 0, (2.17)

node c —/c. - // = 0, (2.18)

node d // - /, = 0. (2.19)

Note that Eqs. 2.16-2.19 are not an independent set, because any one of the four can be derived from the other three. In any circuit with *n* nodes, *n* — 1 independent current equations can be derived from Kirchhoffs current law.1 Let's disregard Eq. 2.19 so that we have six independent equations, namely, Eqs. 2.13-2.18. We need one more, which we can derive from Kirchhoffs voltage law.

Before we can state Kirchhoffs voltage law, we must define a closed **path** or **loop.** Starting at an arbitrarily selected node, we trace a closed path in a circuit through selected basic circuit elements and return to the original node without passing through any intermediate node more than once. The circuit shown in Fig. 2.15 has only one closed path or loop. For example, choosing node a as the starting point and tracing the circuit clockwise, we form the closed path by moving through nodes d, c, b, and back to node a. We can now state Kirchhoffs voltage law:

The algebraic sum of all the voltages around any closed path in a circuit equals zero.

To use Kirchhoffs voltage law, we must assign an algebraic sign (refer ence direction) to each voltage in the loop. As we trace a closed path, a volt age will appear either as a rise or a drop in the tracing direction. Assigning a positive sign to a voltage rise requires assigning a negative sign to a voltage drop. Conversely, giving a negative sign to a voltage rise requires giving a positive sign to a voltage drop.

We now apply Kirchhoffs voltage law to the circuit shown in Fig. 2.15. We elect to trace the closed path clockwise, assigning a positive algebraic sign to voltage drops. Starting at node d leads to the expression

*v, - vc + vx - vs* = 0, (2.20)

which represents the seventh independent equation needed to find the seven unknown circuit variables mentioned earlier.

The thought of having to solve seven simultaneous equations to find the current delivered by a pair of dry cells to a flashlight lamp is not very appealing. Thus in the coming chapters we introduce you to analytical techniques that will enable you to solve a simple one-loop circuit by writ

ing a single equation. However, before moving on to a discussion of these circuit techniques, we need to make several observations about the detailed analysis of the flashlight circuit. In general, these observations are true and therefore are important to the discussions in subsequent chap

ters. They also support the contention that the flashlight circuit can be solved by defining a single unknown.

Wc say more about this observation in Chapter 4.

2.4 Kirchhoff's Laws **39**

First, note that if you know the current in a resistor, you also know the

voltage across the resistor, because current and voltage are directly

related through Ohm's law. Thus you can associate one unknown variable

with each resistor, either the current or the voltage. Choose, say, the cur

rent as the unknown variable. Then, once you solve for the unknown cur

rent in the resistor, you can find the voltage across the resistor. In general,

if you know the current in a passive element, you can find the voltage

across it, greatly reducing the number of simultaneous equations to be

solved. For example, in the flashlight circuit, we eliminate the voltages *vc,*

*V{,* and *V\* as unknowns. Thus at the outset we reduce the analytical task to

solving four simultaneous equations rather than seven.

The second general observation relates to the consequences of con

necting only two elements to form a node. According to Kirchhoff s cur

rent law, when only two elements connect to a node, if you know the

current in one of the elements, you also know it in the second element.

In other words, you need define only one unknown current for the two

elements. When just two elements connect at a single node, the elements

are **said to** be **in series.** The importance of this second observation is

obvious when you note that each node in the circuit shown in Fig. 2.15

involves only two elements. Thus you need to define only one unknown

current. The reason is that Eqs. 2.16-2.18 lead directly to

*h* = *h* = *~tf = lb* (2.21)

which states that if you know any one of the element currents, you

know them all. For example, choosing to use *is* as the unknown elimi

nates **rj,ic,** and //.The problem is reduced to determining one unknown,

namely,/.,.

Examples 2.6 and 2.7 illustrate how to write circuit equations based

on Kirchhoff s laws. Example 2.8 illustrates how to use Kirchhoff s laws

and Ohm's law to find an unknown current. Example 2.9 expands on the

technique presented in Example 2.5 for constructing a circuit model for a

device whose terminal characteristics are known.

**Example 2.6 Using Kirchhoff's Cu**rr**ent Law**

Sum the currents at each node in the circuit shown

in Fig. 2.16. Note that there is no connection dot (•)

in the center of the diagram, where the 4 fi branch

crosses the branch containing the ideal current

source /a.

**Solution**

In writing the equations, we use a positive sign for a

current leaving a node. The four equations are

node a /j + /4 - /2 - *i$ =* 0, node b *i2* + /3 - /1 - /b - /a = 0, node c /b - /3 - /4 - /c = 0, node d /5 + *L* + ic = 0.

**Figure 2.16 A** The circuit for Example 2.6.

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**Usi**n**g Ki**r**chhoff's Voltage Law**

Sum the voltages around each designated path in the circuit shown in Fig. 2.17.

**So**l**ution**

In writing the equations, we use a positive sign for a voltage drop. The four equations are

path a path b path c

**-^1 + *V2 + V4 - Vh -* #3 = 0, *~% + v3*+ *v5 =* 0,**

***Vb - VA - Vc - V(y - V>,* = 0,**

path d — *va - V] + v2 — vc + v7 - v^* = 0. **Figure 2.17 •** The circuit for Example 2.7.  **Example 2.8 Applyi**n**g Ohm's Law a**n**d Ki**r**chhoff's Laws to Fi**n**d a**n **U**n**k**n**ow**n **Cu**rr**e**n**t**

a) Use Kirchhoff's laws and Ohm's law to find *i0* in the circuit shown in Fig. 2.18.

50 n

**Figure 2.18 A** The circuit for Example 2.8.

b) Test the solution for *i0* by verifying that the total power generated equals the total power dissipated.

**So**l**utio**n

a) We begin by redrawing the circuit and assigning an unknown current to the 50 12 resistor and unknown voltages across the 10 XI and 50 *O.* resistors. Figure 2.19 shows the circuit. The nodes are labeled a, b, and c to aid the discussion.

10 n *><>*

+ *v»* -

120 V 50 n

**Figure 2.19 •** The circuit shown in Fig. 2.18, with the unknowns ix, v,„ and V\ defined.

Because *i0* also is the current in the 120 V source, we have two unknown currents and

therefore must derive two simultaneous equa tions involving *i.(,* and /x. We obtain one of the equations by applying Kirchhoff's current law to either node b or c. Summing the currents at node b and assigning a positive sign to the currents leaving the node gives

**/] — *i()* — 6 = 0.**

We obtain the second equation from Kirchhoff's voltage law in combination with Ohm's law. Noting from Ohm's law that *v0* is *\Qi0* and *Vy* is 50/j, we sum the voltages around the closed path cabc to obtain

-120 + 1()/,, + 50/j = 0.

In writing this equation, we assigned a positive sign to voltage drops in the clockwise direc tion. Solving these two equations for *i()* and *ix* yields

= - 3 A and h = 3 A.

b) The power dissipated in the 50 H resistor is A50Q *=* O)2(50) = 450 W.

The power dissipated in the 10 *Ci* resistor is *Pum =* (-3)2(10) = 90 W.

2.4 Kirchhoffs Laws **41**

The power delivered to the 120 V source is

Therefore

p12ov = -120/,, = -120(-3) = 360 W. The power delivered to the 6 A source is *P6A*= \_v l( 6)^ bu t *vi =*50'l = 15 0 V-

*p6A* = -150(6) = -900 W.

The 6 A source is delivering 900 W, and the 120 V source is absorbing 360 W. The total power absorbed is 360 + 450 + 90 = 900 W. Therefore, the solution verifies that the power delivered equals the power absorbed.

Example 2.9 Constructing a Circuit Model Based on Terminal Measurements

The terminal voltage and terminal current were

measured on the device shown in Fig. 2.20(a), and

the values of *v,* and *it* are tabulated in Fig. 2.20(b).

t»,(V) 30

15

0

**MA) 0**

3

6

(b)

**Figure 2.20 A** (a) Device and (b) data for Example 2.9.

a) Construct a circuit model of the device inside the box.

b) Using this circuit model, predict the power this device will deliver to a 10 0 resistor.

**Solution**

a) Plotting the voltage as a function of the current yields the graph shown in Fig. 2.21(a). The equa tion of the line plotted is

*vt =* 30 - 5/,.

Now we need to identify the components of a cir cuit model that will produce the same relation ship between voltage and current. Kirchhoffs voltage law tells us that the voltage drops across two components in series. From the equation, one of those components produces a 30 V drop regardless of the current. This component can be modeled as an ideal independent voltage source. The other component produces a positive volt age drop in the direction of the current *it.* Because the voltage drop is proportional to the current, Ohm's law tells us that this component can be modeled as an ideal resistor with a value of 5 fl.The resulting circuit model is depicted in the dashed box in Fig. 2.21(b).

10 O

(b)

**Figure 2.21 •** (a) The graph of v, versus i, for the device in Fig. 2.20(a). (b) The resulting circuit model for the device in Fig. 2.20(a), connected to a 10 XI resistor.

b) Now we attach a 10 *il* resistor to the device in Fig. 2.21(b) to complete the circuit. Kirchhoffs current law tells us that the current in the 10 *ft* resistor is the same as the current in the 5 *ft* resis

tor. Using Kirchhoffs voltage law and Ohm's law, we can write the equation for the voltage drops around the circuit, starting at the voltage source and proceeding clockwise:

-30 + *Si +* 10/ = 0.

Solving for /, we get

/ = 2 A.

Because this is the value of current flowing in the 10 O resistor, we can use the power equation *p* = *i2R* to compute the power delivered to this resistor:

*Pmi =* (2)2(10) = 40 W.

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**^/ASSESSMENT PROBLEMS**

**Objective 2—Be able to state and use Ohm's law and Kirchhoff's current and voltage laws**

2.5 For the circuit shown, calculate (a) z5; (b) Vj; (c) *v2;* (d) *v5;* and (e) the power delivered by the 24 V source.

**Answer:** (a) 2 A;

(b)-4V;

(c) 6 V;

(d)14V;

(e) 48 W.

3fl

**—-Wv-**

+ y-> -

***hi v5<m***

24 V

+ w, -

2.7 a) The terminal voltage and terminal current were measured on the device shown. The values of *vt* and *i,* are provided in the table. Using these values, create the straight line plot of *vt* versus *it.* Compute the equation of the line and use the equation to construct a circuit model for the device using an ideal voltage source and a resistor.

b) Use the model constructed in (a) to predict the power that the device will deliver to a 25 H resistor.

**Answer:** (a) A 25 V source in series with a 100 (1 resistor;

(b) 1W.

**—VA** 2 a

2.6 Use Ohm's law and Kirchhoff s laws to find the value of *R* in the circuit shown.

*v,* (V) 25

15

5

0

***i, (A)*** 0

0.1

0.2

0.25

**Answer:** *R* = 4 O.

2.8

(a) (b)

Repeat Assessment Problem 2.7 but use the equation of the graphed line to construct a cir cuit model containing an ideal current source and a resistor.

200 V

**Answer:** (a) A 0.25 A current source connected between the terminals of a 100 O resistor;

(b) 1 W.

*NOTE: Also try Chapter Problems 2.14,2.I*7,*2.18, and 2.19.*

**2.5 Analysis of a Circuit Containing**

**Dependent Sources**

We conclude this introduction to elementary circuit analysis with a discus

sion of a circuit that contains a dependent source, as depicted in Fig. 2.22.

500 **V**

**Figure 2.22 •** A circuit with a dependent source.

We want to use Kirchhoff's laws and Ohm's law to find *v„* in this cir cuit. Before writing equations, it is good practice to examine the circuit diagram closely. This will help us identify the information that is known and the information we must calculate. It may also help us devise a strat egy for solving the circuit using only a few calculations.

2.5 Analysis of a Circuit Containing Dependent Sources 43

A look at the circuit in Fig. 2.22 reveals that

• Once we know *ia,* we can calculate *v0* using Ohm's law.

• Once we know /A, we also know the current supplied by the dependent

source *5iA.*

• The current in the 500 V source is /A.

There are thus two unknown currents, *iA* and /„. We need to construct and

solve two independent equations involving these two currents to produce

a value for *v(>.*

From the circuit, notice the closed path containing the voltage source,

the 5 ft resistor, and the 20 ft resistor. We can apply Kirchhoff s voltage

law around this closed path. The resulting equation contains the two

unknown currents:

500 = 5/A + 2Gi(,. (2.22)

Now we need to generate a second equation containing these two

currents. Consider the closed path formed by the 20 ft resistor and the

dependent current source. If we attempt to apply Kirchhoffs voltage

law to this loop, we fail to develop a useful equation, because we don't

know the value of the voltage across the dependent current source. In

fact, the voltage across the dependent source is *vv,* which is the voltage

we are trying to compute. Writing an equation for this loop does not

advance us toward a solution. For this same reason, we do not use the

closed path containing the voltage source, the 5 ft resistor, and the

dependent source.

There are three nodes in the circuit, so we turn to Kirchhoffs current

law to generate the second equation. Node a connects the voltage source

and the 5 ft resistor; as we have already observed, the current in these two

elements is the same. Either node b or node c can be used to construct the

second equation from Kirchhoffs current law. We select node b and pro

duce the following equation:

*to =* 'A + 5zA = 6 'V (2.23)

Solving Eqs. 2.22 and 2.23 for the currents, we get

\*A = 4 A,

4 = 24 A. (2.24)

Using Eq. 2.24 and Ohm's law for the 20 ft resistor, we can solve for the

voltage *v0:*

*v0* = 20i„ = 480 V.

Think about a circuit analysis strategy before beginning to write equa

tions. As we have demonstrated, not every closed path provides an oppor

tunity to write a useful equation based on Kirchhoffs voltage law. Not

every node provides for a useful application of Kirchhoffs current law.

Some preliminary thinking about the problem can help in selecting the

most fruitful approach and the most useful analysis tools for a particular

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problem. Choosing a good approach and the appropriate tools will usually

reduce the number and complexity of equations to be solved. Example 2.10

illustrates another application of Ohm's law and Kirchhoff s laws to a cir

cuit with a dependent source. Example 2.11 involves a much more compli

cated circuit, but with a careful choice of analysis tools, the analysis is

relatively uncomplicated.

**Example 2.10 Applyi**n**g Ohm's Law a**n**d Kirchhoffs Laws to Fi**n**d a**n **U**n**k**n**ow**n **Voltage**

a) Use Kirchhoffs laws and Ohm's law to find the voltage *va* as shown in Fig. 2.23.

b) Show that your solution is consistent with the constraint that the total power developed in the circuit equals the total power dissipated.

2 n

'3/, *3Cliv()*

**Figure 2.23 •** The circuit for Example 2.10.

**Solution**

a) A close look at the circuit in Fig. 2.23 reveals that: • There are two closed paths, the one on the left with the current /s and the one on the right with the current *ia.*

• Once *i„* is known, we can compute *v0.* We need two equations for the two currents. Because there are two closed paths and both have voltage sources, we can apply Kirchhoffs voltage law to each to give the following equations:

10 = 6/5,

3/v *= 2ia +* 3/,,.

Solving for the currents yields

*is=* 1.67 A,

*L* = 1 A.

Applying Ohm's law to the 3 ft resistor gives the desired voltage:

*v0 =* 3/,, *=* 3 V.

b) To compute the power delivered to the voltage sources, we use the power equation in the form *p* = *vi.* The power delivered to the independent voltage source is

*p* = (10)(-1.67) = -16.7 W.

The power delivered to the dependent voltage source is

/> = (3/,)(-/,,) = (5)(-1) = - 5 W.

Both sources are developing power, and the total developed power is 21.7 W.

To compute the power delivered to the resis tors, we use the power equation in the form *p -* /2/?.The power delivered to the 6 ft resistor is

*p* = (1.67)2(6) = 16.7 W.

The power delivered to the 2 ft resistor is p = (1)2(2) = 2 W.

The power delivered to the 3 ft resistor is /> = (1)2(3) = 3W.

The resistors all dissipate power, and the total power dissipated is 21.7 W, equal to the total power developed in the sources.

2.5 Analysis of a Circuit Containing Dependent Sources

**Example 2.11 Applyi**n**g Ohm's Law a**n**d Ki**r**chhoff's Law i**n **a**n **Amplifie**r **Ci**r**cuit**

The circuit in Fig. 2.24 represents a common config uration encountered in the analysis and design of transistor amplifiers. Assume that the values of all

the circuit elements — *R\, R2, Rc> RE,* Kr^ arjd *VQ—* are known.

a) Develop the equations needed to determine the current in each element of this circuit.

b) From these equations, devise a formula for com puting *iB* in terms of the circuit element values.

**Figure 2.24 A** The circuit for Example 2.11.

**Solution**

A careful examination of the circuit reveals a total of six unknown currents, designated *i\, i2, iB,* /\*c *ig,* and *icc.* In defining these six unknown currents, we used the observation that the resistor *Rc* is in series with the dependent current source /3/#. We now must derive six independent equations involving these six unknowns.

a) We can derive three equations by applying Kirchhoff s current law to any three of the nodes a, b, c, and d. Let's use nodes a, b, and c and label the currents away from the nodes as positive:

A fourth equation results from imposing the constraint presented by the series connection of *Rc* and the dependent source:

**(4) ic = piB,**

We turn to Kirchhoff s voltage law in deriv ing the remaining two equations. We need to select two closed paths in order to use Kirchhoff s voltage law. Note that the voltage across the dependent current source is unknown, and that it cannot be determined from the source current *(3iB.* Therefore, we must select two closed paths that do not contain this dependent current source.

We choose the paths bcdb and badb and specify voltage drops as positive to yield

(5) *V0 + iERE - i2R2 =* 0,

(6) - *i ^ + Vcc - 12R2* = 0.

b) To get a single equation for *iB* in terms of the known circuit variables, you can follow these steps:

• Solve Eq. (6) for £], and substitute this solu tion for *i1* into Eq. (2).

• Solve the transformed Eq. (2) for /2, and sub stitute this solution for *i2* into Eq. (5).

• Solve the transformed Eq. (5) for *iE,* and sub stitute this solution for *iE* into Eq. (3). Use Eq. (4) to eliminate *ic* in Eq. (3).

• Solve the transformed Eq. (3) for *iB,* and rearrange the terms to yield

*(VccRMRi* + \*2) - *Vo*

**<B**

(1) *i] + ic - icc =* 0,

OMaVtfi + Ka) + (1 + *P)RE* . (2.25)

(2) *iB + i2 - i\ =* 0, (3) *iE - iB - ic =* 0.

Problem 2.31 asks you to verify these steps. Note that once we know *iB,* we can easily obtain the remaining currents.

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**^ASSESSMEN T PROBLEM S**

**Objective 3—Know how to calculate power for each element in a simple circuit**

**2.9** For the circuit shown find (a) the current /j in microamperes, (b) the voltage *v* in volts, (c) the total power generated, and (d) the total power absorbed.

**Answer:** (a) 25 /xA;

(b) -2 V;

(c) 6150 MW;

(d)6150/iW.

54kI2 1.8 kn

**2.10** The current *i^* in the circuit shown is 2 A. Calculate

a) *vs,*

b) the power absorbed by the independent voltage source,

*NOTE: Also try Chapter Problems 2.22 and 2.28.*

c) the power delivered by the independent cur rent source,

d) the power delivered by the controlled cur rent source,

e) the total power dissipated in the two resistors.

**Answer:** (a) 70 V;

**(b)210W;**

(c) 300 W;

(d) 40 W;

(e) 130 W.

**Practical Perspective**

**Electrical Safety**

At the beginning of this chapter, we said that current through the body can cause injury. Let's examine this aspect of electrical safety. You might think that electrical injury is due to burns. However, that is not the case. The most common electrical injury is to the nervous system. Nerves use electrochemical signals, and electric currents can disrupt those signals. When the current path includes only skeletal muscles, the effects can include temporary paralysis (cessation of nervous signals) or involun tary muscle contractions, which are generally not life threatening. However, when the current path includes nerves and muscles that control the supply of oxygen to the brain, the problem is much more serious. Temporary paral ysis of these muscles can stop a person from breathing, and a sudden mus cle contraction can disrupt the signals that regulate heartbeat. The result is a halt in the flow of oxygenated blood to the brain, causing death in a few

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minutes unless emergency aid is given immediately. Table 2.1 shows a range

of physiological reactions to various current levels. The numbers in this

table are approximate; they are obtained from an analysis of accidents

because, obviously, it is not ethical to perform electrical experiments on

people. Good electrical design will limit current to a few milliamperes or less

under all possible conditions.

**TABLE 2.1 Physiological Reactions to Current Levels in Humans**

**Physiological Reaction Current**

Barely perceptible Extreme pain

Muscle paralysis Heart stoppage

3-5 mA 35-50 mA 50-70 mA 500 mA

Note: Data taken from W. F. Cooper, Electrical Safety Engineering, 2d ed. (London: Butterworth, 1986); and C. D. Winburn, Practical Electrical Safety (Monticello, N.Y.: Marcel Dekker, 1988).

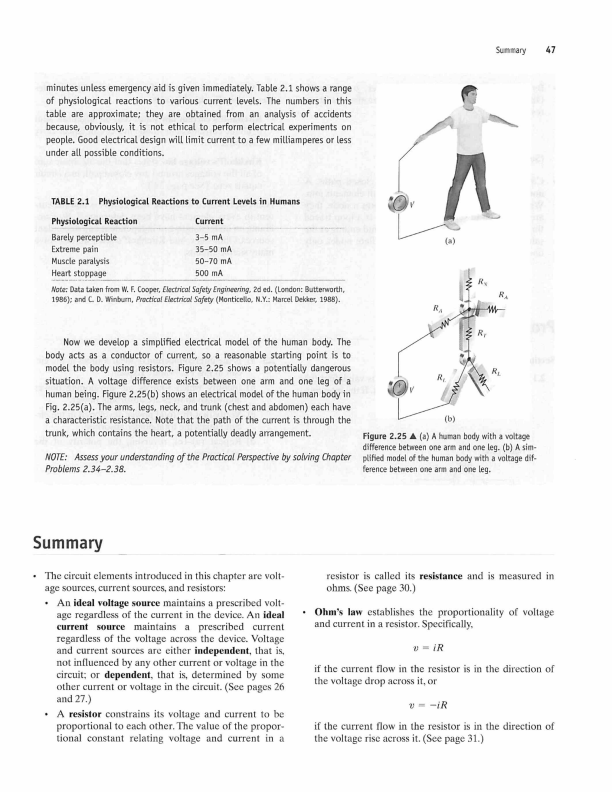
Now we develop a simplified electrical model of the human body. The body acts as **a** conductor of current, so a reasonable starting point is to model the body using resistors. Figure 2.25 shows a potentially dangerous situation. A voltage difference exists between one arm and one leg of a human being. Figure 2.25(b) shows an electrical model of the human body in Fig. 2.25(a). The arms, legs, neck, and trunk (chest and abdomen) each have a characteristic resistance. Note that the path of the current is through the

trunk, which contains the heart, a potentially deadly arrangement.

**Figure 2.25 •** (a) A human body with a voltage difference between one arm and one leg. (b) A sim

NOTE: Assess your understanding of the Practical Perspective by solving Chapter

plified model of the human body with a voltage dif

Problems 2.34-2.38. 

**Summary**

The circuit elements introduced in this chapter are volt age sources, current sources, and resistors:

• An **ideal voltage source** maintains a prescribed volt age regardless of the current in the device. An **ideal current source** maintains a prescribed current regardless of the voltage across the device. Voltage and current sources are either **independent,** that is, not influenced by any other current or voltage in the circuit; or **dependent,** that is, determined by some other current or voltage in the circuit. (See pages 26 and 27.)

• A **resistor** constrains its voltage and current to be proportional to each other. The value of the propor tional constant relating voltage and current in a

ference between one arm and one leg.

resistor is called its **resistance** and is measured in ohms. (See page 30.)

**Ohm's law** establishes the proportionality of voltage and current in a resistor. Specifically,

***v = iR***

if the current flow in the resistor is in the direction of the voltage drop across it, or

***v* = *-iR***

if the current flow in the resistor is in the direction of the voltage rise across it. (See page 31.)

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By combining the equation for power, *p = vi,* with Ohm's law, we can determine the power absorbed by a resistor:

**- ,2 r, \_**

***p = rR* = *vl/R.***

(See page 32.)

Circuits are described by nodes and closed paths. A **node** is a point where two or more circuit elements join. When just two elements connect to form a node, they are said to be **in series.** A **closed path** is a loop traced through connecting elements, starting and ending at the same node and encountering intermediate nodes only once each. (See pages 37-39.)

**Problems**

**Section 2.1**

**2.1** If the interconnection in Fig. P2.1 is valid, find the total power developed in the circuit. If the intercon nection is not valid, explain why.

The voltages and currents of interconnected circuit ele ments obey Kirchhoffs laws:

« **Kirchhoff's current law** states that the algebraic sum of all the currents at any node in a circuit equals zero. (See page 37.)

• **Kirchhoff's voltage law** states that the algebraic sum of all the voltages around any closed path in a circuit equals zero. (See page 38.)

A circuit is solved when the voltage across and the cur rent in every element have been determined. By com bining an understanding of independent and dependent sources, Ohm's law, and Kirchhoffs laws, we can solve many simple circuits.

2.3 a) Is the interconnection of ideal sources in the cir cuit in Fig. P2.3 valid? Explain.

b) Identify which sources are developing power and which sources are absorbing power.

c) Verify that the total power developed in the cir cuit equals the total power absorbed.

d) Repeat (a)-(c), reversing the polarity of the

**Figure P2.1** 50 V

10 V **e**

**5 A e** 40 V

20 V source. **Figure P2.3**

20 V

15V

2.2 If the interconnection in Fig. P2.2 is valid, find the total power developed by the voltage sources. If the interconnection is not valid, explain why.

**Figure P2.2**

2.4 If the interconnection in Fig. P2.4 is valid, find the power developed by the current sources. If the interconnection is not valid, explain why.

40 V

10 V( j 20V 100 V 5A

**Figure P2.4**

40 V **e**

100 **V f>A**

Problems 49

2.5 If the interconnection in Fig. P2.5 is valid, find the

total power developed in the circuit. If the intercon

nection is not valid, explain why.

Figure P2.5

Figure P2.8

12V

2.6 The interconnection of ideal sources can lead to an indeterminate solution. With this thought in mind, explain why the solutions for *V\* and *v2* in the circuit in Fig. P2.6 are not unique.

20 V

2.9 a) Is the interconnection in Fig. P2.9 valid? Explain. b) Can you find the total energy developed in the circuit? Explain.

Figure P2.9

20 V

8A( f ) 100V

Figure P2.6

20 V **e**

Sections 2.2-2.3

5mA(t J ,;i(t *J*15mA 60 V 20 mA

2.7 If the interconnection in Fig. P2.7 is valid, find the total power developed in the circuit. If the intercon nection is not valid, explain why.

2.10 A pair of automotive headlamps is connected to a 12 V battery via the arrangement shown in Fig. P2.10. In the figure, the triangular symbol • is used to indicate that the terminal is connected directly to the metal frame of the car.

a) Construct a circuit model using resistors and an independent voltage source.

b) Identify the correspondence between the ideal circuit element and the symbol component that it represents.

Figure P2.7 Figure P2.10

50 V

f J25A

**6 *iA*** *\+/* 80V M

2.8 Find the total power developed in the circuit in Fie. P2.8 if *v„* = 5 V.

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2.11 The terminal voltage and terminal current were measured on the device shown in Fig. P2.11(a). The values of *v* and *i* are given in the table of Fig. P2.11(b). Use the values in the table to con

struct a circuit model for the device consisting of a single resistor from Appendix H.

Figure P2.ll

Figure P2.13

**FT ©**

**»(V) -10**

**-5**

**5**

**10**

**15**

**20**

**p(mW) 17.86**

**4.46**

**4.46**

**17.86**

40.18

**71.43**

*i* (mA) **-4**

-2

**2**

**4**

6

y(V) -108 -54 **54**

**108**

**162**

**(a) (b)**

2.14 The voltage and current were measured at the ter minals of the device shown in Fig. P2.14(a). The results are tabulated in Fig. P2.14(b).

(a)

**(b)**

a) Construct a circuit model for this device using an ideal current source and a resistor.

b) Use the model to predict the amount of power the device will deliver to a 20 *il* resistor.

2.12 A variety of current source values were applied to the device shown in Fig. P2.12(a). The power absorbed by the device for each value of current is recorded in the table given in Fig. P2.12(b). Use the values in the table to construct a circuit model for the device consisting of a single resistor from Appendix H.

Figure P2.12

**p(mW)**

/ (/xA)

Figure P2.14 **^ - +**

(a)

***vt(V)***

100

**120**

**140**

**160**

180

**(b)**

;,(A) 0

4

8

**12**

16

50

**100**

150

**200**

**250**

**300**

**(b)**

5.5

**22.0** 49.5 88.0

137.5 198.0

2.15 The voltage and current were measured at the ter minals of the device shown in Fig. P2.15(a). The results are tabulated in Fig. P2.15(b).

a) Construct a circuit model for this device using an ideal voltage source and a resistor.

b) Use the model to predict the value of *it* when *v,* is zero.

Figure P2.15

2.13 A variety of voltage source values were applied to the device shown in Fig. P2.13(a). The power absorbed by the device for each value of voltage is recorded in the table given in Fig. P2.13(b). Use the values in the table to construct a circuit model for the device consisting of a single resistor from Appendix H.

***vt(V)*** 50

66

82

98

**114 130**

\*<A) 0

2

4

6

8

**10**

(a) **(b)**

Problems **51**

**2.16** The table in Fig. P2.16(a) gives the relationship

**Figure P2.17**

between the terminal current and voltage of the practical constant current source shown in

*is* (mA)

«k(V)

Fig. P2.16(b).

a) Plot *is* versus *vs.*

b) Construct a circuit model of this current source that is valid for 0 < *vs* s 75 V. based on the equation of the line plotted in (a).

c) Use your circuit model to predict the current delivered to a 2.5 *kfl* resistor.

24 22 20 18 15 10 0

0

8

16 24 32 40 48

CVS

d) Use your circuit model to predict the open-circuit voltage of the current source.

e) What is the actual open-circuit voltage? f) Explain why the answers to (d) and (e) are not the same.

Figure P2.16

*is* (mA)

*Vs* (V)

(a) **(b)**

**Section 2.4**

**2.18** a) Find the currents ir and *i2* in the circuit in PSPICE Rg.P2.18.

MUITISIM °

b) Find the voltage *va.*

c) Verify that the total power developed equals the

20.0 17.5 15.0 12.5

9.0 4.0 0.0

0

25 50 75

100 125 140

total power dissipated. Figure P2.18

1.5 A

15011

250 O

(a) (b)

**2.19** Given the circuit shown in Fig. P2.19, find

PSPICE

MULTISIM

**2.17** The table in Fig. P2.17(a) gives the relationship between the terminal voltage and current of the practical constant voltage source shown in Fig. P2.17(b).

a) Plot *vs* versus *is.*

b) Construct a circuit model of the practical source that is valid for 0 < *is* < 24 mA, based on the

equation of the line plotted in (a). (Use an ideal

voltage source in series with an ideal resistor.)

c) Use your circuit model to predict the current delivered to a 1 kO resistor connected to the

terminals of the practical source.

d) Use your circuit model to predict the current delivered to a short circuit connected to the ter

minals of the practical source.

a) the value of (a,

b) the value of /b,

c) the value of *v(„*

d) the power dissipated in each resistor, e) the power delivered by the 50 V source.

Figure P2.19

50 V 8012

e) What is the actual short-circuit current? f) Explain why the answers to (d) and (e) are not the same.

**2.20** The current *ia* in the circuit shown in Fig. P2.20 is P5PICE 2 mA. Find (a) *i.*,; (b) L: and (c) the power delivered MULTISIM V \*• by the independent current source.

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Figure P2.20

4kO

**2.21** The current *i(}* in the circuit in Fig. P2.21 is 1 A.

Figure P2.23

240 v r \* j

ion:

5 0

—-VW- - 4 A 4H

—'VW

60

**- A W**

ion :14fi

MULTISIM a ; rinui] .

b) Find the power dissipated in each resistor. c) Verify that the total power dissipated in the cir cuit equals the power developed by the 150 V source.

Figure **P2.21**

150 V 25 O

2.22 The voltage across the 16 ft resistor in the circuit in

**2.24** The variable resistor *R* in the circuit in Fig. P2.24 is 'SPICE adjusted until *va* equals 60 V Find the value of *R.*

Figure P2.24

240 V 12 a

**2.25** The currents *i]* and *i2* in the circuit in Fig. P2.25 are 21 A and 14 A, respectively.

a) Find the power supplied by each voltage source. b) Show that the total power supplied equals the

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Fig. P2.22 is 80 V, positive at the upper terminal. a) Find the power dissipated in each resistor. b) Find the power supplied by the 125 V ideal volt age source.

c) Verify that the power supplied equals the total power dissipated.

total power dissipated in the resistors. Figure P2.25

Figure P2.22 125 V **6**

15 a

30 a i 6 a

147 V 147 V

*h.tsn*

35 a

*h* 1110 a

**2.26** The currents /a and /b in the circuit in Fig. P2.26 are

2.23 For the circuit shown in Fig. P2.23, find (a) *R* and

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4 A and —2 A, respectively. a) Find *ig,*

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**MULTISIM**

(b) the power supplied by the 240 V source.

b) Find the power dissipated in each resistor.

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c) Find *vg.*

**Figure P2.29**

d) Show that the power delivered by the current source is equal to the power absorbed by all the other elements.

**Figure P2.26**

60 n

"i *i* so n (| )40 n *i v(1* J IO n

r40i2

ion

**2.30** For the circuit shown in Fig. P2.30, calculate (a) *iA* and >sptCE *v0* and (b) show that the power developed equals the

100 V

**Section** 2.5

**4 0** power absorbed.

Figure **P2.30**

*5ia* **O *',r***

2.27 Find (a) /„, (b) *ih* and (c) *i2* in the circuit in Fig. P2.27. **PSPICE**

**MULTISIM**

**Figure P2.27**

12 ft

50 V

*iA* | | 18 ft *vAioa*

20 V

18V

**2.28** a) Find the voltage *vv* in the circuit in Fig. P2.28. MULTISIM b) Show that the total power generated in the cir cuit equals the total power absorbed.

**Figure P2.28**

0.8 V 500 ft

lOkft

**-VW**

**2.31**

**2.32**

**PSPICE**

**MULTISIM**

Derive Eq. 2.25. *Hint:* Use Eqs. (3) and (4) from Example 2.11 to express *iE* as a function of *iB.* Solve Eq. (2) for *i2* and substitute the result into both Eqs. (5) and (6). Solve the "new" Eq. (6) for z'i and substitute this result into the "new" Eq. (5). Replace *iE* in the "new" Eq. (5) and solve for *iB.* Note that because *iCc* appears only in Eq. (1), the solution for *iB* involves the manipulation of only five equations.

For the circuit shown in Fig. 2.24, *R{* = 40 kO, *R2 =* 60 kO, *Rc* = 750 a , *RE =* 120 H, *Vcc =* 10 V, *V0 =* 600 mV, and /3 = 49. Calculate *iB, ic, iE,* u3d, ^bd\* *h-> l\->*vab' f co and v13. *(Note:* In the double sub

script notation on voltage variables, the first sub script is positive with respect to the second subscript. See Fig. P2.32.)

15.2 V

25 V

Figure P2.32 3

**+**

2.29 Find *V\* and *v\** in the circuit shown in Fig. P2.29

**PSPICE**

**MULTISIM**

when *v0* equals 5 V. *(Hint:* Start at the right end of the circuit and work back toward *vr)*

54 Circuit Elements

Sections 2.1-2.5

2.33 It is often desirable in designing an electric wiring

2.34 a) Suppose the power company installs some PERSPECTIVE equipment that could provide a 250 V shock to a human being. Is the current that results danger

DESIGN PROBLEM

system to be able to control a single appliance from two or more locations, for example, to control a lighting fixture from both the top and bottom of a stairwell. In home wiring systems, this type of con

trol is implemented with three-way and four-way switches. A three-way switch is a three-terminal, two-position switch, and a four-way switch is a four terminal, two-position switch. The switches are shown schematically in Fig. P2.33(a), which illustrates a three-way switch, and P2.33(b), which illustrates a four-way switch.

a) Show how two three-way switches can be con nected between a and b in the circuit in Fig. P2.33(c) so that the lamp / can be turned ON or OFF from two locations.

b) If the lamp (appliance) is to be controlled from more than two locations, four-way switches are used in conjunction with two three-way

ous enough to warrant posting a warning sign and taking other precautions to prevent such a shock? Assume that if the source is 250 V, the resistance of the arm is 400 *Cl,* the resistance of the trunk is 50 *Cl,* and the resistance of the leg is 200 *Cl.* Use the model given in Fig. 2.25(b).

b) Find resistor values from Appendix H that could be used to build a circuit whose behavior is the closest to the model described in part (a).

2.35 Based on the model and circuit shown in Fig. 2.25, PERSPECWE draw a circuit model of the path of current through the human body for a person touching a voltage source with both hands who has both feet at the

same potential as the negative terminal of the volt age source.

2.36 a) Using the values of resistance for arm, leg, and

switches. One four-way switch is required for each location in excess of two. Show how one four-way switch plus two three-way switches can be connected between a and b in Fig. P2.33(c) to control the lamp from three locations. *(Hint:* The four-way switch is placed between the three-way switches.)

Figure P2.33

Position 1 Position 2

(a)

PRACTICAL PERSPECTIVE

trunk provided in Problem 2.34, calculate the power dissipated in the arm, leg, and trunk. b) The specific heat of water is 4.18 X 103 J/kg°C, so a mass of water *M* (in kilograms) heated by a power *P* (in watts) undergoes a rise in tempera ture at a rate given by

*(IT* 2.39 X *]0~4P*

*dt M* °C/s.

Assuming that the mass of an arm is 4 kg, the mass of a leg is 10 kg, and the mass of a trunk is 25 kg, and that the human body is mostly water, how many seconds does it take the arm, leg, and trunk to rise the 5°C that endangers living tissue?

c) How do the values you computed in (b) com pare with the few minutes it takes for oxygen starvation to injure the brain?

3 4

Position 1 Position 2 (b)

***-6***

(c)

2.37 A person accidently grabs conductors connected to PERSPECTIVE eac n en d °f a dc voltage source, one in each hand. a) Using the resistance values for the human body provided in Problem 2.34, what is the minimum source voltage that can produce electrical shock sufficient to cause paralysis, preventing the per son from letting go of the conductors?

b) Is there a significant risk of this type of accident occurring while servicing a personal computer, which typically has 5 V and 12 V sources?

2.38 To understand why the voltage level is not the sole RSPECWE determinant of potential injury due to electrical shock, consider the case of a static electricity shock mentioned in the Practical Perspective at the start of this chapter. When you shuffle your feet across a carpet, your body becomes charged. The effect of

this charge is that your entire body represents a volt age potential. When you touch a metal doorknob, a

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voltage difference is created between you and the doorknob, and current flows—but the conduction material is air, not your body!

Suppose the model of the space between your hand and the doorknob is a 1 Mfl resistance. What voltage potential exists between your hand and the doorknob if the current causing the mild shock is 3 mA?