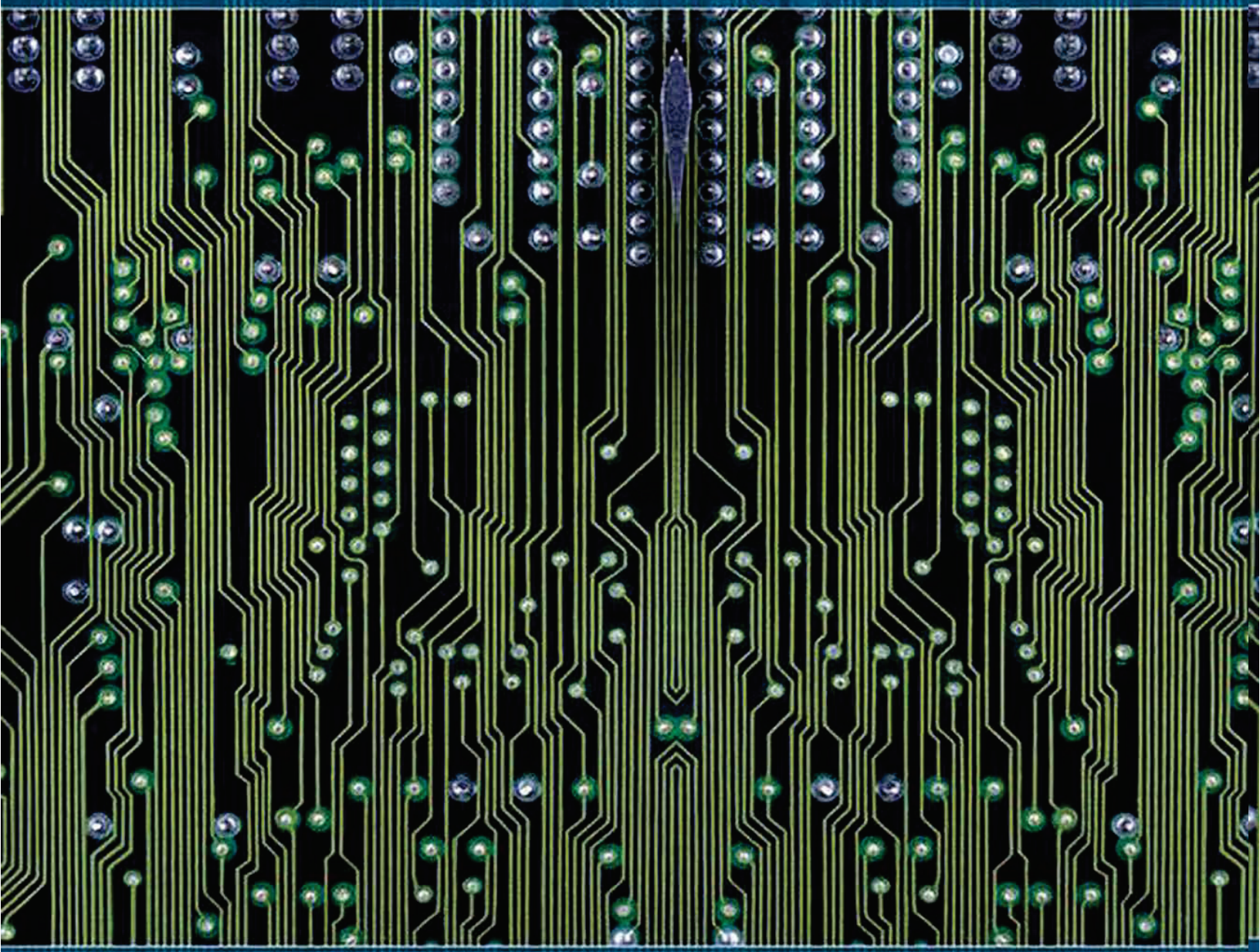
THE ANALYSIS & DESIGN OF LINEAR CIRCUITS

SEVENTH EDITION



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Skyworks Ex 2017
Kangxi v. Skyworks
IPR2025-00372

The Analysis and Design of Linear Circuits

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Library of Congress Cataloging-in-Publication Data

Thomas, Roland E., 1930-
The analysis and design of linear circuits / Roland E. Thomas, Albert J. Rosa, Gregory J. Toussaint.—7th ed.
p. cm.
Includes index.
ISBN 978-1-118-06558-7 (hardback)
1. Electric circuits, Linear—Design and construction. 2. Electric circuit analysis. I. Rosa, Albert J., 1942- II. Toussaint, Gregory J. III. Title.
TK454.T466 2012
621.39'5—dc23

2011042676

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

To our wives
Juanita, Kathleen, and Tricia

PREFACE

WHY THIS TEXT?

We approach the art of teaching circuits in our textbook differently than most others. We recognize that studying circuits can be rewarding and useful, even for students who are not majoring in electrical or computer engineering. Electric circuits dominate so much of our modem technology that many students are interested in learning about them. Most students who pursue engineering studies want to be creative and design things. Most circuits texts do not focus on this basic desire, rather spend their pages teaching why electric circuits work without affording the student an opportunity to put this learning into practice. The longer it takes students to try their hand in designing stuff, the more likely it is that they will become disillusioned and perhaps change to a different major.

The authors have long believed that an early introduction to design and design evaluation raises the excitement level and greatly increases student interest in their chosen discipline. Over 50 years of combined teaching experience at the USAF Academy, the University of Denver, the University of Colorado at Denver, and the Air Force Institute of Technology, have only served to strengthen our belief. This new edition furthers this strategy by adding more design and evaluation examples, exercises, homework problems, and real-world applications. In addition, students today solve problems using computers, as well as, by hand and with a calculator. Access to personal computers is nearly ubiquitous, and key software used in circuit analysis and design has become available for free or at very deep discounts for students. This edition of our text includes many software examples, exercises, and discussions geared to making the study of circuits more in line with today's student. Our text has always included software, but generally as an extension for solving circuits by hand. This edition continues our effort begun with the sixth edition by integrating software intimately into the solution of circuit problems whenever and wherever it really helps to solve the problems. It still recognizes that using computers does not replace the intuition that engineers must develop to analyze, design, and make smart judgments about different working solutions or designs.

The seventh edition of *The Analysis and Design of Linear Circuits* improves on the sixth edition and remains friendly to users who prefer a *Laplace Early* approach or those favoring the more traditional *Phasor First* approach to ac circuits. A later section discusses how to use this text to pursue either a traditional Phaser First approach or the Laplace Early approach using three different focuses. In this edition we have added many skills-level examples, exercises, and problems that can help develop the student's confidence in mastering the different objectives. The seventh edition assumes the same student prerequisites as past editions and continues to rely on students having access to personal computers—although computer access is not essential for using this textbook, we believe it improves learning. This edition targets

students of all engineering disciplines who need an introductory circuit analysis course of one or two terms. The seventh edition continues the authors' combined commitment to providing a modem and innovative approach to teaching circuit analysis and design, as well as circuit evaluation.

CONTINUING FEATURES

OBJECTIVES

This text remains structured around a sequence of carefully defined learning objectives and related evaluation tools based on Bloom's Taxonomy of Educational Objectives. The initial learning objectives focus on enabling skills at the *knowledge*, *comprehension*, and *application* levels of the taxonomy that we call Chapter Learning Objectives or CLOs. As students demonstrate mastery of these lower levels, they are introduced to higher-level objectives involving *analysis*, *synthesis* (design), and *evaluation*. Each learning objective is explicitly stated in terms of expected student proficiency in the homework sections, and each is followed by at least 10 homework problems specifically designed to evaluate student mastery of the objective. This framework has been a standard feature of all seven editions of this book and has allowed us to maintain a consistent level of expected student performance over the years. We also list our objectives in the chapter openers to orient the student to the expected outcomes. These objectives make it easier to assess student learning and prepare for accreditation reviews. To fulfill ABET Criterion 3 "*the program must have documented student outcomes that prepare graduates to attain the program educational objectives.*" And to fulfill Criterion 4 "*the program must regularly use appropriate, documented processes for assessing and evaluating the extent to which both the program educational objectives and the student outcomes are being attained. There must be measurable outcomes and an assessment and evaluation process that periodically documents and demonstrates the degree to which the program outcomes are attained.*"

CIRCUIT ANALYSIS AND DESIGN

Our experience convinces us that an interweaving of analysis and design topics reinforces a student's grasp of circuit analysis fundamentals. Early involvement in design provides motivation as students apply their newly acquired analysis tools to practical situations. Using computer simulation software to verify their designs gives students an early degree of confidence that they have actually created a design that meets stated specifications. Ideally, a supporting laboratory program where students actually build and test their designs provides the final confirmation that they can create useful products. Design efforts as described in this text are very useful in helping to meet ABET's design Criterion 3(c)—*specifically, an ability to design a system, component, or process to meet desired needs*.... We identify design examples, exercises, and homework problems with an icon D.

DESIGN EVALUATION

Realistic design problems do not have unique solutions, so it is natural for students to wonder how their designs compare with those of others. An often asked question is "is my design a good one?" Using judgment to compare alternative solutions is a fundamental trait of good engineering. The evaluation of alternative designs introduces students to real-world engineering practice. We also include judgment problems that ask students to evaluate an "off-the-shelf" design and ask if it could meet a specific need. In such problems, we ask the student "Would you buy it?"

Including design and the evaluation of design in an introductory course helps to convince students that circuits perform useful functions and that circuit design courses are not simply vehicles for teaching routine skills such as node-voltage and mesh-current analyses. Although this philosophy is implicit in all previous editions, this edition offers expanded coverage of design and evaluation among the worked examples, exercises, and homework problems. We use software extensively to help students visualize specifications and results. This, in turn, helps them to create better designs and make smart choices between competing designs. Evaluation generally involves the practical side of design and can support ABET Criterion 3(c)—specifically, . . . *to meet desired needs within realistic constraints, such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.* We identify evaluation examples, exercises, and homework problems with an icon E.

The OP AMP

An early introduction and integrated treatment of the OP AMP continues to be a central feature of this text. The modular form of OP AMP circuits simplifies analog circuit analysis and design by minimizing the effects of loading. This feature allows the interconnection of simple building blocks to produce complex signal processing functions that are especially useful to instrumentation and signal shaping applications. The close agreement between theory, simulation, and hardware allows students to analyze, design, and successfully build useful OP AMP circuits in the laboratory. The text covers numerous OP AMP applications, such as digital-to-analog conversion, transducer interface circuits, comparator circuits, block diagram realization, first-order filters, and multiple-pole active filters. These applications, which have been again expanded in this new edition, are especially useful to students from other engineering disciplines that require knowledge of instrumentation, filtering, or signal processing.

Laplace Transforms

In electrical engineering, Laplace transforms are used to treat important concepts such as zero-state and zero-input responses, impulse and step responses, convolution, frequency response, and filter design. An important pedagogical question is where Laplace transforms should be taught—in the Circuits course, the Signals and Systems course, a Differential Equations course, or elsewhere? The traditional approach has been to first teach phasors and use them to study ac circuit analysis, steady-state ac power, polyphase circuit analysis, magnetically coupled circuits, and frequency response. This extended treatment of phasor analysis means that Laplace transforms are often delayed to the last weeks of the second semester and treated as an advanced topic along with Fourier methods and two-port networks. Typically, then, Laplace transforms are taught in earnest in a Signals and Systems course, where their linkage to phasors is often overlooked. The authors have long advocated an early Laplace approach, one in which Laplace transforms are introduced and applied to circuit analysis before phasors are introduced. The advantage of treating Laplace-based circuit analysis first is that once mastered, it makes learning phasor-based analysis easier and more intuitive. Students quickly make the connection between phasor analysis and the concepts of network functions, transient response, and sinusoidal steady-state response developed through *s*-domain circuit analysis. We do not claim that Laplace analysis is more fundamental or even more important than phasor analysis. We do claim that the learning effort needed to master both phasor analysis and Laplace analysis is not a zero-sum game. Our experience is that less classroom time is needed to ensure mastery of both methods of analysis when

Laplace transform analysis is treated before phasor analysis. Emphasizing transform methods in the circuit course also better prepares students to handle the profusion of transforms they will encounter in subsequent Signals and Systems courses.

SIGNAL PROCESSING

We begin our treatment of dynamic circuits with a separate chapter on waveforms and signal characteristics. This chapter gives students early familiarity with important input and output signals encountered in the study of linear circuits. Introducing signals at the beginning of dynamic circuit analysis lets students become comfortable with time-varying signals without having to simultaneously deal with new concepts. A further emphasis on signal processing and systems is achieved through the use of block diagrams, input-output relationships, and transforms methods. The ultimate goal is for students to understand that time domain waveforms and frequency-domain transforms are simply alternative ways to characterize signals and signal processing. Viewing signals in both domains naturally leads to discussions of important concepts like signal bandwidth, signal sampling, and reciprocal spreading. It is also useful knowledge in choosing alternative design approaches to filters.

COMPUTER TOOLS

Our philosophy recognizes that students come to the Circuits course already knowing how to use several computer tools. Although many know how to use a spreadsheet and may be familiar with math solvers and possibly simulation software, our goal is to help them learn how to effectively use these tools. Knowing when to use these tools and how to interpret the results is essential to understanding circuits. Three types of computer programs are used in this text to illustrate computer-aided circuit analysis, namely spreadsheets (Excel®), math solvers (MATLAB®), and circuit simulators (OrCAD®). Examples, exercises, and homework problems related to computer-aided circuit analysis are integrated into all chapters, beginning with Chapter 1. The purpose of the examples is to help students develop a problem-solving style that includes the intelligent use of the productivity tools routinely used by practicing engineers. Exercises following the examples help students immediately practice the software skill demonstrated in the example. Homework problems that require the use of a particular computer tool are identified by a computer icon (). In this edition we moved much of the discussion on how to use software tools to a new web appendix and included additional examples. This approach streamlines the text for more accomplished students and permits those needing more guidance to have access to additional exposure. This approach directly supports ABET's Criterion 3(k)—*an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.*

APPLICATION EXAMPLES

The text has many examples that link directly to practical uses. The purpose of these examples is to show the student that the topics being covered are more than a pedagogical exercise. These real-world examples find use in common applications and products. We have increased to thirty-one the number of Application Examples. They include topics, such as batteries, source-load interfacing, bipolar junction transistor (BJT) operation, digital multimeters, common-mode rejection ratio (CMRR) in instrumentation amplifiers, electrocardiograph (ECG) and clock timing waveforms, how to obtain a waveform equation from an oscilloscope, sample-hold circuits, clock waveform timing circuits, resonance, impedance bridge, gain-bandwidth product, digital filtering, frequency content of a full-wave rectifier,

isolation and auto-transformers, and others. These examples can be used to support ABET Criterion 3(j)—*a knowledge of contemporary issues.*

TEXT AND WEB APPENDICES

We have included an appendix on complex numbers since many students need to review this essential mathematical knowledge. There are four web appendices: One on the solution of linear equations (A), one on Butterworth and Chebyshev Poles (B), a new appendix on software tools (C), and a new one with all the Exercises worked out (D). These appendices are available at www.wiley.com/college/thomas.

NEW FEATURES OF THE SEVENTH EDITION

SKILLS-BUILDING EXAMPLES, EXERCISES, AND PROBLEMS

Users have asked that we include easier, skills-building examples, exercises, and problems as a means of helping students build confidence. Throughout the text, but especially in the early chapters, we have added several one-concept examples and exercises to key sections. In addition, we added numerous such problems in support of each learning objective. These skill-building items are at the Bloom's Taxonomy ''Comprehension'' level, rather than the more advanced ''Application'' and ''Analysis'' levels. Answers to Exercises have always been provided with the Exercise, but with this edition we have added solutions to each Exercise in a special Web Appendix D. The authors would appreciate feedback as to the usefulness of these added skills-building efforts.

CIRCUIT DESIGN AND EVALUATION

There are dozens of new design examples and exercises. In addition, there are 17 evaluation examples (listed below) and as many evaluation exercises, many of which are new. Our emphasis on creating solutions and choosing the better or best one has been strengthened with the inclusion of 212 design and 54 evaluation homework problems.

Page	Example	Evaluation Example Topic
130	3-26	Power loss comparison
132	3-28	Interface circuit comparison
201	4-21	Block diagram realization comparison
204	4-22	Comparison of two instrumentation systems
205	4-23	Instrumentation I/O comparison
215	4-24	Temperature transducer interface design comparison
337	7-14	First-order transient circuit comparison
424	8-27	High-pass filter evaluation
559	11-7	Cascade connection loading mitigation
571	11-14	Hum elimination circuit evaluation
592	11-24	Active step-response circuit design comparison
623	12-8	High-pass filter comparison
629	12-10	Band-stop filter comparison
661	12-23	Piezoelectric pressure transducer filtering
755	14-5	Notch filter requirement comparison
778	14-9	Multipole low-pass filter time-frequency responses tradeoff
837	16-7	Residential 3-wire system evaluation

OP AMPS

The treatment of OP AMPs in Chapter 4 has been revised to further emphasize design and evaluation. Compared to the sixth edition, several OP AMP sections have

been expanded to include even more building blocks and practical examples for interfacing transducers. We have also added more design examples, including one on instrumentation amplifiers.

FREQUENCY RESPONSE AND ACTIVE FILTERS

We have improved Chapter 12 on frequency response and Chapter 14 on active filters. These chapters are excellent means of understanding the frequency behavior of circuits. We have continued our integration of software to assist the student in understanding frequency behavior through Bode diagrams and pole-zero diagrams in both chapters. Users have told us that Chapter 14 often proves useful to students in subsequent design courses where knowledge of active filters may be needed. As a result, we have expanded our coverage of active multipole notch and tuned filters. And we added a brief overview of Butterworth, Chebyshev, and Elliptic filters. Both chapters have more design and evaluation examples as well as more homework problems.

MUTUAL INDUCTANCE AND TRANSFORMERS

We have replaced the transformer equivalent circuit discussion with examples of the application of the transformer's electrical isolation properties to include a careful definition of isolation.

AC POWER SYSTEMS

We have improved Chapter 16, on three-phase ac power circuits, to make it more in line with what today's students should know. We continued our focus away from phasor circuit analysis toward power flow and systems, both single-phase and three-phase, with new examples and exercises. We simplified the power flow discussion while placing greater emphasis on the fact that power flow does not require phasors. Power flow in a balanced three-phase circuit can be determined using only the magnitudes of the line voltage and line current.

TWO-PORTS

In response to several users, we have updated and moved the chapter on two-ports (Chapter 17) from the web to the main text. This chapter is fully integrated into the text, with examples, exercises, and problems. It has index references and answers to selected homework problems. We have added discussion, examples, and exercises to illustrate that two-port parameters are not just another way to find voltage and current responses. Rather, their primary utility is to determine global circuit properties such as voltage gain, current gain, feedback, and Thévenin equivalence. We would appreciate feedback on the content of this chapter for consideration in future editions.

USING THIS EDITION FOR LAPLACE EARLY

The seventh edition is designed so that it can be used as a Laplace Early version as well as a traditional Phasor First version. The phasor analysis chapter (Chapter 8) comes before the study of Laplace transform techniques (Chapters 9 to 11). Those wishing to follow the traditional approach can follow the seventh edition chapter organization through Chapter 8, on phasor analysis, with a possible delaying of Chapter 7 until the second semester. Those choosing a Laplace Early approach can follow the present chapter organization through Chapter 7, skip Chapter 8, and proceed directly to the Laplace chapters. The current edition includes an

introduction to phasor analysis in Sect. 11–5, dealing with the sinusoidal steady state. As a result, Laplace Early users can study phasor analysis in Chapter 8 at any point after Chapter 11. The following table shows suggested chapter sequencing for the traditional and Laplace Early approaches for three different subject matter emphases. The second author used the Traditional–Electronics sequence at the USAF Academy and has used the Laplace Early–Systems sequence at the University of Denver. Enough material is available in the printed text and in the Web appendix to allow the construction of other topic sequences. Other organizational options are available in the Instructor Manual.

EMPHASIS	SEMESTER 1										SEMESTER 2				
Traditional (Phasor First)															
Power	1	2	3	4	5	6	8/7	7/8	15	16	9	10	11	12	13
Systems								7/8	9	10	11	12	13	14	15
Electronics								7/8	9	10	11	12	14	15	17
Laplace Early															
Power	1	2	3	4	5	6	7	9	10	11	12	13	8	15	16
Systems								9	10	11	12	13	14	8	15
Electronics								9	10	11	12	14	8	15	17

USE OF SOFTWARE IN THIS EDITION

Software use throughout the text has been increased and strengthened to include many new MATLAB, OrCAD, and Excel examples to help practice using the software. We have added a new expanded web appendix to simplify students' use of software. There are 257 homework problems that suggest solutions using MATLAB, OrCAD, or both.

ACKNOWLEDGMENTS

Individuals at John Wiley & Sons, Inc. involved with this edition include Dan Sayre, Associate Publisher; Charlotte Cerf, Editorial Assistant; Chris Ruel, Marketing Manager; Joyce Poh, Senior Production Editor; and Don Fowley, VP and Executive Publisher. Over the years numerous faculty, engineers, staff, students, and others have helped shape this work in too many ways to list. In particular we would like to acknowledge the contributions of the following individuals to whom we are indebted: Robert M. Anderson, Iowa State University; Doran J. Baker, Utah State University; James A. Barby, University of Waterloo; William E. Bennett, United States Naval Academy; Maqsood A. Chaudhry, California State University at Fullerton; Michael Chier, Milwaukee School of Engineering; Don E. Cottrell, University of Denver; Robert Curtis, Ohio University; Michael L. Daley, University of Memphis; Ronald R. Delyser, University of Denver; Prasad Enjeti, Texas A&M University; John C. Getty, University of Denver; James G. Gottling, Ohio State University; Frank Gross, Florida State University; Robert Kotiuga, Boston University; Hans H. Kuehl, University of Southern California; K.S.P. Kumar, University of Minnesota; Nicholas Kyriakopoulos, George Washington University; Michael Lightner, University of Colorado at Boulder; Jerry I. Lubell, Jaycor; Reinhold Ludwig, Worcester Polytechnic Institute; Lloyd W. Massengill, Vanderbilt University; Frank L. Merat, Case Western Reserve University; Richard L. Moat, Motorola; Gene Moriarty, San Jose State University; Dudley Outcalt, Milwaukee School of

Engineering; Anil Pahwa, Kansas State University; Michael Polis, Oakland University; Pradeep Ramuhalli, Michigan State University; William Rison, New Mexico Institute of Mining and Technology; Martin S. Roden, California State University at Los Angeles; Pat Sannuti, the State University of New Jersey; Alan Schneider, University of California at San Diego; Ali O. Shaban, California Polytechnic State University; Jacob Shekel, Northeastern University; Kadagattur Srinidhi, Northeastern University; Peter J. Tabolt, University of Massachusetts at Boston; Len Trombetta, University of Houston; David Voltmer, Rose-Hulman Institute of Technology; Bruce F. Wollenberg, University of Minnesota; Robert Whitman, University of Denver; Albert Batten, USAF Academy; Daniel Pack, USAF Academy; Michael Drew, USAF Academy; Alan R. Klayton, USAF Academy; and Robert A. Weller, Vanderbilt University. Special recognition goes to Suzanne Ingrao Production Manager for editions three through six of this text, and to James K. Kang of California State University at Pomona for his meticulous editing of the homework solutions for the fourth, fifth, sixth, and seventh editions.

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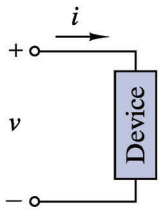


FIGURE 2–1 *Voltage and current reference marks for a two-terminal device.*

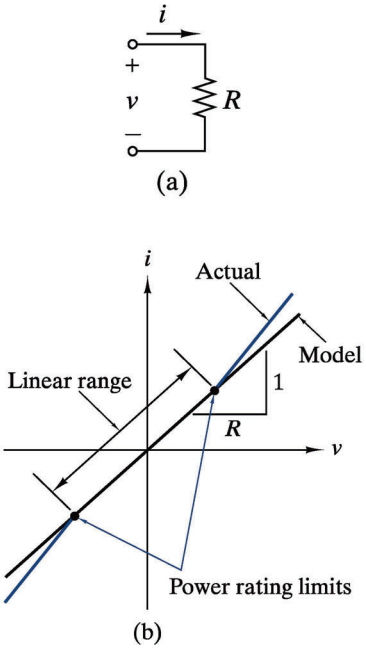




FIGURE 2–2 *The resistor: (a) Circuit symbol. (b) i–v characteristics. (c) Carbon or film resistors. (d) Wire-wound resistors.*

2–1 ELEMENT CONSTRAINTS

A **circuit** is a collection of interconnected electrical devices. An electrical **device** is a component that is treated as a separate entity. The rectangular box in Figure 2–1 is used to represent any one of the two-terminal devices used to form circuits. A two-terminal device is described by its ***i–v* characteristic**, that is, by the relationship between the voltage across and current through the device. In most cases the relationship is complicated and nonlinear, so we use a linear model that approximates the dominant features of a device.

To distinguish between a device (the real thing) and its model (an approximate stand-in), we call the model a circuit **element**. Thus, a device is an article of hardware described in manufacturers' catalogs and parts specifications. An element is a model described in textbooks on circuit analysis. This book is no exception, and a catalog of circuit elements will be introduced as we go on.

THE LINEAR RESISTOR

The first element in our catalog is a linear model of the device described in Figure 2–2. The actual *i–v* characteristic of this device is shown in Figure 2–2(b). To model this curve accurately across the full operating range shown in the figure would require at least a cubic equation. However, the graph in Figure 2–2(b) shows that a straight line is a good approximation to the *i–v* characteristic if we operate the device within its linear range. The power rating of the device limits the range over which the *i–v* characteristics can be represented by a straight line through the origin.

For the passive sign convention used in Figure 2–2(a), the equations describing the *linear resistor* element are

$$v = Ri \quad \text{or} \quad i = Gv \tag{2–1}$$

where R and G are positive constants that are reciprocally related:

$$G = \frac{1}{R} \tag{2–2}$$

The relationships in Eq. (2–1) are collectively known as **Ohm's law**. The parameter R is called **resistance** and has the unit **ohms**, Ω. The parameter G is called **conductance**, with the unit **siemens**, S. In earlier times the unit of conductance was cleverly called the mho, with the unit abbreviation symbol ℧ ("ohm" spelled backward and the ohm symbol upside down). Note that Ohm's law presumes that the passive sign convention is used to assign the reference marks to voltage and current.

The Ohm's law model is represented graphically by the black straight line in Figure 2–2(b). The *i–v* characteristic for the Ohm's law model defines a circuit element that is said to be linear and bilateral. **Linear** means that the defining characteristic is a straight line through the origin. Elements whose characteristics do not pass through the origin or are not a straight line are said to be **nonlinear**. **Bilateral** means that the *i–v* characteristic curve has odd symmetry about the origin.[1] With a bilateral resistor, reversing the polarity of the applied voltage reverses the direction but not the magnitude of the current, and vice versa. The net result is that we can connect a bilateral resistor into a circuit without regard to which terminal is which. This is important because devices such as diodes and batteries are not bilateral, and we must carefully identify each terminal.

Figures 2–2(c) and (d) show photos of discrete resistor devices.

[1]A curve $i = f(v)$ has odd symmetry if $f(-v) = -f(v)$.

The power associated with the resistor can be found from $p = vi$. Using Eq. (2–1) to eliminate v from this relationship yields

$$p = i^2R \tag{2–3}$$

or using the same equations to eliminate i yields

$$p = v^2G = \frac{v^2}{R} \tag{2–4}$$

Since the parameter R is positive, these equations tell us that the power is always nonnegative. Under the passive sign convention, this means that the resistor **always absorbs or consumes power**.



(d)

FIGURE 2–2 *(Continued)*

EXAMPLE 2 – 1

A 2.2-kΩ resistor has 12 V impressed across its terminals. Find the current through the resistor and the power it dissipates.

SOLUTION:

By Ohm's law $i = v/R$. Therefore, $i = 12/2200 = 0.00545 = 5.45$ mA. The power dissipated is found using Eq. (2–3) $p = i^2R = (0.00545)^2\,2200 = 65.4$ mW which is the same answer we get if we were to use Eq. (2–4) $p = v^2/R = 12^2/2200 = 65.4$ mW or Eq. (1–5) $p = iv = 0.00545 \times 12 = 65.4$ mW. ■

Exercise 2–1

A 6-V lantern battery powers a light bulb that draws 3 mA of current. What is the resistance of the lamp? How much power does the lantern use?

Answers: $R = 2$ kΩ; $p = 18$ mW

EXAMPLE 2 – 2

A resistor operates as a linear element as long as the voltage and current are within the limits defined by its power rating. Suppose we have a 47 kΩ resistor with a power rating of 0.25 W. Determine the maximum current and voltage that can be applied to the resistor and have it remain within its linear operating range.

SOLUTION:

Using Eq. (2–3) to relate power and current, we obtain

$$I_{MAX} = \sqrt{\frac{P_{MAX}}{R}} = \sqrt{\frac{0.25}{47 \times 10^3}} = 2.31\,\text{mA}$$

Similarly, using Eq. (2–4) to relate power and voltage, we obtain

$$V_{MAX} = \sqrt{RP_{MAX}} = \sqrt{47 \times 10^3 \times 0.25} = 108\,\text{V}$$ ■

Exercise 2–2

What is the maximum current that can flow through a $^1/_8$-W, 6.8-kΩ resistor? What is the maximum voltage that can be across it?

Answers: $I_{MAX} = 4.287$ mA; $V_{MAX} = 29.15$ V

OPEN AND SHORT CIRCUITS

The next two circuit elements can be thought of as limiting cases of the linear resistor. Consider a resistor R with a voltage v applied across it. Let's calculate the

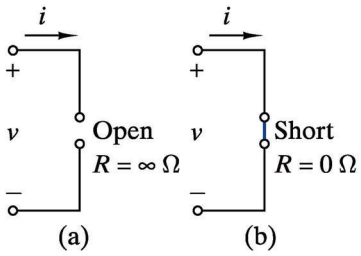


FIGURE 2–3 *Circuit symbols: (a) Open-circuit symbol. (b) Short-circuit symbol.*

current i through the resistor for different values of resistance. If $v = 10\,\text{V}$ and $R = 1\,\Omega$, using Ohm's law we readily find that $i = 10\,\text{A}$. If we increase the resistance to $100\,\Omega$, we find i has decreased to 0.1 A or 100 mA. If we continue to increase R to $1\,\text{M}\Omega$, i becomes a very small $10\,\mu\text{A}$. Continuing this process, we arrive at a condition where R is very nearly infinite and i just about zero. When the current $i = 0$, we call the special value of resistance (i.e., $R = \infty\Omega$) an **open circuit**. Similarly, if we reduce R until it approaches zero, we find that the voltage is very nearly zero. When $v = 0$, we call the special value of resistance (i.e., $R = 0\,\Omega$) a **short circuit**. The circuit symbols for these two elements are shown in Figure 2–3. In circuit analysis the elements in a circuit model are assumed to be interconnected by zero-resistance wire (that is, by short circuits).

THE IDEAL SWITCH

A switch is a familiar device with many applications in electrical engineering. The **ideal switch** can be modeled as a combination open- and short-circuit element. Figure 2–4(a) and (b) show the circuit symbol and the i–v characteristic of an ideal switch. When the switch is closed,

$$v = 0 \quad \text{and} \quad i = \text{any value} \tag{2–5a}$$

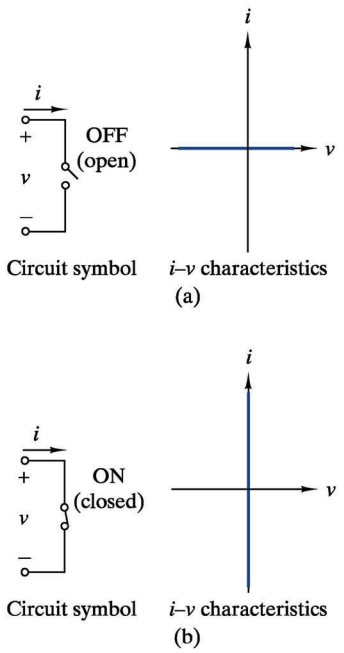
and when it is open,

$$i = 0 \quad \text{and} \quad v = \text{any value} \tag{2–5b}$$

When the switch is closed, the voltage across the element is zero and the element will pass any current that may result. When open, the current is zero and the element will withstand any voltage across its terminals. The power is always zero for the ideal switch, since the product $vi = 0$ when the switch is either open ($i = 0$) or closed ($v = 0$). Actual switch devices have limitations, such as the maximum current they can safely carry when closed and the maximum voltage they can withstand when open. The switch is operated (opened or closed) by some external influence, such as a mechanical motion, temperature, pressure, or an electrical signal.

Figure 2–4(c) shows an actual toggle switch, which is simply used to turn things ON and OFF, and Figure 2–4(d) shows a DIP (dual in-line package) switch designed for use on a printed circuit board.

The ideal switch is also a basic concept in digital circuits, where OFF usually represents a logic 0 state and ON represents a logic 1 state.



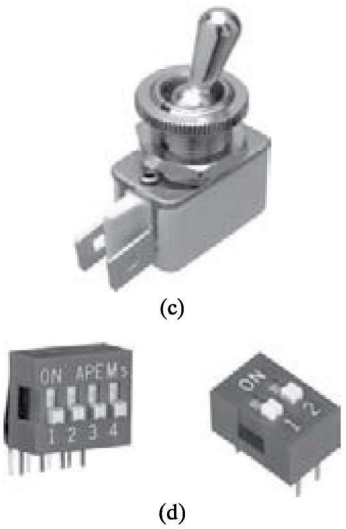


FIGURE 2–4 *The circuit symbol and i–v characteristics of an ideal switch: (a) Switch OFF. (b) Switch ON. (c) Toggle switch. (d) DIP switch.*

APPLICATION EXAMPLE 2 – 3

The **analog switch** is an important device found in analog-to-digital interfaces. Figures 2–5(a) and (b) show the two basic versions of the device. In either type the switch is actuated by applying a voltage to the terminal labeled *gate*. The switch in Figure 2–5(a) is said to be *normally open* because it is open when no voltage is applied to the gate terminal and closes when voltage is applied. The switch in Figure 2–5(b) is said to be *normally closed* because it is closed when no voltage is applied to the controlling gate and opens when voltage is applied.

Figure 2–5(c) shows an application in which complementary analog switches are controlled by the same gate. When gate voltage is applied, the upper switch closes and the lower opens so that point A is connected to point C. Conversely, when no gate voltage is applied, the upper switch opens and the lower switch closes to connect point B to point C. In the analog world this arrangement is called a double throw switch since point C can be connected to two other points. In the digital world it is called a two-to-one multiplexer (or MUX) because it

allows you to select the analog input at point A or point B under control of the digital signal applied to the gate.

In many applications an analog switch can be treated as an ideal switch. In other cases, it may be necessary to account for its nonideal characteristics. When the switch is open an analog switch acts like a very large resistance (R_{OFF}), as suggested in Figure 2–5(d). This resistance is negligible because it ranges from perhaps 10^9 to $10^{11}\ \Omega$. When the switch is closed it acts like a small resistor (R_{ON}), as suggested in Figure 2–5(e). Depending on other circuit resistances, it may be necessary to account for R_{ON}, because it ranges from perhaps a few mΩ to as high as $100\ \Omega$.

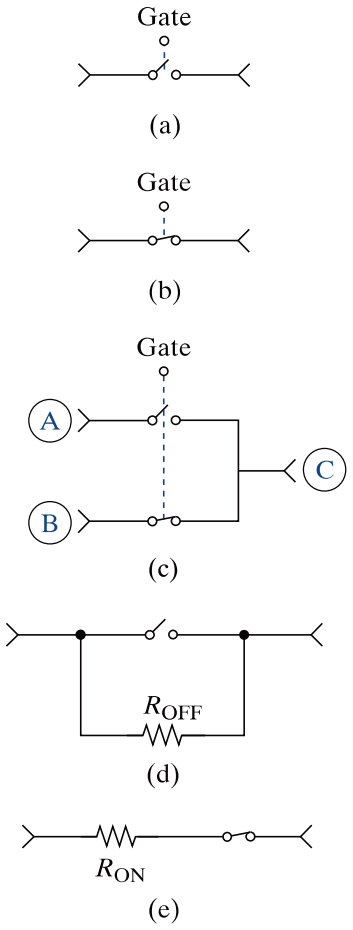


FIGURE 2–5 *The analog switch: (a) Normally open model. (b) Normally closed model. (c) Double throw model. (d) Model with finite OFF resistance. (e) Model with finite ON resistance.*

This example illustrates how ideal switches and resistors can be combined to model another electrical device. It also suggests that no single model can serve in all applications. It is up to the engineer to select a model that adequately represents the actual device in each application.

IDEAL SOURCES

The signal and power sources required for the operation of electronic circuits are modeled using two elements: **voltage sources** and **current sources**. These sources can produce either constant or time-varying signals. The circuit symbols and the i–v characteristic of an ideal voltage source are shown in Figure 2–6, while the circuit symbol and i–v characteristic of an ideal current source are shown in Figure 2–7. The symbol in Figure 2–6(a) represents either a time-varying or constant voltage source. The battery symbol in Figure 2–6(b) is used exclusively for a constant voltage source. There is no separate symbol for a constant current source.

The i–v characteristic of an **ideal voltage source** in Figure 2–6(c) is described by the following element equations:

$$v = v_S \quad \text{and} \quad i = \text{any value} \tag{2–6}$$

The element equations mean that the ideal voltage source produces v_S volts across its terminals and will supply whatever current may be required by the circuit to which it is connected.

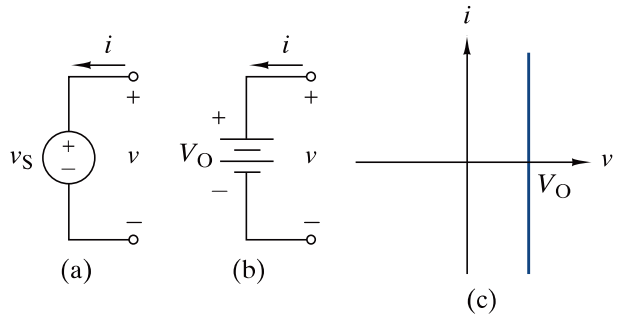


FIGURE 2–6 *Circuit symbols and i–v characteristic of an ideal independent voltage source: (a) Time-varying. (b) Constant (Battery). (c) Constant source i–v characteristics.*

The i–v characteristic of an **ideal current source** in Figure 2–7(b) is described by the following element equations:

$$i = i_S \quad \text{and} \quad v = \text{any value} \tag{2–7}$$

The ideal current source produces i_S amperes in the direction of its arrow symbol and will furnish whatever voltage is required by the circuit to which it is connected.

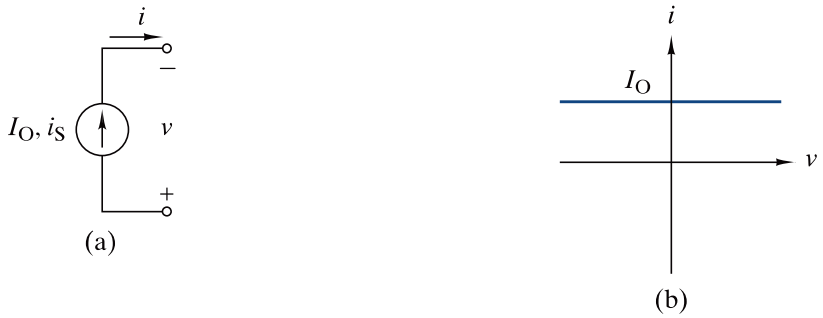


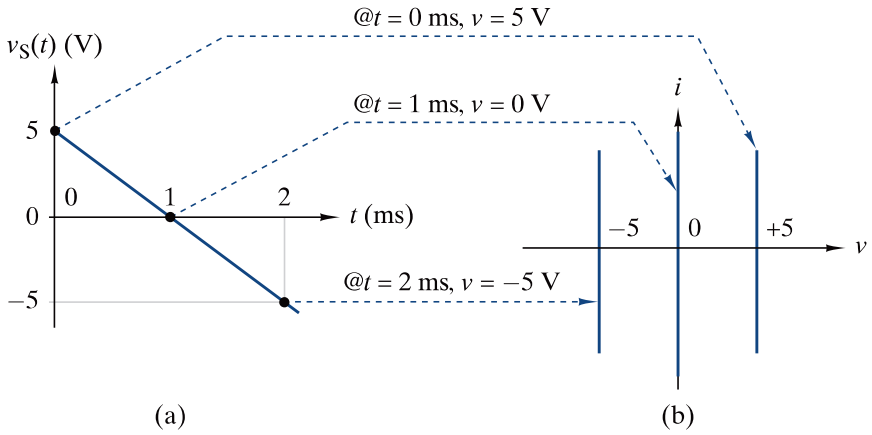
FIGURE 2–7 *Circuit symbol and i–v characteristic of an ideal independent current source: (a) Time-varying or constant source. (b) Constant source i–v characteristics.*

The voltage or current produced by these ideal sources is called a **forcing function** or a **driving function** because it represents an input that causes a circuit response. When the voltage or current varies with time, it is customary to write $v(t)$ or $i(t)$.

EXAMPLE 2 – 4

Given an ideal voltage source with the time-varying voltage shown in Figure 2–8(a), sketch its *i–v* characteristic at the times $t = 0$, 1, and 2 ms.

FIGURE 2–8



SOLUTION:

At any instant in time, the time-varying source voltage has only one value. We can treat the voltage and current at each instant of time as constants representing a snapshot of the source *i–v* characteristic. For example, at $t = 0$, the equations defining the *i–v* characteristic are $v_S = 5$ V and $i =$ any value. Figure 2–8(b) shows the *i–v* relationship at the other instants of time. Curiously, the voltage source *i–v* characteristic at $t = 1$ ms ($v_S = 0$ and $i =$ any value) is the same as that of a short circuit [see Eq. (2–5a) or Figure 2–3(b)]. ■

Exercise 2–3

A digital clock is a voltage that switches between two values at a constant rate that is used to time digital circuits. A particular clock switches between 0 V and 5 V every 10 μs. Sketch the clock's *i*-v characteristics for the times when the clock is at 0 V and at 5 V.

Answers: On a standard *i-v* graph a vertical line through the origin for the times the clock is at 0 V and a vertical line crossing at 5 V when the clock is at 5 V.

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