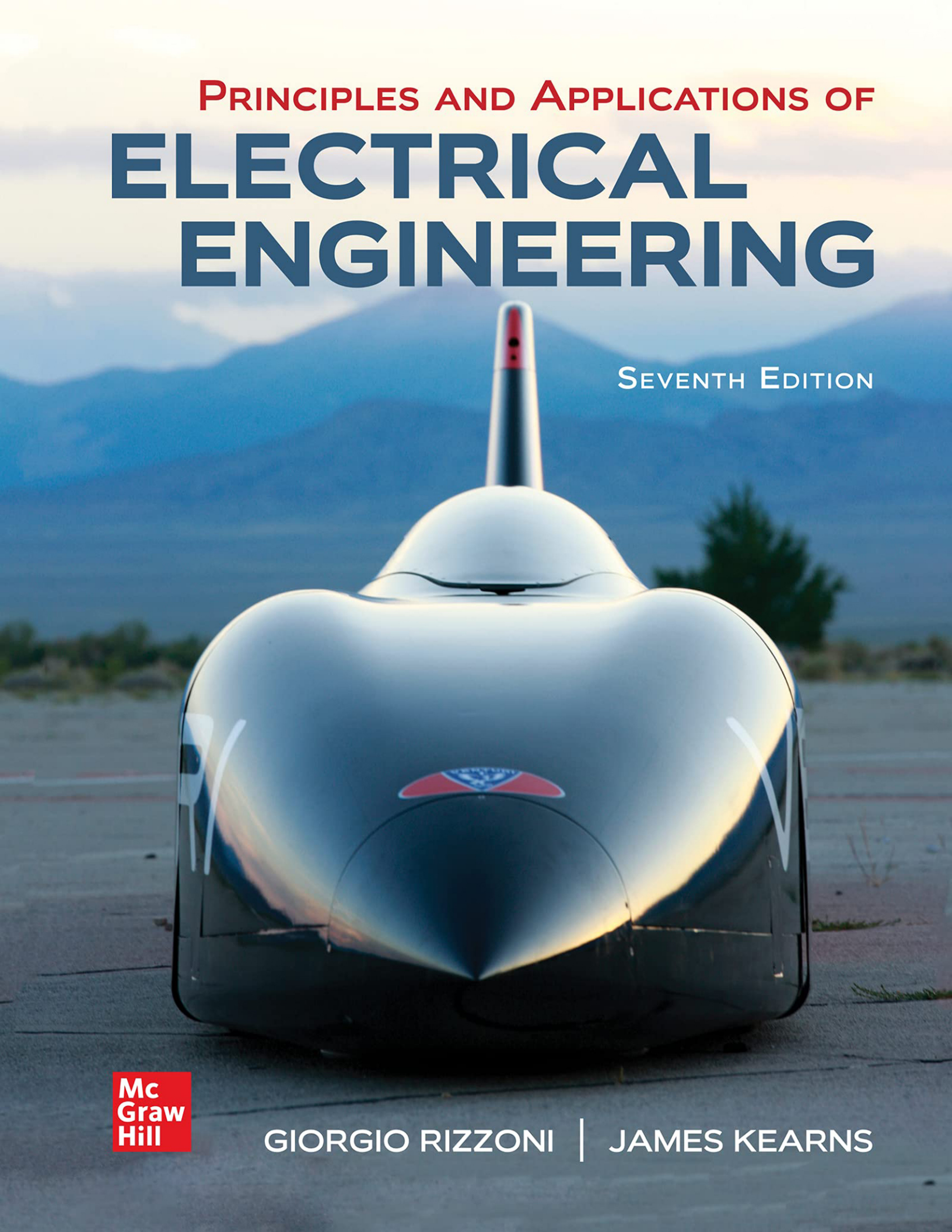
Principles and Applications of
ELECTRICAL ENGINEERING

Seventh Edition



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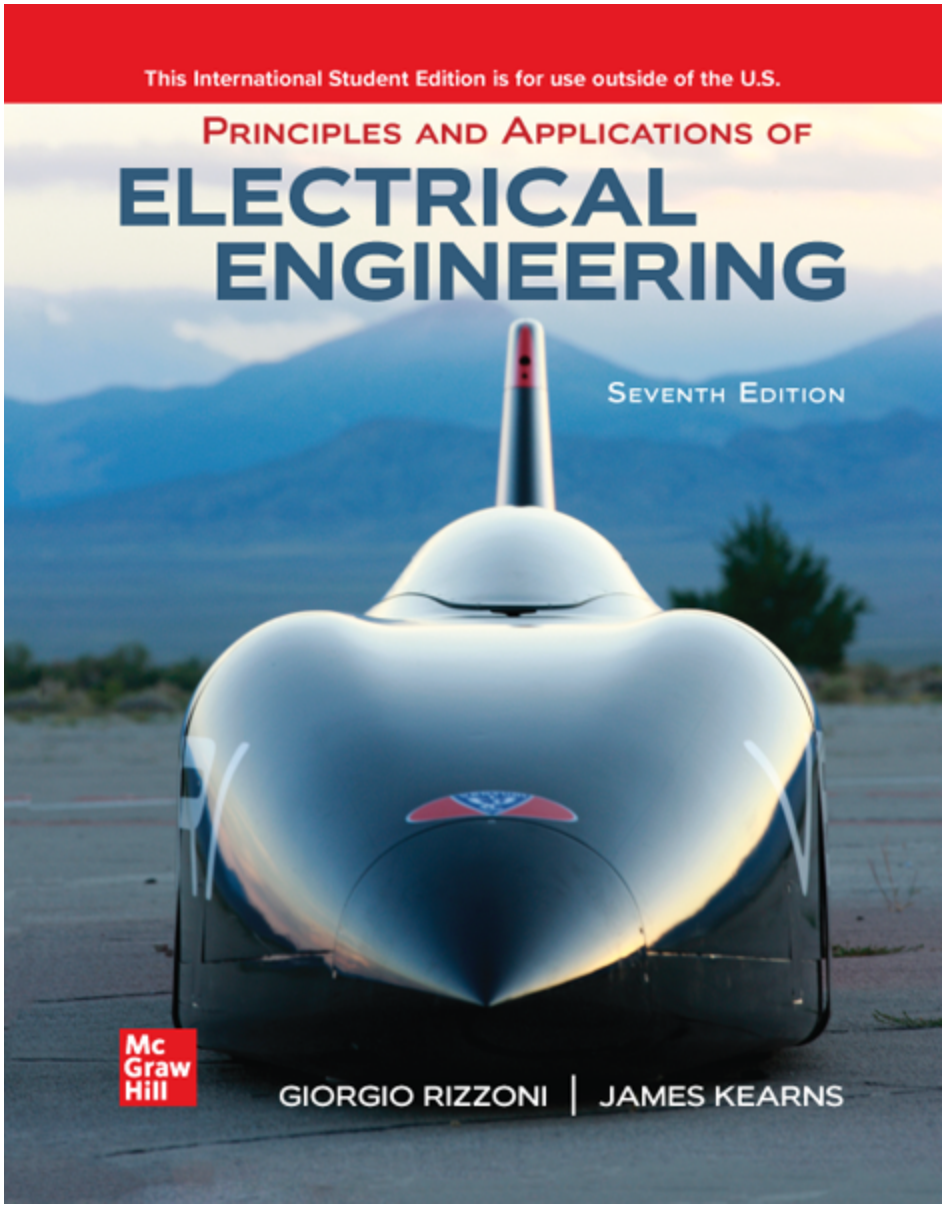
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PRINCIPLES AND APPLICATIONS OF
ELECTRICAL ENGINEERING
SEVENTH EDITION
Mc Graw Hill
GIORGIO RIZZONI | JAMES KEARNS

PRINCIPLES AND APPLICATIONS OF ELECTRICAL ENGINEERING

Seventh Edition

Giorgio Rizzoni
The Ohio State University

James Kearns
York College of Pennsylvania

PRINCIPLES AND APPLICATIONS OF ELECTRICAL ENGINEERING

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About the Authors

Giorgio Rizzoni, the *Ford Motor Company Chair in ElectroMechanical Systems*, is a Professor of Mechanical and Aerospace Engineering and of Electrical and Computer Engineering at The Ohio State University (OSU). He received his B.S. in 1980, his M.S. in 1982, and his Ph.D. in 1986, in Electrical and Computer Engineering, all from the University of Michigan. Since 1999 he has been the director of the Ohio State University Center for Automotive Research (CAR), an interdisciplinary research center in the OSU College of Engineering.

Dr. Rizzoni's research interests are in the dynamics and control of future ground vehicle propulsion systems, including advanced engines, alternative fuels, electric and hybrid-electric drivetrains, energy storage systems, and fuel cell systems. He has contributed to the development of a graduate curriculum in these areas and has served as the director of three U.S. Department of Energy Graduate Automotive Technology Education Centers of Excellence: *Hybrid Drivetrains and Control Systems* (1998–2004), *Advanced Propulsion Systems* (2005–2011), and *Energy Efficient Vehicles for Sustainable Mobility* (2011–2016).

In 1999 Dr. Rizzoni established an automotive industry research consortium that today sees the participation of over 20 automotive OEMs and suppliers; in 2008 he created the SMART@CAR consortium, focusing on plug-in hybrid and electric vehicles and vehicle-grid interaction, with funding from electric utilities, automotive OEMS, and electronics suppliers. Through the Ohio Third Frontier Wright Project Program he created a *Center of Excellence for Commercial Hybrid Vehicles* in 2009, and a *Center of Excellence for Energy Storage Technology* in 2010.

Dr. Rizzoni is a Fellow of IEEE (2004), a Fellow of SAE (2005), a recipient of the 1991 National Science Foundation Presidential Young Investigator Award, and of several other technical and teaching awards.

The OSU Center for Automotive Research

The OSU Center for Automotive Research, CAR, is an interdisciplinary research center in the OSU College of Engineering founded in 1991 and located in a 50,000 ft^2 building complex on the west campus of OSU. CAR conducts interdisciplinary research in collaboration with the OSU colleges of Engineering, Medicine, Business, and Arts and Sciences, and with industry and government partners. CAR research aims to: develop efficient vehicle propulsion and energy storage systems; develop new sustainable mobility concepts; reduce the impact of vehicles on the environment; improve vehicle safety and reduce occupant and pedestrian injuries; increase vehicle autonomy and intelligence; and create quieter and more comfortable automobiles. A team of 50 administrative and research staff supports some 40 faculty, 120 graduate and 300 undergraduate students and maintains and makes use of advanced experimental facilities. Dr. Rizzoni has led CAR for over a decade, growing its research expenditures from $1M per year to over $10M today, and engaging CAR in a broad range of technology commercialization activities, start-up company incubation and spin-out, as well as providing a broad range of engineering services to the automotive industry.

CAR is also the home of the OSU Motorsports program, which supports the activities of five student vehicle competition programs of several student vehicle competition programs including: the Buckeye Bullet (holder of all current U.S. and FIA electric vehicle land speed records), the EcoCAR hybrid-electric vehicle team, the Formula Buckeyes and Baja Buckeyes SAE teams, and the Buckeye Current electric motorcycle racing team.

Jim Kearns is an Associate Professor of Electrical & Computer Engineering at York College of Pennsylvania. He received a B.S. in Mechanical Engineering (SEAS) and a B.S. in Economics (Wharton) from the University of Pennsylvania in 1982. Subsequently, he received his M.E. from Carnegie-Mellon University in 1984, and his Ph.D. from the Georgia Institute of Technology in 1990, both in Mechanical Engineering. While at Georgia Tech he was the recipient of a Presidential

Fellowship. Subsequently, he worked as a Postdoctoral Fellow at the Applied Research Laboratory of the University of Texas—Austin.

In 1992, Dr. Kearns took his first teaching position at the Universidad del Turabo in Gurabo, Puerto Rico, where he worked with a small group of faculty and staff to build and develop a new school of engineering. In addition to other duties, he was tasked with developing a curriculum on electromechanics. During this time Dr. Kearns spent his summers at Sandia National Laboratories as a University Fellow.

In 1996, Dr. Kearns was the second full-time engineering faculty member hired by York College of Pennsylvania to (once again) develop a new engineering program with an emphasis on Mechatronics. As a result of that work, Jim was asked in 2003 to develop new electrical and computer engineering programs at YCP. Jim served as program coordinator until July 2010.

Throughout Dr. Kearns professional career he has been involved in teaching and research related to physical acoustics and electromechanical systems. His interest in electrical engineering began during his Ph.D. studies, when he built spark generators, DC power supplies, and signal amplifiers for his experiments. His steady pursuit of electromechanical engineering education has been the hallmark of his professional career. Dr. Kearns has been involved in a variety of pedagogical activities, including the development and refinement of techniques in electrical engineering education.

Dr. Kearns is a member of IEEE and ASEE. He is active in faculty governance at York College, where he is a past chair of its Tenure and Promotion committee and its Student Welfare committee. Dr. Kearns recently completed a four-year term as Vice-President and then President of the York College Academic Senate.

About the Cover

On the cover, an image of the Venturi Buckeye Bullet 3 at the Bonneville Salt Flats, UT, in 2016. On Monday, September 19, 2016, The Ohio State University's Venturi Buckeye Bullet 3 student team and driver Roger

Schroer took this electric streamliner vehicle to a world record two-way average top speed of 341.4 miles per hour (549.4 kilometers per hour). The vehicle was designed and built by a team of engineering students at The Ohio State University, advised by Dr. Giorgio Rizzoni.

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Preface

The pervasive presence of electronic devices and instrumentation in all aspects of engineering design and analysis is one of the manifestations of the electronic revolution that has characterized the last 60 years. Every aspect of engineering practice, and of everyday life, has been affected in some way or another by electrical and electronic devices and instruments. Laptop and tablet computers along with so-called "smart" phones and touchscreen interfaces are perhaps the most obvious manifestations. These devices, and their underlying technology, have brought about a revolution in computing, communication, and entertainment. They allow us to store, process, and share professional and personal data and to access audio (most notably, music) and video of every variety. These advances in electrical engineering technology have had enormous impacts on all other fields of engineering, including mechanical, industrial, computer, civil, aeronautical, aerospace, chemical, nuclear, materials, and biological engineering. This rapidly expanding electrical and electronic technology has been adopted, leveraged, and incorporated in engineering designs across all fields. As a result, engineers work on projects requiring effective communication across multiple disciplines, one of which is nearly always electrical engineering.

0.1 OBJECTIVES

Engineering education and professional practice continue to undergo profound changes in an attempt to best utilize relevant advances in electronic technology. The need for textbooks and other learning resources that relate these advances to engineering disciplines beyond electrical and computer engineering continues to grow. This fact is evident in the ever-expanding application and integration of electronics and computer technologies in commercial products and processes. This textbook and its associated learning resources represent one effort to make the principles of

electrical and computer engineering accessible to students in various engineering disciplines.

The principal objective of the book is to present the *principles* of electrical, electronic, and electromechanical engineering to an audience of engineering majors enrolled in introductory and more advanced or specialized electrical engineering courses.

A second objective is to present these principles with a focus on important results and common yet effective *analytical and computational* tools to solve practical problems.

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

These three objectives are met through the use of various pedagogical features and methods.

0.2 ORGANIZATION

The basic organizational structure of a generic chapter remains essentially unchanged from the previous edition. Example problems and associated methods and procedures of problem solving remain organized so that students are able to easily and efficiently locate them when doing homework and preparing for exams. Page xAdditional unguided exercises are provided to test student understanding. Relevant and stimulating applications to practical measurement challenges are included in nearly every chapter.

A continued and enhanced emphasis on problem solving can be found in this edition. All the highlighted *Focus on Problem Solving* boxes have been reviewed and revised to clarify and add additional detail to the steps needed by students to successfully complete end-of-chapter homework problems.

An effort was also made to reduce the aesthetic complexity of the book, without sacrificing technical content or overall aesthetic appeal. Effective reading is promoted by less clutter and visual "noise." A thorough,

exhaustive, page-by-page search was made to locate errors in the text, equations, figures, references to equations and figures, examples, and homework problems.

The book is now divided into five major parts:

I. **Circuit Analysis**
II. **Systems and Instrumentation**
III. **Analog Electronics**
IV. **Digital Electronics**
V. **Electric Power and Machines**

The pedagogical enhancements made within each part are discussed below.

0.3 PEDAGOGY AND CONTENT

Part I: Circuit Analysis

Once again, the first part of the book has undergone a significant revision from the previous edition.

Chapter 1 begins with an emphasis on developing a student's ability to recognize structure within a circuit diagram. It is the authors' experience that this ability is key to student success. Yet, many books contain little content on developing this ability. The result is that many students wander into more difficult topics still viewing a circuit as simply an unruly collection of wires and elements.

The approach taken in this book is to encourage students to initially *focus on nodes*, rather than elements, in a circuit. For example, some of the earliest exercises in this book ask students to count the number of nodes in a circuit diagram. One immediate advantage of this patient approach is that students learn to disregard the particular aesthetic structure of a circuit diagram and instead focus on the technical structure and content. Chapter 1 also immediately engages students in the terminology, laws, and methods needed to solve basic DC problems and introduces the first of many electromechanical analogies.

Chapter 2 introduces students to more sophisticated analytic methods with a focus on appreciating the implications and utility of equivalent networks. The students' skill at recognizing circuit structure is further developed by the introduction of elements in series and parallel, applied to the more general concept of equivalent resistance between two nodes. The principle of superposition and the *source-load perspective* followed by Thévenin and Norton equivalent networks complete Chapter 2. The section on the source-load perspective revisits the concepts of voltage and current division to develop their graphical solution as the intersection of a Page xisource's load line with the load's *v-i* relation. This section is not essential but it can be very helpful to students when introduced prior to the usually difficult topic of Thévenin equivalent networks.

Methods of Problem Solving were enhanced and clarified. Throughout these chapters students are encouraged to think of problem solving in two steps: first **simplify**; then **solve**. In addition to being an effective problem-solving method, this method provides context for the power and importance

of equivalent networks in general, and Thévenin's theorem, in particular. Chapter 3 continues the emphasis on equivalent networks applied to AC circuit analysis. In the following chapters on transient analysis and frequency response, foundational first- and second-order circuit *archetypes* are identified. Students are encouraged to continue to use Thévenin and Norton equivalent networks to simplify, when possible, transient circuit problems to these archetypes, which, in effect, become targets for students.

Finally, emphasis continues to be placed on visualizing phasors in the complex plane and understanding the key role of the unit phasor and Euler's theorem. Throughout the chapter on AC circuits students are encouraged to focus on the concepts of impedance and power triangles, and their similarity. Single-phase AC power concepts are now addressed in the chapter on AC circuits, whereas material related to transformers and three-phase power were moved to Part V.

Part II: Systems and Instrumentation

This part of the textbook brings together all of the material related to measurement and instrumentation found in the sixth edition and represents a significant change. The chapter on operational amplifiers continues to emphasize three amplifier archetypes (the unity-gain buffer, the inverting amplifier, and the noninverting amplifier) before introducing variations and applications, which are now more readily related to issues and challenges commonly encountered when conducting measurements using electronic instrumentation. The discussion of instrumentation amplifiers, in particular, was expanded and clarified. It is hoped that the reorganization of this material will bring greater relevance and practicality to students at an early stage of their study and allow instructors to complete this material and that in Part I in a one-semester course.

Part III: Analog Electronics

While much of the content on electronics is unchanged from the sixth edition, the problem-solving strategies and techniques for transistor circuits were further enhanced and clarified. The focus on simple but useful circuit examples was not changed.

The emphasis on large-signal models of BJTs and FETs and their applications was retained; however, an appropriate, but limited, presentation of small-signal models was included to support the discussion of AC amplifiers. These chapters present an uncomplicated and practical treatment of the analysis and design of simple amplifiers and switching circuits.

The chapter on power electronics is no longer included in the textbook but can be found in the online resources that support the book.

Part IV: Digital Electronics

The chapters on digital electronics remain largely unchanged except for a needed update of the material on encoders, gate arrays, and programmable logic devices. A greater number of end-of-chapter problems are now included in the chapter on digital systems.

It should be noted that the chapters on communication systems have been removed from the textbook but can be found in the online resources that support it.

Part V: Electric Power and Machines

Part V reflects a change in the organization of the book that brings together those aspects of electrical engineering that are related to electric power systems. Every instructor understands that there is no unique way of presenting introductory electrical engineering material, and the positioning of Part V in the book is somewhat arbitrary, as the section could really be placed anywhere after Section I. Chapter 13 covers the fundamentals of electric power systems, largely unchanged from previous editions, introducing AC power, complex power, and elements of three-phase power systems. Chapters 14 and 15 offer an introductory treatment of electrical machines, with focus on DC, and AC synchronous and induction machines. Two ancillary chapters are available online for instructors who wish to have a more in-depth treatment of electromechanical systems: one on power electronics, which introduces devices and systems for electric power conversion; the other on special-purpose electric machines, which presents a survey of electric machines commonly used in industrial systems and consumer products, such as step motors, brushless DC machines, switched reluctance machines, and single-phase AC machines. The content of Chapters 14 and 15 and of the ancillary chapters was developed by the first author for use in a required junior-year system dynamics course for mechanical engineers, and in a technical elective on mechatronics systems.

0.4 NOTATION

The notation used in this book for various symbols (variables, parameters, and units) has been updated but still follows generally accepted conventions. Distinctions in notation can be subtle. Luckily, very often the context in which a symbol appears makes its meaning clear. When the meaning of a symbol is not clear from its context a correct reading of the notation is important. A reasonably complete listing of the symbols used in this book and their notation is presented below.

For example, an uppercase roman font is used for units such as volts (V) and amperes (A). An uppercase italics math font is used for real parameters and variables such as resistance (R) and DC voltage (V). Notice the difference between the variable V and the unit V. Further, an uppercase bold

math font is used for complex quantities such as voltage and current phasors (**V** and **I**) as well as impedance (**Z**), conductance (**Y**), and frequency response functions (**H** and **G**). Lowercase italic symbols are, in general, time dependent variables, such as voltage (v or $v(t)$) and current (i or $i(t)$), where (t) is an explicit indication of time Page xiiidependence. Lowercase italic variables may represent constants in specific cases. Uppercase italic variables are reserved for constant (time-invariant) values exclusively.

Various subscripts are also used to denote particular instances or multiple occurrences of parameters and variables. Exponents are italicized superscripts.

Finally, in electrical engineering the imaginary unit $\sqrt{-1}$ is always represented by j rather than i, which is used by mathematicians. The reason for the use of j instead of i should be obvious!

Quantity	Symbol	Description
Voltage	v or $v(t)$	Time Dependent and Real
	V	Time Invariant and Real
	V	Complex Phasor
Effective (rms) voltage	$\tilde{V}$	Time Invariant and Real
Current	i or $i(t)$	Time Dependent and Real
	I	Time Invariant and Real
	I	Complex Phasor
Effective (rms) current	$\tilde{I}$	Time Invariant and Real
Volts	V	Unit of voltage
Amperes	A	Unit of current
Resistance	R	Real
Inductance	L	Real
Capacitance	C	Real
Reactance	X	Frequency Dependent and Real
Impedance	**Z**	Frequency Dependent and Complex
Conductance	**Y**	Frequency Dependent and Complex
Transfer Function	**G** or **H**	Frequency Dependent and Complex
Cyclical Frequency	f	Time Invariant and Real
Angular Frequency	ω	Time Invariant and Real
Angle	θ	Time Invariant and Real
Amplitude	A	Time Invariant and Real

0.5 SYSTEM OF UNITS

This book employs the International System of Units (also called SI, from the French Système International des Unitès). SI units are adhered to by virtually all professional engineering societies and are based upon the seven fundamental quantities listed in Table 0.1. All other units are derived from these base units. An example of a derived unit is the radian, which is a measure of plane angles. In this book, angles are in units of radians unless explicitly given otherwise as degrees.

Since quantities often need to be described in large multiples or small fractions of a unit, the standard prefixes listed in Table 0.2 are used to denote SI units in powers of 10. In general, engineering units are expressed in powers of 10 that are multiples of 3. For example, 10^{-4} s would be expressed as 100×10^{-6} s, or 100 μs.

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Tables 0.1 and 0.2 are useful references when reading this book.

Table 0.1 SI units

Quantity	Unit	Symbol
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electric current	Ampere	A
Temperature	Kelvin	K
Substance	Mole	mol
Luminous intensity	Candela	cd

Table 0.2 Standard prefixes

Prefix	Symbol	Power
atto	a	10^{-18}
femto	f	10^{-15}
pico	p	10^{-12}
nano	n	10^{-9}
micro	μ	10^{-6}
milli	m	10^{-3}
centi	c	10^{-2}
deci	d	10^{-1}
deka	da	10
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}
tera	T	10^{12}

0.6 ADDITIONAL FEATURES OF THE SEVENTH EDITION

Pedagogy

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

- **Learning Objectives** offer an overview of key chapter ideas. Each chapter opens with a list of major objectives, and throughout the chapter the learning objective icon indicates targeted references to each objective.
- **Focus on Problem Solving** sections summarize important methods and procedures for the solution of common problems and assist the student in developing a methodical approach to problem solving.
- **Clearly Illustrated Examples** illustrate relevant applications of electrical engineering principles. The examples are fully integrated with the Focus on Problem Solving material, and each one is organized according to a prescribed set of logical steps.
- **Check Your Understanding** exercises follow each set of examples and allow students to confirm their mastery of concepts.
- **Make the Connection** sidebars present analogies that illuminate electrical engineering concepts using other concepts from engineering disciplines.