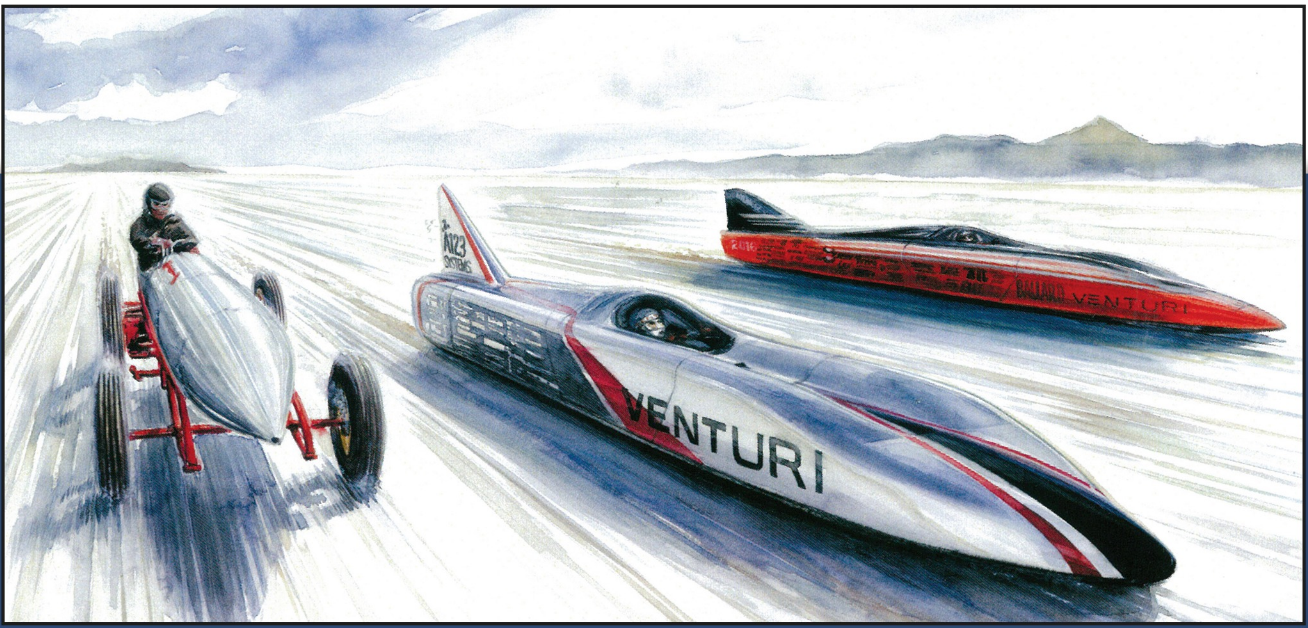
SIXTH EDITION

Principles and Applications of
Electrical Engineering



GIORGIO RIZZONI | JAMES KEARNS

Mc Graw Hill Education

PRINCIPLES AND APPLICATIONS OF ELECTRICAL ENGINEERING

Sixth Edition

Giorgio Rizzoni
The Ohio State University
James Kearns
York College of Pennsylvania

Mc
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Education

A Donatella
To my family

PRINCIPLES AND APPLICATIONS OF ELECTRICAL ENGINEERING, SIXTH EDITION

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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). Since January 2011 he has been the OSU Site Director for the U.S. Department of Energy's China–USA Clean Energy Research Center on Clean Vehicles.

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 collaboration with Vanner, Inc., and other industry partners in 2009, and a *Center of Excellence for Energy Storage Technology* in collaboration with CAR Technologies LLC and other industry partners in 2010.

Prof. 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 50,00 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 20 faculty, 80 graduate and 200 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: the Buckeye Bullet (holder of all current U.S. and FIA electric vehicle land speed records), the EcoCAR 2 and EcoCAR 3 hybrid-electric vehicle teams, 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 mechanical engineering. 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) build and develop a new mechanical engineering program. In 2000, that program was accredited by ABET. Three years later, Jim began to develop a new electrical and computer engineering program at YCP. The program's first group of students arrived in the fall of 2006. Jim was program coordinator until July 2010. Later, the program was formally accredited by ABET in 2012.

Throughout Dr.Kearns professional career he has been involved in teaching and research related to acoustics and electromechanical system. 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 in physical acoustics. While at the Universidad del Turabo, Dr. Kearns was responsible for developing and teaching electrical engineering–related content to mechanical engineering majors. When hired by York Collage, he was asked to develop the mechatronics stem of its new mechanical engineering program. Dr. Kearns' research interest continues today in his work on microbial fuel cells.

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, is the current chair of the Student Welfare committee, and is a member of the Academic Senate Executive committee.

Brief Contents

Contents

Preface

T 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 fifty 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 computers, smart phones, handheld digital audio players, digital cameras, 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. 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 must be able to communicate effectively within the interdisciplinary teams in which they work.

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 that relate these advances to engineering disciplines beyond electrical and computer engineering has only grown since the first edition of this book. This fact is evident in the ever-expanding application and integration of electronics and computer technologies in commercial products and process. This book represents one effort to make the principles of electrical and computer engineering accessible to students in other 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, ranging from sophomores in an introductory electrical engineering course to seniors and first-year graduate students enrolled in more specialized courses in electronics, electromechanics, and mechatronics.

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 sixth edition contains several significant organizational changes. However, the substance of the book, while updated, is essentially unchanged. The most obvious organizational change is the location of example problems within each chapter. In previous editions, examples were mixed in with the text so that students would encounter examples immediately after each key concept. While this type of organization works well for a first read, it has the disadvantage of making example problems difficult to locate for review. Since it is critical that students be able to easily and efficiently locate example problems when preparing for exams, in this edition of the book, with few exceptions, all example problems have been placed at the end of each section within a chapter.

A continued and enhanced emphasis on problem solving can be found in this edition. All the highlighted *Focus on Methodology* boxes found in the fifth edition were renamed *Focus on Problem Solving*, and many of them were rewritten 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. We believe that effective reading is promoted by less clutter and visual "noise," if you will. For example, a careful comparison of the fifth and sixth editions will reveal our effort to produce cleaner and sharper figures that retain only that information relevant to the issue or problem being discussed.

In addition, 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. Speaking of homework problems, the sixth edition contains roughly 300 new homework problems and, where necessary and appropriate, example problems were updated.

The book remains divided into four major parts:

I. **Circuits**
II. **Electronics**
III. **Communication Systems**
IV. **Electromechanics**

The pedagogical enhancements made within each part are discussed below.

0.3 PEDAGOGY AND CONTENT

Part I: Circuits

The first part of the book has undergone major revision from the fifth edition.

Chapter 2 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 simply ask students to count the number of nodes in a circuit diagram. One immediate advantage of this patient approach is that it teaches students to disregard the particular aesthetic structure shown in a circuit diagram and instead to recognize and focus on the technical structure and content.

The students' skill at recognizing circuit structure is further developed by the introduction of the *source-load perspective* in the last section of Chapter 2. That section revisits the concepts of voltage and current division from the source-load perspective and develops their graphical solution as the intersection of a source's load line with the load's v-i relation. While this section is not essential to subsequent chapters, it can be very helpful to students to, early on, adopt the source-load perspective and to be exposed to the concept of a load line 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 circuits, in general, and Thévenin's theorem, in particular. In the chapters on transient analysis and frequency response, foundational first- and second-order circuit *archetypes* are identified. Students are encouraged to simplify, when possible, transient circuit problems to these archetypes. In effect, they become clear targets for students when problem solving. Thévenin's and Norton's theorems and the principle of superposition are used throughout these chapters to simplify complicated circuits to the archetypes.

Finally, a greater emphasis was placed on visualizing phasors in the complex plane and understanding the key role of the unit phasor and Euler's theorem. Throughout the chapters on AC circuits and power students are encouraged to focus on the concepts of impedance and power triangles, and their similarity.

Part II: Electronics

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

Similar to the approach taken in Part I, Chapter 8 on operational amplifiers emphasizes three *amplifier archetypes* (the unity-gain buffer, the inverting amplifier, and the non-inverting amplifier) before introducing variations and applications.

The emphasis in Chapters 10 and 11 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 two chapters present an uncomplicated and practical treatment of the analysis and design of simple amplifiers and switching circuits using large-signal models.

Chapter 12, on power electronics, was updated in a few limited instances. On the other hand, Chapter 14 includes a significant update. The discussion of the antiquated MC68HC05 microcontroller was replaced by a new discussion of the **Atmel ATmega328P® microcontroller** and the **Arduino Uno R3** open-source prototyping platform.

Aside from error correction, Chapters 13 and 15 remain largely unchanged.

Part III: Communication Systems

Aside from the reorganization of content, the chapters on analog and digital communications remain largely unchanged. The focus on applications was retained. Chapter 17, courtesy of Dr. Michael Carr introduces the basic principles of digital communications systems. This chapter was clarified by incorporating a discussion of the IEEE 488 standard within the context of parallel communication and incorporating a discussion of the RS-232 standard within the context of serial communication. A new and expanded discussion of the Universal Serial Bus (USB) now immediately follows. The discussion of the Ethernet and CAN protocols are now set off as separate subsections so that they can be found more easily.

Part IV: Electromechanics

Part IV on electromechanics has been revised for accuracy and pedagogy, but its contents are largely unchanged. This part has been used by the first author for many years as a supplement in a junior-year System Dynamics course for mechanical engineers.

Instructors can find additional materials at the book's website PLACE URL HERE. Suggestions and sample curricula from users of the book are welcome!

0.4 FEATURES OF THE SIXTH EDITION

Pedagogy

The sixth 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.
- **Focus on Measurements** boxes emphasize the great relevance of electrical engineering to the science and practice of measurement.

Supplements

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Instructors have access to these files, which are housed in Connect.

- **PowerPoint presentation slides** of important figures from the text
- **Instructor's Solutions Manual** with complete solutions
- ***COSMOS*** (Complete Online Solutions Manual Organizing System)
- **MATLAB** solution files for selected problems

Instructors can provide these files, which are also housed in Connect, to students.

- **Algorithmic problems** that allow step-by-step problem-solving using a recursive computational procedure to create an infinite number of problems.

To access the Instructor Resources through Connect, you must first contact your McGraw-Hill Learning Technology Representative to obtain a password. If you do not know your McGraw-Hill representative, please go to www.mhhe.com/rep, to find your representative.

Once you have your password, please go to connect.mheducation.com, and log in. Click on the course for which you are using *Principles and Applications of Electrical Engineering, 6e*. If you have not added a course, click "Add Course," and select "Engineering" from the drop-down menu. Select this textbook and click "Next."

Once you have added the course, click on the "Library" link, and then click "Instructor Resources."

0.5 ACKNOWLEDGMENTS

The authors would like to recognize the help and assistance of reviewers, student's, and colleagues who have provided invaluable support. In particular, Dr. Ralph Tanner of Western Michigan University has painstakingly reviewed the book for accuracy and has provided rigorous feedback, and Ms. Jiyu Zhang, PhD student at Ohio State, has been generous in her assistance with the electromechanical systems portion of the chapter. The authors are especially grateful to Dr. Domenico Bianchi and Dr. Gian Luca Storti for creating many new homework problems and solutions and for their willingness to pitch in whenever needed. This sixth edition is much improved due to their efforts.

Throughout the preparation of this edition, Kathryn Rizzoni has provided editorial support and has served as an interface to the editorial staff at MHHE. We are grateful for her patience, her time invested in the project, her unwavering encouragement, her kind words, and her willingness to discuss gardening and honeybees.

The book has been critically reviewed by:

- Riadh Habash—The University of Ottawa
- Ahmad Nafisi—California Polytechnic State University
- Raveendra Rao—The University of Western Ontario
- Belinda Wang—The University of Toronto
- Brian Peterson—United States Air Force Academy
- John Durkin—University of Akron
- Chris Klein—Ohio State University
- Ting-Chung Poon—Virginia Tech
- James R. Rowland—University of Kansas
- N. Jill Schoof—Maine Maritime Academy
- Shiva Kumar—McMaster University
- Tom Sullivan—Carnegie Mellon University
- Dr. Kala Meah—York College of Pennsylvania

In addition, we would like to thank the many colleagues who have pointed out errors and inconsistencies and who have made other valuable suggestions.

Comments by Giorgio Rizzoni

As always, a new edition represents a new era. I am truly grateful to my friend and co-author, Jim Kearns, for taking on a new challenge and for bringing his perspective and experience to the book. Jim and I share a passion for teaching, and throughout this project we have invariably agreed on which course to take. It is not easy to find a suitable co-author in the life of a project of this magnitude, and I have been fortunate to find a friend willing to undertake a new journey with me.

When the first edition of the book was nearing, so was the birth of our first child, Alessandro (Alex). The second and third editions were marked by the births of Maria Caterina (Cat), and Michael. Time passes, and now Alex and Cat are away at college, and Michael is in high school. The years go by, but my family continues to be an endless source of joy, pleasant surprises and, always, smiles. Many thanks to Kathryn, Alex, Cat, and Michael for always being there to support and encourage me.

Comments by James Kearns

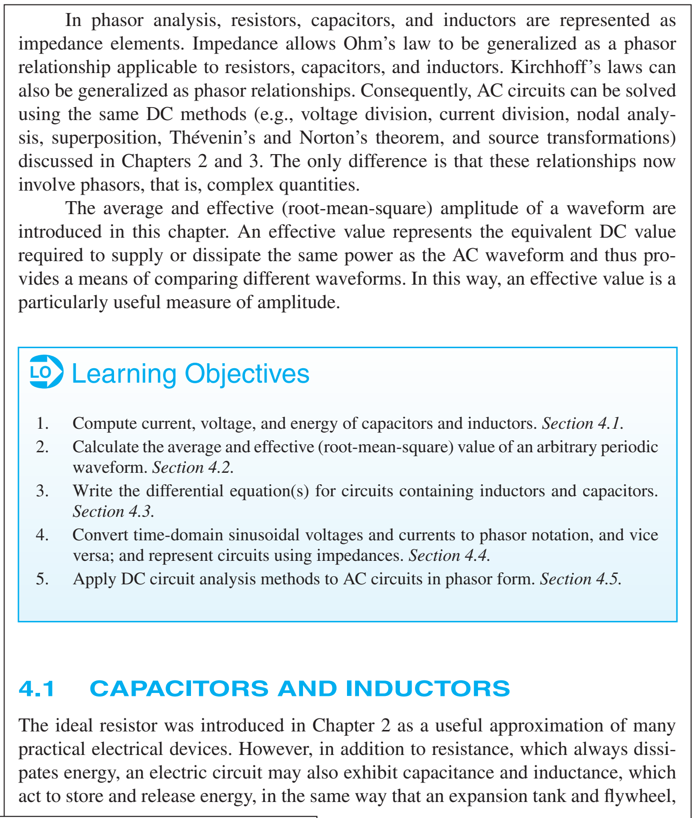
First, I am grateful to Giorgio Rizzoni for inviting and trusting me to be part of this project. I don't know that I deserved his trust, but I hope my work on this new edition has lived up to the high standards established by the previous editions. Being asked to come on board as a co-author was a dream come true for me, and a great privilege to be associated with this remarkable book. Giorgio is an exceptional engineer, inspiring educator, and one energetic human being! Working with Giorgio was a pleasure, particularly as I discovered our many shared perspectives on engineering education. He was, from start to finish, a gentleman and friend.

Over the past few years of working on the sixth edition I have witnessed my son, Kevin, develop into a truly fine young man and my daughters, Claire and Caroline, blossom into beautiful and intelligent young girls. I hope they will forgive me for the many hours I spent working on this book. Perhaps, one day they will find some inspiration from this book, knowing that their father was thinking of them throughout its development.

I could not have completed this work without the knowledge that my children were safe, secure, and healthy because of the care of Cindy and Perri.

Finally, I would be remiss not to thank my parents for their many years of love and support. Can anyone ever begin to measure the value of loving parents? I remain humbled and awestruck by all they have done for me throughout my life.

Guided Tour



In phasor analysis, resistors, capacitors, and inductors are represented as impedance elements. Impedance allows Ohm's law to be generalized as a phasor relationship applicable to resistors, capacitors, and inductors. Kirchhoff's laws can also be generalized as phasor relationships. Consequently, AC circuits can be solved using the same DC methods (e.g., voltage division, current division, nodal analysis, superposition, Thévenin's and Norton's theorem, and source transformations) discussed in Chapters 2 and 3. The only difference is that these relationships now involve phasors, that is, complex quantities.

The average and effective (root-mean-square) amplitude of a waveform are introduced in this chapter. An effective value represents the equivalent DC value required to supply or dissipate the same power as the AC waveform and thus provides a means of comparing different waveforms. In this way, an effective value is a particularly useful measure of amplitude.

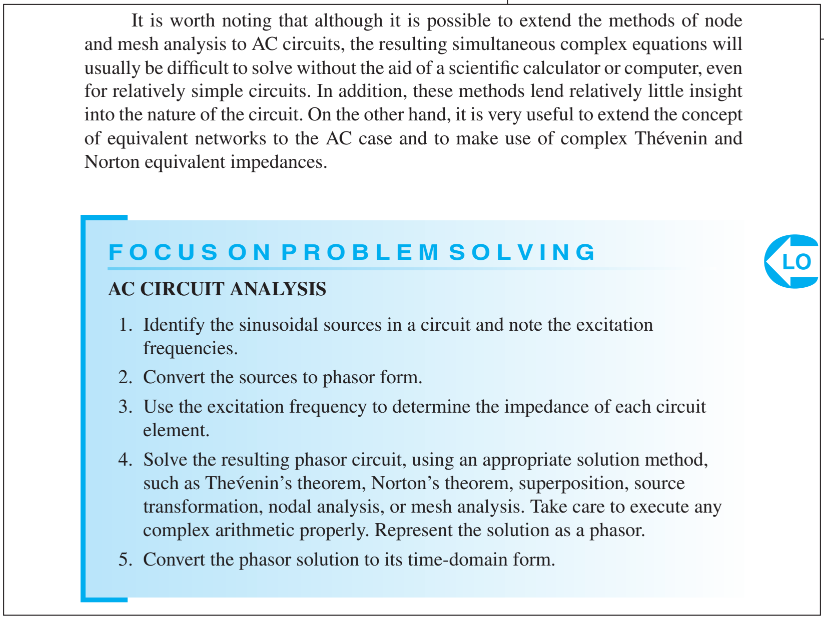
LO Learning Objectives

1. Compute current, voltage, and energy of capacitors and inductors. *Section 4.1.*
2. Calculate the average and effective (root-mean-square) value of an arbitrary periodic waveform. *Section 4.2.*
3. Write the differential equation(s) for circuits containing inductors and capacitors. *Section 4.3.*
4. Convert time-domain sinusoidal voltages and currents to phasor notation, and vice versa; and represent circuits using impedances. *Section 4.4.*
5. Apply DC circuit analysis methods to AC circuits in phasor form. *Section 4.5.*

4.1 CAPACITORS AND INDUCTORS

The ideal resistor was introduced in Chapter 2 as a useful approximation of many practical electrical devices. However, in addition to resistance, which always dissipates energy, an electric circuit may also exhibit capacitance and inductance, which act to store and release energy, in the same way that an expansion tank and flywheel,

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.



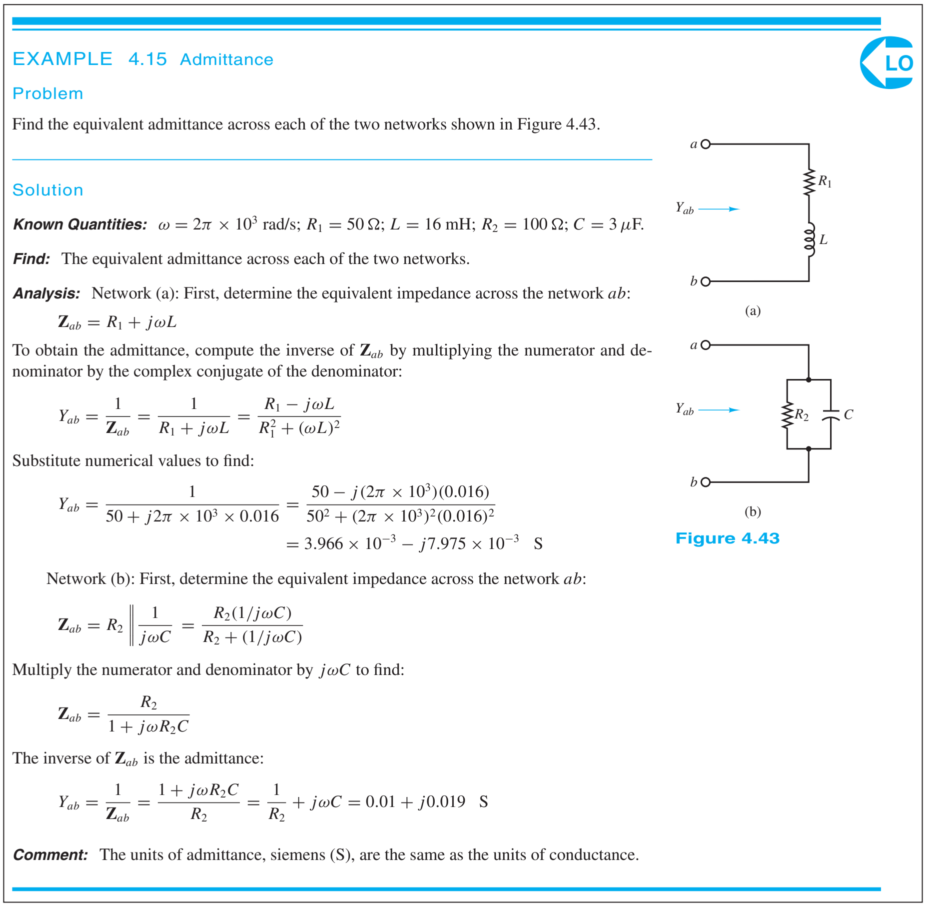
It is worth noting that although it is possible to extend the methods of node and mesh analysis to AC circuits, the resulting simultaneous complex equations will usually be difficult to solve without the aid of a scientific calculator or computer, even for relatively simple circuits. In addition, these methods lend relatively little insight into the nature of the circuit. On the other hand, it is very useful to extend the concept of equivalent networks to the AC case and to make use of complex Thévenin and Norton equivalent impedances.

FOCUS ON PROBLEM SOLVING

AC CIRCUIT ANALYSIS

1. Identify the sinusoidal sources in a circuit and note the excitation frequencies.
2. Convert the sources to phasor form.
3. Use the excitation frequency to determine the impedance of each circuit element.
4. Solve the resulting phasor circuit, using an appropriate solution method, such as Thévenin's theorem, Norton's theorem, superposition, source transformation, nodal analysis, or mesh analysis. Take care to execute any complex arithmetic properly. Represent the solution as a phasor.
5. Convert the phasor solution to its time-domain form.

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.



EXAMPLE 4.15 Admittance

Problem

Find the equivalent admittance across each of the two networks shown in Figure 4.43.

Solution

Known Quantities: $\omega = 2\pi \times 10^3$ rad/s; $R_1 = 50\ \Omega$; $L = 16$ mH; $R_2 = 100\ \Omega$; $C = 3\ \mu$F.

Find: The equivalent admittance across each of the two networks.

Analysis: Network (a): First, determine the equivalent impedance across the network ab:

$$\mathbf{Z}_{ab} = R_1 + j\omega L$$

To obtain the admittance, compute the inverse of $\mathbf{Z}_{ab}$ by multiplying the numerator and denominator by the complex conjugate of the denominator:

$$Y_{ab} = \frac{1}{\mathbf{Z}_{ab}} = \frac{1}{R_1 + j\omega L} = \frac{R_1 - j\omega L}{R_1^2 + (\omega L)^2}$$

Substitute numerical values to find:

$$Y_{ab} = \frac{1}{50 + j2\pi \times 10^3 \times 0.016} = \frac{50 - j(2\pi \times 10^3)(0.016)}{50^2 + (2\pi \times 10^3)^2(0.016)^2}$$
$$= 3.966 \times 10^{-3} - j7.975 \times 10^{-3} \quad \text{S}$$

Network (b): First, determine the equivalent impedance across the network ab:

$$\mathbf{Z}_{ab} = R_2 \left\| \frac{1}{j\omega C} \right. = \frac{R_2(1/j\omega C)}{R_2 + (1/j\omega C)}$$

Multiply the numerator and denominator by $j\omega C$ to find:

$$\mathbf{Z}_{ab} = \frac{R_2}{1 + j\omega R_2 C}$$

The inverse of $\mathbf{Z}_{ab}$ is the admittance:

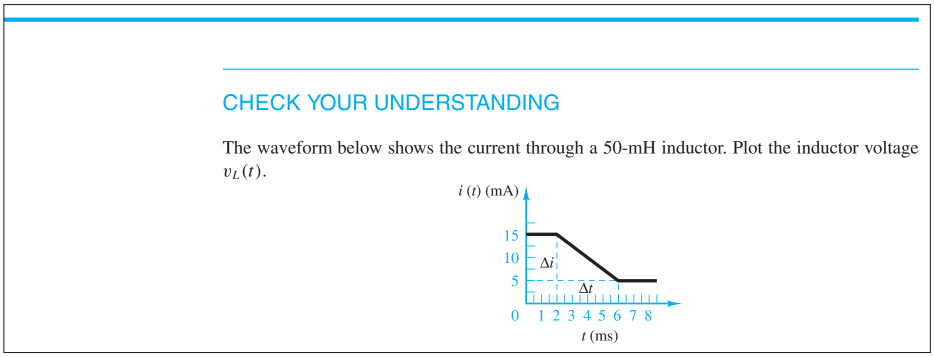
$$Y_{ab} = \frac{1}{\mathbf{Z}_{ab}} = \frac{1 + j\omega R_2 C}{R_2} = \frac{1}{R_2} + j\omega C = 0.01 + j0.019 \quad \text{S}$$

Comment: The units of admittance, siemens (S), are the same as the units of conductance.

Figure 4.43

Clearly illustrated examples present 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.

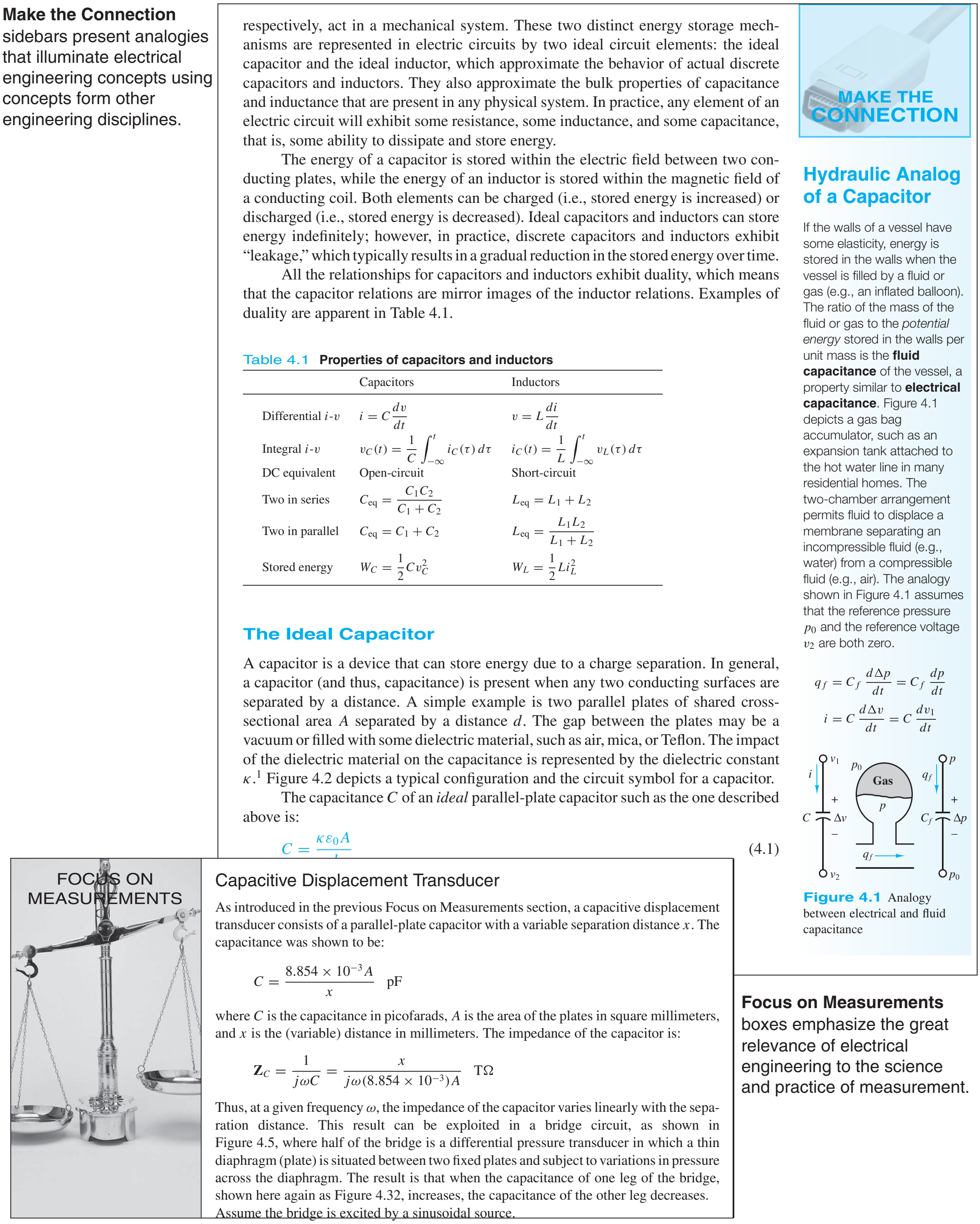
Check Your Understanding exercises follow each set of examples and allow students to confirm their mastery of concepts.



CHECK YOUR UNDERSTANDING

The waveform below shows the current through a 50-mH inductor. Plot the inductor voltage $v_L(t)$.

Make the Connection sidebars present analogies that illuminate electrical engineering concepts using concepts form other engineering disciplines.



respectively, act in a mechanical system. These two distinct energy storage mechanisms are represented in electric circuits by two ideal circuit elements: the ideal capacitor and the ideal inductor, which approximate the behavior of actual discrete capacitors and inductors. They also approximate the bulk properties of capacitance and inductance that are present in any physical system. In practice, any element of an electric circuit will exhibit some resistance, some inductance, and some capacitance, that is, some ability to dissipate and store energy.

The energy of a capacitor is stored within the electric field between two conducting plates, while the energy of an inductor is stored within the magnetic field of a conducting coil. Both elements can be charged (i.e., stored energy is increased) or discharged (i.e., stored energy is decreased). Ideal capacitors and inductors can store energy indefinitely; however, in practice, discrete capacitors and inductors exhibit "leakage," which typically results in a gradual reduction in the stored energy over time.

All the relationships for capacitors and inductors exhibit duality, which means that the capacitor relations are mirror images of the inductor relations. Examples of duality are apparent in Table 4.1.

Table 4.1 **Properties of capacitors and inductors**

	Capacitors	Inductors
Differential i-v	$i = C\frac{dv}{dt}$	$v = L\frac{di}{dt}$
Integral i-v	$v_C(t) = \frac{1}{C}\int_{-\infty}^{t} i_C(\tau)\,d\tau$	$i_C(t) = \frac{1}{L}\int_{-\infty}^{t} v_L(\tau)\,d\tau$
DC equivalent	Open-circuit	Short-circuit
Two in series	$C_{eq} = \frac{C_1 C_2}{C_1 + C_2}$	$L_{eq} = L_1 + L_2$
Two in parallel	$C_{eq} = C_1 + C_2$	$L_{eq} = \frac{L_1 L_2}{L_1 + L_2}$
Stored energy	$W_C = \frac{1}{2}Cv_C^2$	$W_L = \frac{1}{2}Li_L^2$

The Ideal Capacitor

A capacitor is a device that can store energy due to a charge separation. In general, a capacitor (and thus, capacitance) is present when any two conducting surfaces are separated by a distance. A simple example is two parallel plates of shared cross-sectional area A separated by a distance d. The gap between the plates may be a vacuum or filled with some dielectric material, such as air, mica, or Teflon. The impact of the dielectric material on the capacitance is represented by the dielectric constant κ.[1] Figure 4.2 depicts a typical configuration and the circuit symbol for a capacitor.

The capacitance C of an *ideal* parallel-plate capacitor such as the one described above is:

$$C = \frac{\kappa \varepsilon_0 A}{} \qquad (4.1)$$

MAKE THE CONNECTION

Hydraulic Analog of a Capacitor

If the walls of a vessel have some elasticity, energy is stored in the walls when the vessel is filled by a fluid or gas (e.g., an inflated balloon). The ratio of the mass of the fluid or gas to the *potential energy* stored in the walls per unit mass is the **fluid capacitance** of the vessel, a property similar to **electrical capacitance**. Figure 4.1 depicts a gas bag accumulator, such as an expansion tank attached to the hot water line in many residential homes. The two-chamber arrangement permits fluid to displace a membrane separating an incompressible fluid (e.g., water) from a compressible fluid (e.g., air). The analogy shown in Figure 4.1 assumes that the reference pressure p_0 and the reference voltage v_2 are both zero.

$$q_f = C_f \frac{d\Delta p}{dt} = C_f \frac{dp}{dt}$$

$$i = C\frac{d\Delta v}{dt} = C\frac{dv_1}{dt}$$

Figure 4.1 Analogy between electrical and fluid capacitance

FOCUS ON MEASUREMENTS

Capacitive Displacement Transducer

As introduced in the previous Focus on Measurements section, a capacitive displacement transducer consists of a parallel-plate capacitor with a variable separation distance x. The capacitance was shown to be:

$$C = \frac{8.854 \times 10^{-3} A}{x} \quad \text{pF}$$

where C is the capacitance in picofarads, A is the area of the plates in square millimeters, and x is the (variable) distance in millimeters. The impedance of the capacitor is:

$$\mathbf{Z}_C = \frac{1}{j\omega C} = \frac{x}{j\omega(8.854 \times 10^{-3})A} \quad \text{T}\Omega$$

Thus, at a given frequency ω, the impedance of the capacitor varies linearly with the separation distance. This result can be exploited in a bridge circuit, as shown in Figure 4.5, where half of the bridge is a differential pressure transducer in which a thin diaphragm (plate) is situated between two fixed plates and subject to variations in pressure across the diaphragm. The result is that when the capacitance of one leg of the bridge, shown here again as Figure 4.32, increases, the capacitance of the other leg decreases. Assume the bridge is excited by a sinusoidal source.

Focus on Measurements boxes emphasize the great relevance of electrical engineering to the science and practice of measurement.

CHAPTER 1

INTRODUCTION TO ELECTRICAL ENGINEERING

The aim of this chapter is to introduce electrical engineering. The chapter is organized to provide the newcomer with a view of the different specialties making up electrical engineering and to place the intent and organization of the book into perspective. Perhaps the first question that surfaces in the mind of the student approaching the subject is, Why electrical engineering? Since this book is directed at a readership having a mix of engineering backgrounds (including electrical engineering), the question is well justified and deserves some discussion. The chapter begins by defining the various branches of electrical engineering, showing some of the interactions among them, and illustrating by means of a practical example how electrical engineering is intimately connected to many other engineering disciplines. In Section 1.2 *mechatronic systems engineering* is introduced, with an explanation of how this book can lay the foundation for interdisciplinary mechatronic product design. This design approach is illustrated by two examples. A brief historical perspective is also provided, to outline the growth and development of this relatively young engineering specialty. Section 1.3 presents a brief review of the history of electrical engineering. In Section 1.4 the fundamental physical quantities, the system of units, and mathematical notation are defined, to set the stage for the chapters that follow.

Finally, in Section 1.5 the organization of the book is discussed, to give the student, as well as the teacher, a sense of continuity in the development of the different subjects covered in Chapters 2 to 20.

1.1 ELECTRICAL ENGINEERING

The typical curriculum of an undergraduate electrical engineering student includes the subjects listed in Table 1.1. Although the distinction between some of these subjects is not always clear-cut, the table is sufficiently representative to serve our purposes. Figure 1.1 illustrates a possible interconnection between the disciplines of Table 1.1. The aim of this book is to introduce engineering students to those aspects of electrical engineering that are likely to be most relevant to his or her professional career. Virtually all the topics of Table 1.1 will be touched on in the book, with varying degrees of emphasis. Example 1.1 illustrates the pervasive presence of electrical, electronic, and electromechanical devices and systems in a very common application: the automobile. As you read through the examples, it will be instructive to refer to Figure 1.1 and Table 1.1.

Table 1.1 **Electrical engineering disciplines**

Circuit analysis
Electromagnetics
Solid-state electronics
Electric machines
Electric power systems
Digital logic circuits
Computer systems
Communication systems
Electro-optics
Instrumentation systems
Control systems

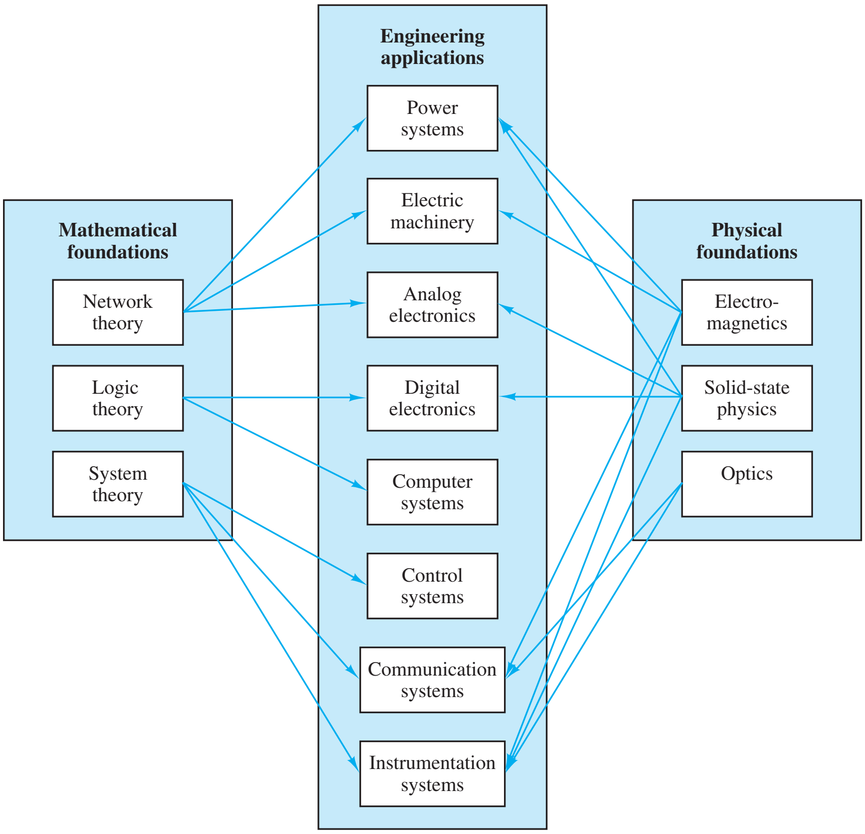


Figure 1.1 Electrical engineering disciplines

EXAMPLE 1.1 Electrical Systems in a Passenger Automobile

A familiar example illustrates how the seemingly disparate specialties of electrical engineering actually interact to permit the operation of a very familiar engineering system: the automobile. Figure 1.2 presents a view of electrical engineering systems in a modern automobile. Even in older vehicles, the electrical system—in effect, an *electric circuit*—plays a very important part in the overall operation (Chapters 2 and 3 describe the basics of electric circuits). An inductor coil generates a sufficiently high voltage to allow a spark to form across the spark plug gap and to ignite the air-fuel mixture; the coil is supplied by a DC voltage provided by a lead-acid battery. Ignition circuits are studied in some detail in Chapter 5. In addition to providing the energy for the ignition circuits, the battery supplies power to many other electrical components, the most obvious of which are the lights, the windshield wipers, and the radio. Electric power (Chapter 7) is carried from the battery to all these components by means of a wire harness, which constitutes a rather elaborate electric circuit (see Figure 2.15 for a closer look). Electronic fuel injection and ignition systems make use of sophisticated electronic circuits. You will study transistors and other electronic devices in Chapters 8 to 10.

Other electrical engineering disciplines are fairly obvious in the automobile. The on-board radio receives electromagnetic waves by means of the antenna, and decodes the communication signals to reproduce sounds and speech of remote origin; other common *communication systems* that exploit *electromagnetics* are satellite radios and cellular phones. Chapters 16 and 17 describe some of the technology that is behind AM and FM radio and other common communication systems. But this is not all! The battery is, in effect, a self-contained 12-VDC *electric power system,* providing the energy for all functions. In order for the battery to have a useful lifetime, a charging system, composed of an alternator and of power electronic devices, is present in every automobile. Electric power systems are covered in Chapter 7 and power electronic devices in Chapter 10. The alternator is an *electric machine*, as are the motors that drive the power mirrors, power windows, power seats, and other convenience features found in most cars. Incidentally, the loudspeakers are also electric machines! All these devices are described in Chapters 18 to 20, and are also pertinent to the technology underlying hybrid and electric vehicles, covered in more detail in Examples 1.2 and 1.3.

The list does not end here, though. In fact, some of the more interesting applications of electrical engineering to the automobile have not been discussed yet. Consider *computer*

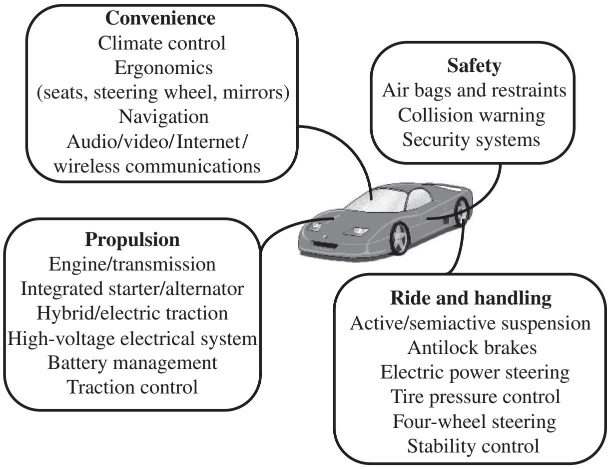


Figure 1.2 Electrical engineering systems in the automobile

systems. You are certainly aware that environmental concerns related to exhaust emissions from automobiles have led to the introduction of sophisticated engine emission *control systems.* The heart of such control systems is a type of computer called a *microprocessor.* The microprocessor receives signals from devices (called *sensors*) that measure relevant variables—such as the engine speed, the concentration of oxygen in the exhaust gases, the position of the throttle valve (i.e., the driver's demand for engine power), and the amount of air aspirated by the engine—and subsequently computes the optimal amount of fuel and the correct timing of the spark to result in the cleanest combustion possible under the circumstances. We present a brief overview of computer systems in Chapter 14. The measurement of the aforementioned variables falls under the heading of *instrumentation*, and the interconnection between the sensors and the microprocessor is usually made up of *digital circuits.* Chapter 15 is devoted to the subject of measurements and instrumentation, although you will find a feature titled "Focus on Measurements" in most chapters. Digital circuits are covered in Chapters 13 and 14. As the presence of computers on board becomes more pervasive—in areas such as antilock braking, electronically controlled suspensions, four-wheel steering systems, and electronic cruise control—communications among the various on-board computers will have to occur at faster and faster rates. Someday in the not-so-distant future, these communications may occur over a fiber-optic network, and *electro-optics* will replace the conventional wire harness. Note that electro-optics is already present in some of the more advanced displays that are part of an automotive instrumentation system.

Finally, today's vehicles also benefit from the significant advances made in *communication systems*. Vehicle navigation systems can include *Global Positioning System*, or GPS, technology, as well as a variety of communications and networking technologies, such as wireless interfaces (e.g., based on the "Bluetooth" standard) and satellite radio and driver assistance systems, such as the GM "OnStar" system.

1.2 ELECTRICAL ENGINEERING AS A FOUNDATION FOR THE DESIGN OF MECHATRONIC SYSTEMS

Many of today's machines and processes, ranging from chemical plants to automobiles, require some form of electronic or computer control for proper operation. Computer control of machines and processes is common to the automotive, chemical, aerospace, manufacturing, test and instrumentation, consumer, and industrial electronics industries. The extensive use of microelectronics in manufacturing systems and in engineering products and processes has led to a new approach to the design of such engineering systems. To use a term coined in Japan and widely adopted in Europe, *mechatronic design* has surfaced as a new philosophy of design, based on the integration of existing disciplines—primarily mechanical, and electrical, electronic, and software engineering.[1]

A very important issue, often neglected in a strictly disciplinary approach to engineering education, is the integrated aspect of engineering practice, which is unavoidable in the design and analysis of large-scale and/or complex systems. One aim of this book is to give engineering students of different backgrounds exposure to the integration of electrical, electronic, and software engineering into their domain. This is accomplished by making use of modern computer-aided tools and by providing relevant examples and references. Section 1.6 describes how some of these goals are accomplished.

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[1] *The Mechatronics Handbook*, 2d ed., CRC Press, Robert H. Bishop, ed., 2007.

Examples 1.2 and 1.3 illustrate some of the thinking behind the mechatronic system design philosophy through two examples: the recently introduced C-MAX family of hybrid-electric vehicles and a land speed record electric vehicle.

EXAMPLE 1.2 Mechatronic Systems—The Ford C-MAX Hybrid

An example of a mechatronic system that is becoming increasingly familiar is found in hybrid-electric vehicles (HEVs). A hybrid powertrain contains at least two power sources, typically an internal combustion engine (ICE) as the primary source of power, and a secondary power source, such as an electric motor. HEVs save fuel by exploring the additional flexibilities available in the design and operation of the hybrid powertrain, including load leveling, regenerative braking, engine shut-down, engine down-sizing, and controlling the mechanical or electromechanical transmission.

This example focuses on the Ford C-MAX family of hybrid vehicles, recently introduced in the North-American market and shown in Figure 1.3. The C-MAX is available as an HEV, the C-MAX *Hybrid*, and also as a plug-in HEV (PHEV), the C-MAX *Energi*. Both models incorporate a number of features that increase the vehicle fuel economy while maintaining the comfort, performance, and utility that customers have come to expect from vehicles of this class.

The Ford C-MAX HEV delivers 188 hp (140 kW) of total system power, using a 2.0-L DOHC inline 4-cylinder Atkinson cycle engine, capable of 141 hp (105 kW) coupled to a electromechanical continuously variable transaxle that uses two AC permanent-magnet synchronous machines[2] capable of delivering up to 118 hp (88 kW) of instantaneous power. The HEV version uses a 1.4 kWh lithium-ion battery pack, while the PHEV employs a 7.6 kWh lithium-ion battery pack that provides an all-electric range of 21 mi (33.8 km). In both versions, peak battery power is 35 kW.

Figure 1.3 Ford C-MAX Hybrid (*Courtesy of Ford Motor Company*)

The 4-cylinder gasoline engine, operated according to the Atkinson cycle, an asymmetrical four-stroke cycle with an expansion ratio greater than the compression ratio, is more fuel efficient than the traditional Otto cycle in use in the majority of gasoline-fueled vehicles today. The combination of a more efficient (but slightly less performing) Atkinson cycle engine with the two electric machines incorporated in the power-split transaxle (shown in Figure 1.4) is capable of torque and acceleration comparable to those of a V-6 engine, while providing the customer with a fuel economy of 47 mpg (5 l/100 km) in both city and highway for the HEV version. The fuel economy of the C-MAX Energi PHEV is difficult to define precisely because of its electric range, but it can significantly exceed that of the C-MAX Hybrid.

The transaxle, shown in a cut-away view in Figure 1.5, consists of two electric machines, both permanent-magnet synchronous AC machines. The two machines are mechanically

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[2] AC electric machines are presented in Chapters 19 and 20.

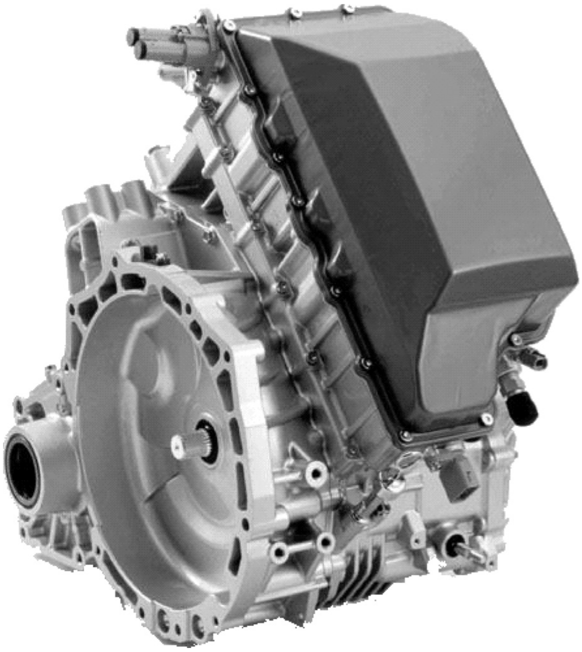


Figure 1.4 HEV transaxle (*Courtesy of Ford Motor Company*)

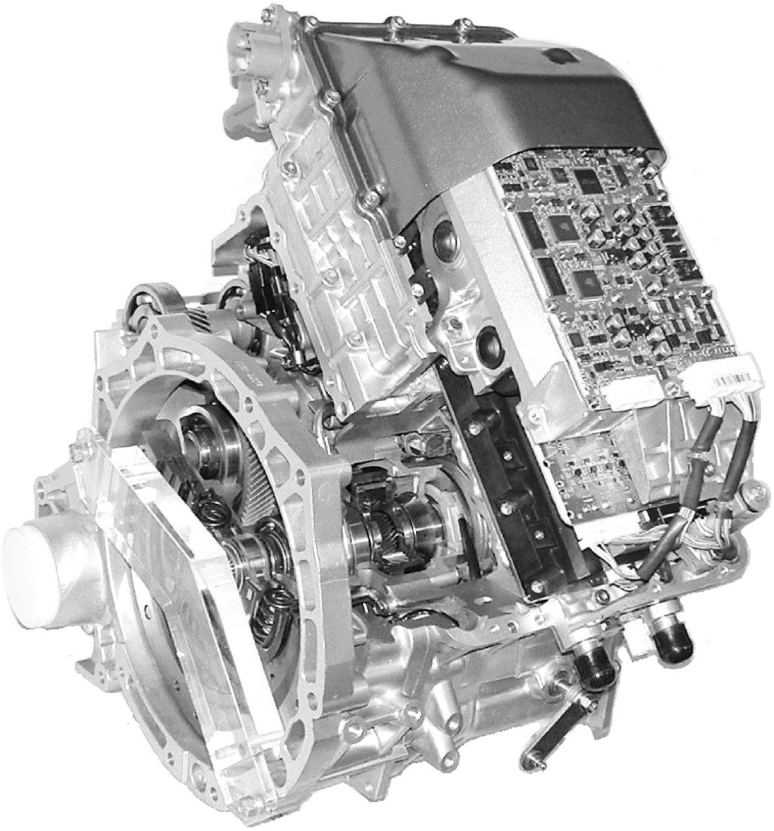
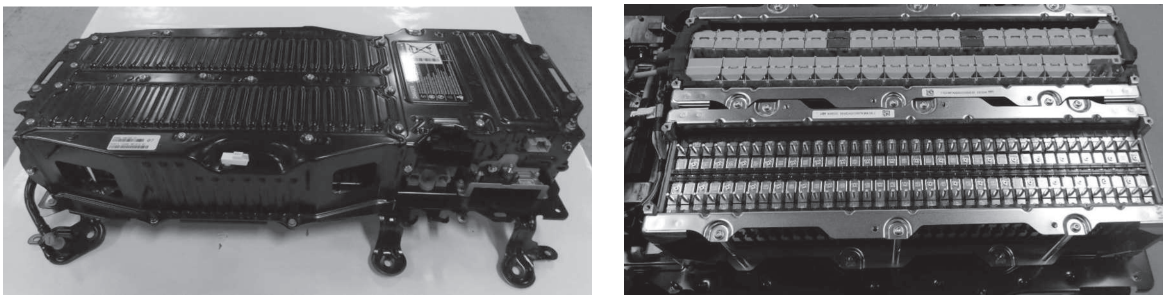
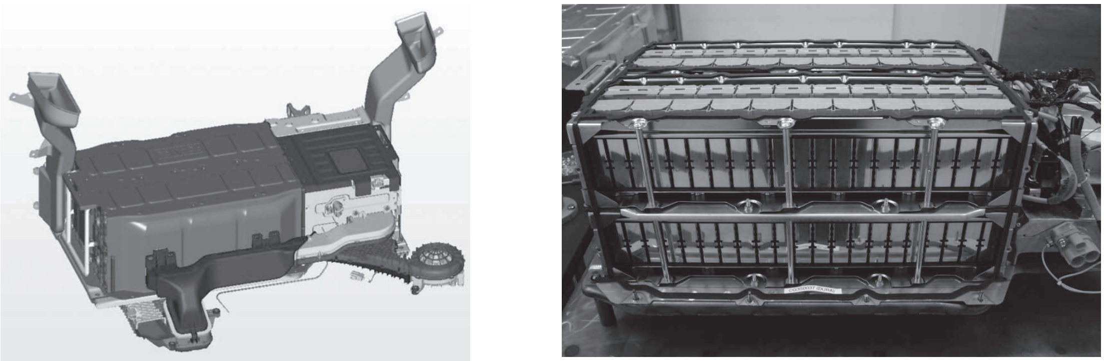


Figure 1.5 Details of the HEV transaxle (*Courtesy of Ford Motor Company*)

connected through a planetary gearset, similar to the gearset used in conventional automatic transmissions. The transaxle also incorporates a power converter,[3] or inverter, that converts the DC power supplied by the battery pack [Figures 1.6(a) and (b)] to the variable frequency AC power[4] required to operate the AC electric machines. In addition to the power converter, the electronics incorporated into the transaxle include a control module, which includes various analog and digital electronic circuits,[5] including a microcontroller that receives information from various sensors to determine the best speed and power of operation of the engine and of each of the two electric machines in the transaxle.



(a) C-MAX hybrid battery pack (b) Internal configuration of C-MAX hybrid battery pack



(c) C-MAX Energi battery pack (d) Internal configuration of C-MAX Energi battery pack

Figure 1.6 Battery pack (*Courtesy of Ford Motor Company*)

In addition to the energy provided by the fuel stored in a conventional tank, an HEV also stores a limited amount of energy in a battery pack. Figure 1.6(a) depicts the C-MAX HEV battery pack; note that the battery pack has been purposely designed to have a flat profile so as not to reduce the useful cargo space. Figure 1.6(b) shows the internal configuration of the battery. The PHEV version of the pack, which stores more than five times the energy of the HEV version, is depicted in Figure 1.6(c) and (d).

Finally, Figure 1.7 depicts the general system operation of the hybrid powertrain, showing how the engine and the generator motor are connected to two of the planetary gearset inputs, while the traction motor is connected to the output of the gearset, and therefore to the front axle. This picture illustrates the various possible modes of operation of the vehicle, showing that the vehicle can be powered by the engine alone through the mechanical transmission, or by

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[3] Power electronics is the subject of Chapter 12.

[4] AC power is the subject of Chapter 7.

[5] Analog and digital electronics are covered in Chapters 8 to 15.

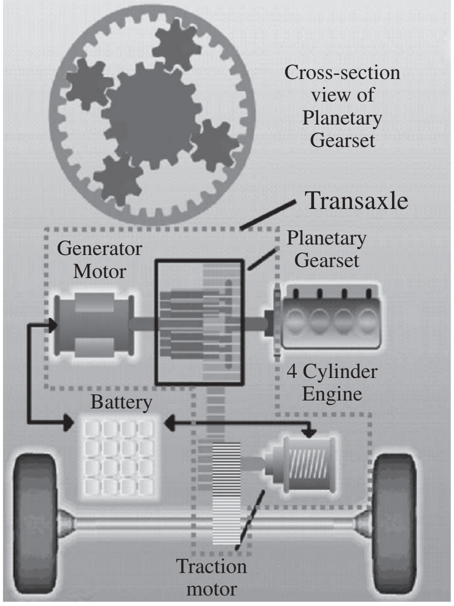

Figure 1.7 Ford HEV architecture (*Courtesy of Ford Motor Company*)

the traction motor alone, or by various combinations of the engine and two electric machines. Further, when the vehicle is decelerating, the mechanical energy stored in the vehicle motion can be in part converted into electrical energy by the generator motor and stored in the battery pack for later use. Another interesting feature of both models is that the traction motor is capable of launching the vehicle from zero speed without the need for any engine power. Thus, the engine can be safely shut off whenever the vehicle stops at a traffic light or in traffic, with significant fuel savings resulting from the complete elimination of engine idle.

EXAMPLE 1.3 Mechatronic Systems—The Buckeye Bullet Electric Land Speed Record Vehicle

Land Speed Record Racing

In the early years of modern automobile engineering, it was electric traction that provided most of the excitement (a surprise, perhaps, to modern internal combustion engine racing enthusiasts). The *Jamais Contente*, shown in Figure 1.8, was the first vehicle to exceed the 100 km/hr mark in 1899—a record that lasted several years, until the internal combustion engine became the dominant propulsion system. For more than a century, combustion engine powered vehicles have dominated motorsports. In recent years, however, interest in electric land speed record racing has once again increased, as both power electronics, electric motor, and battery technology have seen significant advances, motivated by the emergence of a market for electric and especially hybrid-electric vehicles. Modern land speed record (LSR) racing consists of vehicles traveling on a designated track to obtain the fastest speed for that specific vehicle's class. Since the early 1950s, amateurs and professionals have raced toward land speed records in myriad categories on the Bonneville Salt Flats, an ancient lake bed spread across 30,000 acres in Utah, 90 miles west of Salt Lake City. The Bonneville Salt Flats surface

Figure 1.8 “La Jamais Contente” (Never Satisfied) electric racer, the first vehicle to surpass the 100 km/hr mark (105.880 km/hr), driven by Camillo Jenatzy at Achères, France, on April 29, 1899 (© *Hulton Archive/Getty Images*).

consists of packed salt, making it an ideal place to stage a speed race due to the perfectly flat surface and to the high-altitude location with lower air density. The Southern California Timing Association (SCTA) governs LSR racing at Bonneville and sanctions U.S. records. In addition to this, the SCTA establishes the standard for the race and the car depending on vehicle class. World records are established by the Fédération Internationale de l’Automobile (FIA), and if FIA officials are present and FIA rules are followed, world records can also be established at Bonneville.

According to SCTA specifications, electric vehicles (E class) have no body configuration restriction but there are three different classes based on the vehicle’s weight, less that of the driver. The vehicle described in this example, the Venturi Buckeye Bullet, shown in Figure 1.9, belongs to class E.III, the unlimited weight electric class. The race course configuration used for U.S. land speed records, shown in Figure 1.10(a), consists of three different parts: the first two miles are used for the acceleration of the vehicle, while the average speed is recorded over the third, fourth, and fifth miles. After the fifth mile, the vehicle has two miles to decelerate using one or more drag parachutes. For a U.S. record to be homologated, the two runs must occur within a four-hour “impound” period. If an international record is attempted, the vehicle has only one hour to complete both runs, and a typical course has the appearance shown in Figure 1.10(b).

Design of an Electric Streamliner

Vehicle Design

The Buckeye Bullet design layout is shown in Figure 1.11. This particular design is that of the Venturi Buckeye Bullet 3, which is being tested at the time of this writing. The type of vehicle shown in the drawing is called a *streamliner*, a term that indicates a vehicle with enclosed wheels and a long, aerodynamic shape. The solid model of Figure 1.11 shows the all-wheel-drive configuration, in which two electric machines power each axle through a fixed mechanical transmission. The driver is located in the middle of the vehicle, and two battery