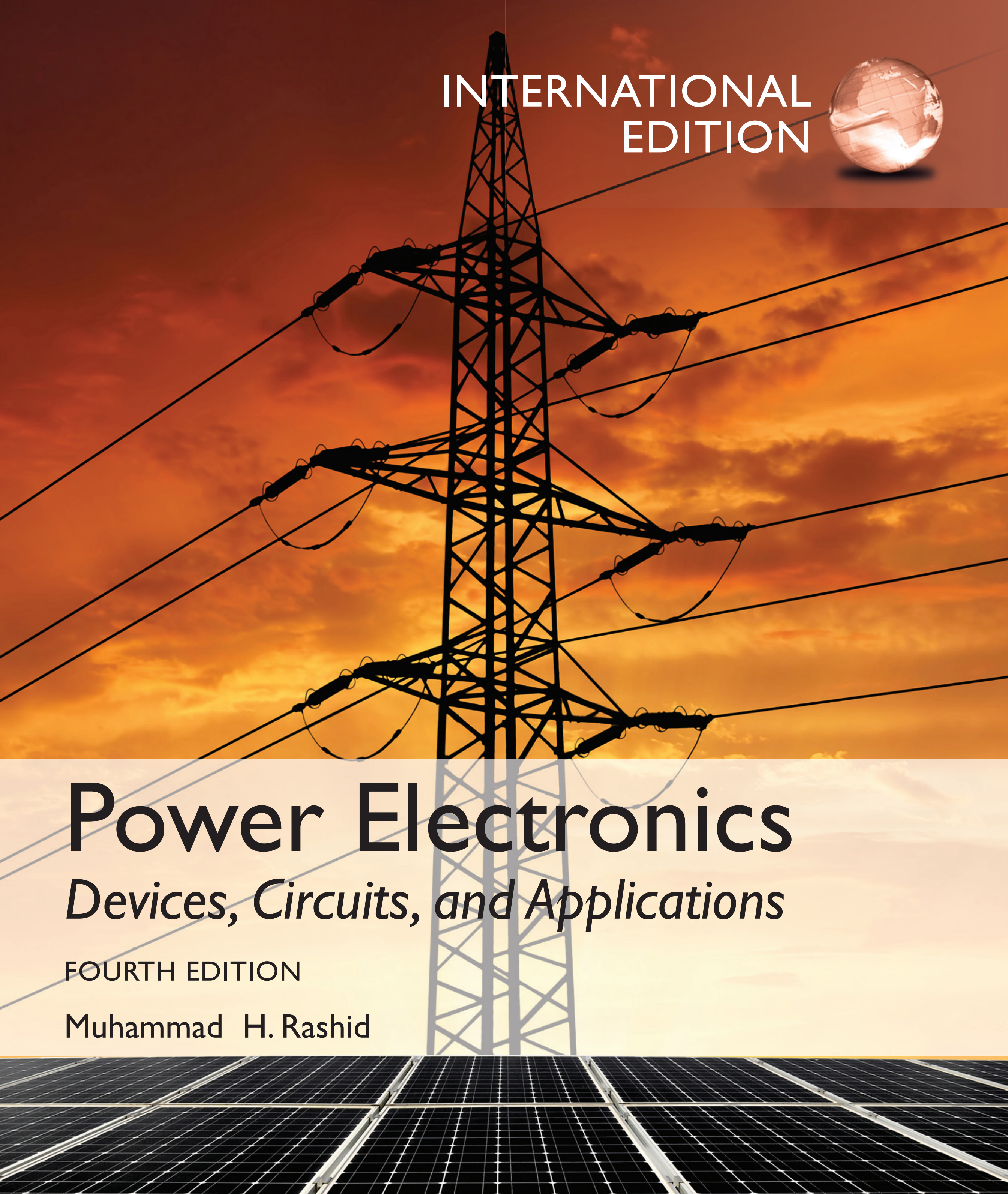

INTERNATIONAL EDITION

Power Electronics

Devices, Circuits, and Applications

FOURTH EDITION

Muhammad H. Rashid

ALWAYS LEARNING

PEARSON

POWER ELECTRONICS

DEVICES, CIRCUITS, AND APPLICATIONS

Fourth Edition

Muhammad H. Rashid,
Fellow IET,
Life Fellow IEEE

Electrical and Computer Engineering
University of West Florida

International Edition contributions by

Narendra Kumar
Department of Electrical Engineering
Delhi Technological University

Ashish R. Kulkarni
Department of Electrical Engineering
Delhi Technological University

PEARSON

Boston Columbus Indianapolis New York San Francisco Upper Saddle River
Amsterdam Cape Town Dubai London Madrid Milan Munich Paris Montréal Toronto
Delhi Mexico City São Paulo Sydney Hong Kong Seoul Singapore Taipei Tokyo

Vice President and Editorial Director, ECS: *Marcia J. Horton*
Executive Editor: *Andrew Gilfillan*
Associate Editor: *Alice Dworkin*
Editorial Assistant: *William Opaluch*
Marketing Manager: *Tim Galligan*
Publishing Operations Director, International Edition: *Angshuman Chakraborty*
Manager, Publishing Operations, International Edition: *Shokhi Shah Khandelwal*
Associate Print and Media Editor, International Edition: *Anuprova Dey Chowdhuri*
Acquisitions Editor, International Edition: *Sandhya Ghoshal*
Publishing Administrator, International Edition: *Hema Mehta*
Project Editor, International Edition: *Karthik Subramanian*
Senior Manufacturing Controller, Production, International Edition: *Trudy Kimber*
Art Director: *Jayne Conte*
Cover Designer: *Jodi Notowitz*
Full-Service Project Management/Composition: *Integra*
Cover Image: *Vaclav Volrab/Shutterstock*
Cover Printer: *Courier*

Pearson Education Limited
Edinburgh Gate
Harlow
Essex CM20 2JE
England

and Associated Companies throughout the world

Visit us on the World Wide Web at:
www.pearsoninternationaleditions.com

Authorized adaptation from the United States edition, entitled Power Electronics: Devices, Circuits, and Applications, Fourth Edition, ISBN 978-0-13-312590-0, *by Muhammad H. Rashid, published by Pearson Education* © 2014.

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

10 9 8 7 6 5 4 3 2 1
14 13 12 11 10

Typeset in 10/12 TimesTenLTStd-Roman by Integra Software Services Pvt. Ltd.

Printed and bound by Courier Westford in The United States of America

PEARSON

ISBN 10: 0-273-76908-1
ISBN 13: 978-0-273-76908-8

To my parents, my wife Fatema, and
my family: Fa-eza, Farzana, Hasan, Hannah, Laith, Laila, and Nora

Contents

Preface

The fourth edition of *Power Electronics* is intended as a textbook for a course on power electronics/static power converters for junior or senior undergraduate students in electrical and electronic engineering. It can also be used as a textbook for graduate students and as a reference book for practicing engineers involved in the design and applications of power electronics. The prerequisites are courses on basic electronics and basic electrical circuits. The content of *Power Electronics* is beyond the scope of a one-semester course. The time allocated to a course on power electronics in a typical undergraduate curriculum is normally only one semester. Power electronics has already advanced to the point where it is difficult to cover the entire subject in a one-semester course. For an undergraduate course, Chapters 1 to 11 should be adequate to provide a good background on power electronics. Chapters 12 to 17 could be left for other courses or included in a graduate course. Table P.1 shows suggested topics for a one-semester course on "Power Electronics" and Table P.2 for a one-semester course on "Power Electronics and Motor Drives."

TABLE P.1 Suggested Topics for One-Semester Course on Power Electronics

Chapter	Topics	Sections	Lectures
1	Introduction	1.1 to 1.12	2
2	Power semiconductor diodes and circuits	2.1 to 2.4, 2.6–2.7, 2.11 to 2.16	3
3	Diode rectifiers	3.1 to 3.11	5
4	Power transistors	4.1 to 4.9	3
5	DC–DC converters	5.1 to 5.9	5
6	PWM inverters	6.1 to 6.7	7
7	Resonant pulse inverters	7.1 to 7.5	3
9	Thyristors	9.1 to 9.10	2
10	Controlled rectifiers	10.1 to 10.5	6
11	AC voltage controllers	11.1 to 11.5	3
	Mid-term exams and quizzes		3
	Final exam		3
	Total lectures in a 15-week semester		45

TABLE P.2 Suggested Topics for One-Semester Course on Power Electronics and Motor Drives

Chapter	Topics	Sections	Lectures
1	Introduction	1.1 to 1.10	2
2	Power semiconductor diodes and circuits	2.1 to 2.7	2
3	Diode rectifiers	3.1 to 3.8	4
4	Power transistors	4.1 to 4.8	1
5	DC–DC converters	5.1 to 5.8	4
15	DC drives	14.1 to 14.7	5
6	PWM inverters	6.1 to 6.10	5
7	Thyristors	9.1 to 9.6	1
Appendix	Three-phase circuits	A	1
10	Controlled rectifiers	10.1 to 10.7	5
11	AC voltage controllers	11.1 to 11.5	2
Appendix	Magnetic circuits	B	1
14	AC drives	15.1 to 15.9	6
	Mid-term exams and quizzes		3
	Final exam		3
	Total lectures in a 15-week semester		45

The fundamentals of power electronics are well established and they do not change rapidly. However, the device characteristics are continuously being improved and new devices are added. *Power Electronics,* which employs the bottom-up approach, covers device characteristics and conversion techniques, and then its applications. It emphasizes the fundamental principles of power conversions. This fourth edition of *Power Electronics* is a complete revision of the third edition. The major changes include the following:

- features a bottom-up rather than top-down approach—that is, after covering the devices, the converter specifications are introduced before covering the conversion techniques;
- covers the development of silicon carbide (SiC) devices;
- introduces the averaging models of dc–dc converters;
- has expanded sections on state-of-the-art space vector modulation technique;
- has deleted the chapter on static switches;
- presents a new chapter on introduction to renewable energy and covers state-of-the-art techniques;
- integrates the gate-drive circuits (Chapter 17 in third edition) to the chapters relating to the power devices and converters;
- expands the control methods for both dc and ac drives;
- has added explanations in sections and/or paragraphs throughout the book.

The book is divided into five parts:

Part I: Power Diodes and Rectifiers—Chapters 2 and 3
Part II: Power Transistors and DC–DC Converters—Chapters 4 and 5

Part III: Inverters—Chapters 6, 7, and 8
Part IV: Thyristors and Thyristorized Converters—Chapters 9, 10, and 11
Part V: Power Electronics Applications and Protection—Chapters 12, 13, 14, 15, 16, and 17

Topics like three-phase circuits, magnetic circuits, switching functions of converters, dc transient analysis, Fourier analysis, and reference frame transformation are reviewed in the appendices. Power electronics deals with the applications of solid-state electronics for the control and conversion of electric power. Conversion techniques require the switching on and off of power semiconductor devices. Low-level electronics circuits, which normally consist of integrated circuits and discrete components, generate the required gating signals for the power devices. Integrated circuits and discrete components are being replaced by microprocessors and signal processing ICs.

An ideal power device should have no switching-on and switching-off limitations in terms of turn-on time, turn-off time, current, and voltage handling capabilities. Power semiconductor technology is rapidly developing fast-switching power devices with increasing voltage and current limits. Power switching devices such as power BJTs, power MOSFETs, SITs, IGBTs, MCTs, SITHs, SCRs, TRIACs, GTOs, MTOs, ETOs, IGCTs, and other semiconductor devices are finding increasing applications in a wide range of products.

As the technology grows and power electronics finds more applications, new power devices with higher temperature capability and low losses are still being developed. Over the years, there has been a tremendous development of power semiconductor devices. However, silicon-based devices have almost reached their limits. Due to research and development during recent years, silicon carbide (SiC) power electronics has gone from being a promising future technology to being a potent alternative to state-of-the-art silicon (Si) technology in high-efficiency, high-frequency, and high-temperature applications. The SiC power electronics has higher voltage ratings, lower voltage drops, higher maximum temperatures, and higher thermal conductivities. The SiC power devices are expected to go through an evolution over the next few years, which should lead to a new era of power electronics and applications.

With the availability of faster switching devices, the applications of modern microprocessors and digital signal processing in synthesizing the control strategy for gating power devices to meet the conversion specifications are widening the scope of power electronics. The power electronics revolution has gained momentum since the early 1990s. A new era in power electronics has been initiated. It is the beginning of the third revolution of power electronics in renewable energy processing and energy savings around the world. Within the next 30 years, power electronics will shape and condition the electricity somewhere between its generation and all its users. The potential applications of power electronics are yet to be fully explored but we've made every effort to cover as many potential applications as possible in this book.

Any comments and suggestions regarding this book are welcomed and should be sent to the author.

Dr. Muhammad H. Rashid
Professor of Electrical and Computer Engineering
University of West Florida
11000 University Parkway
Pensacola, FL 32514–5754

E-mail: mrashid@uwf.edu

PSPICE SOFTWARE AND PROGRAM FILES

The student version PSpice schematics and/or Orcad capture software can be obtained or downloaded from

Cadence Design Systems, Inc.
2655 Seely Avenue
San Jose, CA 95134

Websites: http://www.cadence.com
http://www.orcad.com
http://www.pspice.com

The website http://uwf.edu/mrashid contains all PSpice schematics, Orcad capture, and Mathcad files for use with this book. Instructors who have adopted the text for use in the classroom should contact their local Pearson representative for access to the Solutions Manual and the PowerPoint Slides.

Important Note: The PSpice schematic files (with an extension .SCH) need the user-defined model library file ***Rashid_PE3_MODEL.LIB***, which is included with the schematic files, and ***must be included*** from the Analysis menu of PSpice schematics. Similarly, the Orcad schematic files (with extensions .OPJ and .DSN) need the user-defined model library file ***Rashid_PE3_MODEL.LIB***, which is included with the Orcad schematic files, and ***must be included*** from the PSpice Simulation settings menu of Orcad capture. Without these files being included while running the simulation, it will not run and will give errors.

ACKNOWLEDGMENTS

Many people have contributed to this edition and made suggestions based on their classroom experience as a professor or a student. I would like to thank the following persons for their comments and suggestions:

Mazen Abdel-Salam, *King Fahd University of Petroleum and Minerals, Saudi Arabia*
Muhammad Sarwar Ahmad, *Azad Jammu and Kashmir University, Pakistan*
Eyup Akpnar, *Dokuz Eylül Üniversitesi Mühendislik Fakültesi, BUCA-IZMIR, Turkey*
Dionysios Aliprantis, *Iowa State University*
Johnson Asumadu, *Western Michigan University*
Ashoka K. S. Bhat, *University of Victoria, Canada*
Fred Brockhurst, *Rose-Hulman Institution of Technology*
Jan C. Cochrane, *The University of Melbourne, Australia*
Ovidiu Crisan, *University of Houston*

Joseph M. Crowley, *University of Illinois, Urbana-Champaign*
Mehrad Ehsani, *Texas A&M University*
Alexander E. Emanuel, *Worcester Polytechnic Institute*
Prasad Enjeti, *Texas A&M University*
George Gela, *Ohio State University*
Ahteshamul Haque, *Jamia Millia Islamia Univ- New Delhi- India*
Herman W. Hill, *Ohio University*
Constantine J. Hatziadoniu, *Southern Illinois University, Carbondale*
Wahid Hubbi, *New Jersey Institute of Technology*
Marrija Ilic-Spong, *University of Illinois, Urbana-Champaign*
Kiran Kumar Jain, *J B Institute of Engineering and Technology, India*
Fida Muhammad Khan, *Air University-Islamabad Pakistan*
Potitosh Kumar Shaqdu khan, *Multimedia University, Malaysia*
Shahidul I. Khan, *Concordia University, Canada*
Hussein M. Kojabadi, *Sahand University of Technology , Iran*
Nanda Kumar, *Singapore Institute of Management (SIM) University, Singapore*
Peter Lauritzen, *University of Washington*
Jack Lawler, *University of Tennessee*
Arthur R. Miles, *North Dakota State University*
Medhat M. Morcos, *Kansas State University*
Hassan Moghbelli, *Purdue University Calumet*
Khan M Nazir, *University of Management and Technology, Pakistan.*
H. Rarnezani-Ferdowsi, *University of Mashhad, Iran*
Saburo Mastsusaki, *TDK Corporation, Japan*
Vedula V. Sastry, *Iowa State University*
Elias G. Strangas, *Michigan State University*
Hamid A. Toliyat, *Texas A&M University*
Selwyn Wright, *The University of Huddersfield, Queensgate, UK*
S. Yuvarajan, *North Dakota State University*
Shuhui Li, *University of Alabama*
Steven Yu, *Belcan Corporation, USA*
Toh Chuen Ling, *Universiti Tenaga Nasional, Malaysia*
Vipul G. Patel, *Government Engineering College, Gujarat, India*
L.Venkatesha, *BMS College of Engineering, Bangalore, India*
Haider Zaman, *University of Engineering & Technology (UET), Abbottabad Campus, Pakistan*
Mostafa F. Shaaban, *Ain-Shams University, Cairo, Egypt*

It has been a great pleasure working with the editor, Alice Dworkin, and the production team Abinaya Rajendran and production manager Irwin Zucker. Finally, I would thank my family for their love, patience, and understanding.

MUHAMMAD H. RASHID
Pensacola, Florida

The publishers wish to thank S. Sakthivel Murugan of SSN College of Engineering, Chennai for reviewing the content of the International Edition.

About the Author

Muhammad H. Rashid is employed by the University of West Florida as Professor of Electrical and Computer Engineering. Previously, he was employed by the University of Florida as Professor and Director of UF/UWF Joint Program. Rashid received his B.Sc. degree in electrical engineering from the Bangladesh University of Engineering and Technology, and M.Sc. and Ph.D. degrees from the University of Birmingham in the UK. Previously, he worked as Professor of Electrical Engineering and Chair of the Engineering Department at Indiana University–Purdue University at Fort Wayne. He also worked as Visiting Assistant Professor of Electrical Engineering at the University of Connecticut, Associate Professor of Electrical Engineering at Concordia University (Montreal, Canada), Professor of Electrical Engineering at Purdue University Calumet, and Visiting Professor of Electrical Engineering at King Fahd University of Petroleum and Minerals (Saudi Arabia). He has been employed as a design and development engineer with Brush Electrical Machines Ltd. (England, UK), as a research engineer with Lucas Group Research Centre (England, UK), and as a lecturer and head of Control Engineering Department at the Higher Institute of Electronics (Libya and Malta).

Dr. Rashid is actively involved in teaching, researching, and lecturing in electronics, power electronics, and professional ethics. He has published 17 books listed in the U.S. Library of Congress and more than 160 technical papers. His books are adopted as textbooks all over the world. His book *Power Electronics* has translations in Spanish, Portuguese, Indonesian, Korean, Italian, Chinese, and Persian, and also the Indian economy edition. His book *Microelectronics* has translations in Spanish in Mexico and in Spain, in Italian, and in Chinese.

He has received many invitations from foreign governments and agencies to give keynote lectures and consult; from foreign universities to serve as an external examiner for undergraduate, master's, and Ph.D. examinations; from funding agencies to review research proposals; and from U.S. and foreign universities to evaluate promotion cases for professorship. Dr. Rashid has worked as a regular employee or consultant in Canada, Korea, the United Kingdom, Singapore, Malta, Libya, Malaysia, Saudi Arabia, Pakistan, and Bangladesh. Dr. Rashid has traveled to almost all states in the USA and to many countries to lecture and present papers (Japan, China, Hong Kong, Indonesia, Taiwan, Malaysia, Thailand, Singapore, India, Pakistan, Turkey, Saudi Arabia, United Arab Emirates, Qatar, Libya, Jordan, Egypt, Morocco, Malta, Italy, Greece, United Kingdom, Brazil, and Mexico).

He is Fellow of the Institution of Engineering and Technology (IET, UK) and Life Fellow of the Institute of Electrical and Electronics Engineers (IEEE, USA). He was elected as an IEEE Fellow with the citation "Leadership in power electronics education and contributions to the analysis and design methodologies of solid-state power converters." Dr. Rashid is the recipient of the 1991 Outstanding Engineer Award from the Institute of Electrical and Electronics Engineers. He received the 2002 IEEE Educational Activity Award (EAB), Meritorious Achievement Award in Continuing Education with the citation "for contributions to the design and delivery of continuing education in power electronics and computer-aided-simulation." He is the recipient of the 2008 IEEE Undergraduate Teaching Award with the citation "For his distinguished leadership and dedication to quality undergraduate electrical engineering education, motivating students and publication of outstanding textbooks."

Dr. Rashid is currently an ABET program evaluator for electrical and computer engineering, and also for the (general) engineering program. He is the series editor of *Power Electronics and Applications* and *Nanotechnology and Applications* with the CRC Press. He serves as the editorial advisor of *Electric Power and Energy* with Elsevier Publishing. He lectures and conducts workshops on Outcome-Based Education (OBE) and its implementations including assessments. He is a distinguished lecturer for the IEEE Education Society and a regional speaker (previously Distinguished Lecturer) for the IEEE Industrial Applications Society. He has also authored a book *The Process of Outcome-Based Education—Implementation, Assessment and Evaluations.*

CHAPTER 1

Introduction

After completing this chapter, students should be able to do the following:

- Describe what is power electronics.
- List the applications of power electronics.
- Describe the evolution of power electronics.
- List the major types of power converters.
- List the major parts of power electronic equipment.
- List the ideal characteristics of power switching devices.
- List the characteristics and specifications of practical power switching devices.
- List the types of power semiconductor devices.
- Describe the control characteristics of power semiconductor devices.
- List the types of power modules and the elements of intelligent modules.

Symbols and Their Meanings

Symbol	Meaning
f_s, T_s	Frequency and period of a waveform, respectively
I_{RMS}	Rms value of a waveform
I_{dc}, I_{rms}	Dc and rms components of a waveform, respectively
P_D, P_{ON}, P_{SW}, P_G	Total power dissipation, on-state power, switching power, gate-drive power, respectively
t_d, t_r, t_n, t_s, t_f, t_{o}	Delay, rise, on, storage, fall, and off-time of switching waveform
v_{s}, v_{o}	Instantaneous ac input supply and output voltage, respectively
V_m	Peak magnitude of an ac sinusoidal supply voltage
V_s	Dc supply voltage
v_{g}, V_G	Instantaneous and dc gate/base drive signal of a device, respectively
v_G, v_{GS}, v_B	Instantaneous gate, gate–source, and base drive voltages of power devices, respectively
δ	Duty cycle of a pulse signal

1.1 APPLICATIONS OF POWER ELECTRONICS

The demand for control of electric power for electric motor drive systems and industrial controls existed for many years, and this led to early development of the Ward–Leonard system to obtain a variable dc voltage for the control of dc motor drives. Power electronics has revolutionized the concept of power control for power conversion and for control of electrical motor drives.

Power electronics combines power, electronics, and control. Control deals with the steady-state and dynamic characteristics of closed-loop systems. Power deals with the static and rotating power equipment for the generation, transmission, and distribution of electric energy. Electronics deal with the solid-state devices and circuits for signal processing to meet the desired control objectives. *Power electronics* may be defined as the application of solid-state electronics for the control and conversion of electric power. There is more than one way to define power electronics. One could also define power electronics as the art of converting electrical energy from one form to another in an efficient, clean, compact, and robust manner for the energy utilization to meet the desired needs. The interrelationship of power electronics with power, electronics, and control is shown in Figure 1.1. The arrow points to the direction of the current flow from anode (A) to cathode (K). It can be turned on and off by a signal to the gate terminal (G). Without any gate signal, it normally remains in the off-state, behaves as an open circuit, and can withstand a voltage across the terminals A and K.

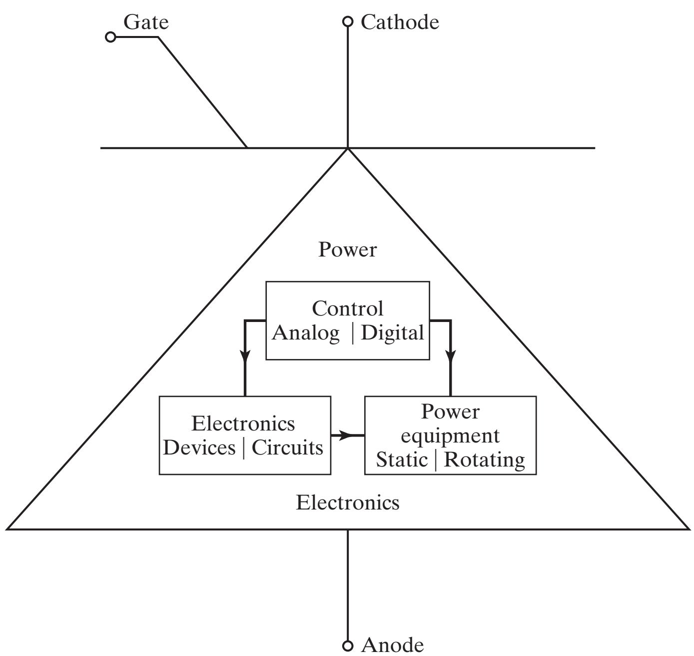

FIGURE 1.1

Relationship of power electronics to power, electronics, and control.

Power electronics is based primarily on the switching of the power semiconductor devices. With the development of power semiconductor technology, the power-handling capabilities and the switching speed of the power devices have improved tremendously. The development of microprocessors and microcomputer technology has a great impact on the control and synthesizing the control strategy for the power semiconductor devices. Modern power electronics equipment uses (1) power semiconductors that can be regarded as the muscle, and (2) microelectronics that have the power and intelligence of a brain.

Power electronics has already found an important place in modern technology and is now used in a great variety of high-power products, including heat controls, light controls, motor controls, power supplies, vehicle propulsion systems, and high-voltage direct-current (HVDC) systems. It is difficult to draw the flexible ac transmissions (FACTs) boundaries for the applications of power electronics, especially with the present trends in the development of power devices and microprocessors. Table 1.1 shows some applications of power electronics [3].

TABLE 1.1 Some Applications of Power Electronics

Advertising	Forklift trucks
Air-conditioning	Furnaces
Aircraft power supplies	Games
Alarms	Garage door openers
Appliances	Gas turbine starting
Audio amplifiers	Generator exciters
Battery charger	Grinders
Blenders	Hand power tools
Blowers	Heat controls
Boilers	High-frequency lighting
Burglar alarms	High-voltage dc (HVDC)
Cement kiln	Induction heating
Chemical processing	Laser power supplies
Clothes dryers	Latching relays
Computers	Light dimmers
Conveyors	Light flashers
Cranes and hoists	Linear induction motor controls
Dimmers	Locomotives
Displays	Machine tools
Electric blankets	Magnetic recordings
Electric door openers	Magnets
Electric dryers	Mass transits
Electric fans	Mercury arc lamp ballasts
Electric vehicles	Mining
Electromagnets	Model trains
Electromechanical electroplating	Motor controls
Electronic ignition	Motor drives
Electrostatic precipitators	Movie projectors
Elevators	Nuclear reactor control rod
Fans	Oil well drilling
Flashers	Oven controls
Food mixers	Paper mills
Food warmer trays	Particle accelerators

(*continued*)

TABLE 1.1 (*Continued*)

People movers	Static circuit breakers
Phonographs	Static relays
Photocopies	Steel mills
Photographic supplies	Synchronous machine starting
Power supplies	Synthetic fibers
Printing press	Television circuits
Pumps and compressors	Temperature controls
Radar/sonar power supplies	Timers
Range surface unit	Toys
Refrigerators	Traffic signal controls
Regulators	Trains
RF amplifiers	TV deflections
Renewable energy including transmission, distribution, and storage	Ultrasonic generators
	Uninterruptible power supplies
Security systems	Vacuum cleaners
Servo systems	Volt-ampere reactive (VAR) compensation
Sewing machines	Vending machines
Solar power supplies	Very low frequency (VLF) transmitters
Solid-state contactors	Voltage regulators
Solid-state relays	Washing machines
Space power supplies	Welding

Source: Ref. 3.

1.2 HISTORY OF POWER ELECTRONICS

The history of power electronics began with the introduction of the mercury arc rectifier in 1900. Then the metal tank rectifier, grid-controlled vacuum-tube rectifier, ignitron, phanotron, and thyratron were introduced gradually. These devices were applied for power control until the 1950s.

The first electronics revolution began in 1948 with the invention of the silicon transistor at Bell Telephone Laboratories by Bardeen, Brattain, and Schokley. Most of today's advanced electronic technologies are traceable to that invention. Modern microelectronics evolved over the years from silicon semiconductors. The next breakthrough, in 1956, was also from Bell Laboratories: the invention of the *PNPN* triggering transistor, which was defined as a thyristor or silicon-controlled rectifier (SCR).

The second electronics revolution began in 1958 with the development of the commercial thyristor by the General Electric Company. That was the beginning of a new era of power electronics. Since then, many different types of power semiconductor devices and conversion techniques have been introduced. The microelectronics revolution gave us the ability to process a huge amount of information at incredible speed. The power electronics revolution is giving us the ability to shape and control large amounts of power with ever-increasing efficiency. Due to the marriage of power electronics, the muscle, with microelectronics, the brain, many potential applications of power electronics are now emerging, and this trend will continue. Within the next 30 years, power electronics will shape and condition the electricity somewhere in the transmission network between its generation and all its users. The power electronics revolution has gained momentum since the late 1980s and early 1990s [1]. A chronological history of power electronics is shown in Figure 1.2.

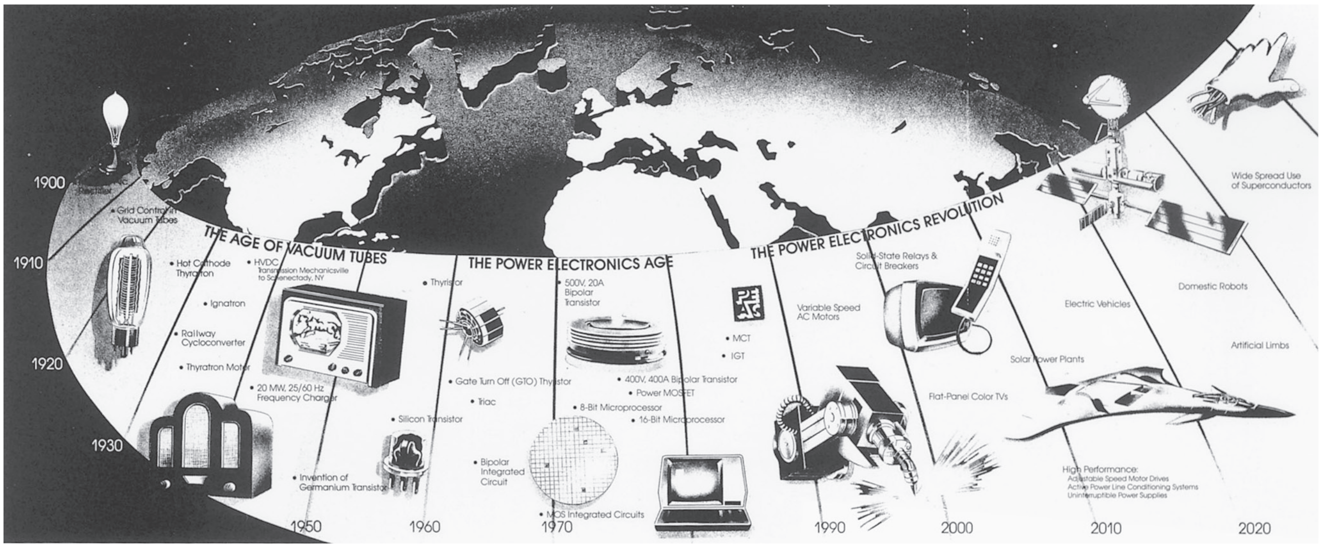

FIGURE 1.2

History of power electronics. (Courtesy of Tennessee Center for Research and Development, a University of Tennessee Affiliated Center.)

With the increasing energy demands around the world, there is a new era of renewable energy. Power electronics is an integral part of renewable energy for its transmission, distribution, and storage. The research and development for energy-efficient automobiles will also lead to increased applications and development of power electronics.

Over the years, there has been a tremendous development of power semiconductor devices [6]. However, silicon-based devices have almost reached their limits. Due to research and development during recent years, silicon carbide (SiC) power electronics has gone from being a promising future technology to being a potent alternative to state-of-the-art silicon (Si) technology in high-efficiency, high-frequency, and high-temperature applications. The SiC power electronics has higher voltage ratings, lower voltage drops, higher maximum temperatures, and higher thermal conductivities. Manufacturers are capable of developing and processing high-quality transistors at costs that permit introduction of new products in application areas where the benefits of the SiC technology can provide significant system advantages [11].

A new era in power electronics has been initiated [12]. It is the beginning of the third revolution of power electronics in renewable energy processing and energy savings around the world. It is expected to continue for another 30 years.

1.3 TYPES OF POWER ELECTRONIC CIRCUITS

For the control of electric power or power conditioning, the conversion of electric power from one form to another is necessary and the switching characteristics of the power devices permit these conversions. The static power converters perform these functions of power conversions. A converter may be considered as a switching matrix, in which one or more switches are turned on and connected to the supply source in order to obtain the desired output voltage or current. The power electronics circuits can be classified into six types:

1. Diode rectifiers
2. Dc–dc converters (dc choppers)
3. Dc–ac converters (inverters)
4. Ac–dc converters (controlled rectifiers)
5. Ac–ac converters (ac voltage controllers)
6. Static switches

The switching devices in the following converters are used to illustrate the basic principles only. The switching action of a converter can be performed by more than one device. The choice of a particular device depends on the voltage, current, and speed requirements of the converter.

Diode rectifiers. A diode rectifier circuit converts ac voltage into a fixed dc voltage and is shown in Figure 1.3. A diode conducts when its anode voltage is higher than the cathode voltage, and it offers a very small voltage drop, ideally zero voltage, but typically 0.7 V. A diode behaves as an open circuit when its cathode voltage is higher than the anode voltage, and it offers a very high resistance, ideally infinite resistance, but typically 10 kΩ. The output voltage is a pulsating dc, but it is distorted