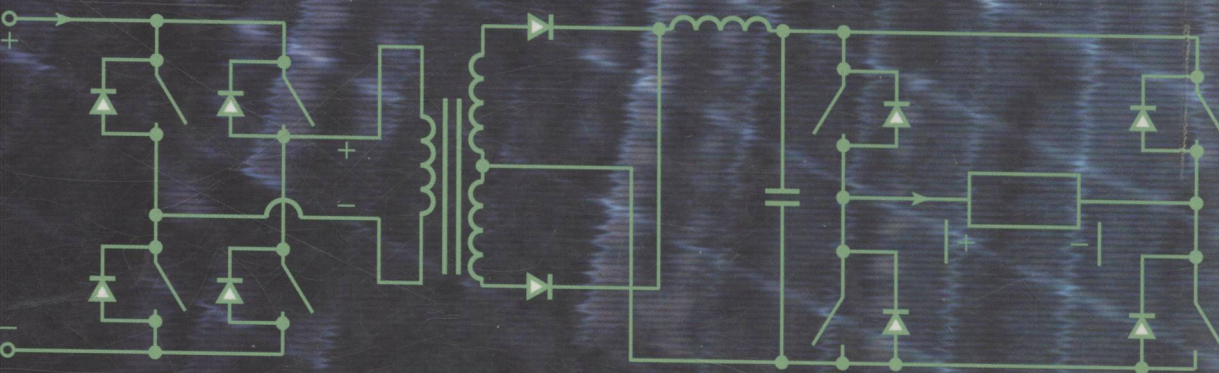


POWER ELECTRONICS

CIRCUITS, DEVICES,
AND APPLICATIONS

THIRD EDITION



MUHAMMAD H. RASHID

M1
224
E-3

POWER ELECTRONICS CIRCUITS, DEVICES, AND APPLICATIONS

Third Edition



Muhammad H. Rashid
Electrical and Computer Engineering
University of West Florida



E200404395



Upper Saddle River, NJ 07458

Library of Congress Cataloging-in-Publication Data

Rashid, M. H.

Power electronics: circuits, devices, and applications / Muhammad Harunur Rashid. — 3rd ed.

p. cm.

Includes bibliographical references and index.

ISBN 0-13-101140-5

1. Power electronics. I. Title.

TK7881.15.R37 2003

621.31'7—dc21

2003048622

Vice President and Editorial Director, ECS: *Marcia J. Horton*

Publisher: *Tom Robbins*

Associate Editor: *Alice Dworkin*

Vice President and Director of Production and Manufacturing, ESM: *David W. Riccardi*

Executive Managing Editor: *Vince O'Brien*

Managing Editor: *David George*

Production Editor: *Donna King*

Director of Creative Services: *Paul Belfanti*

Creative Director: *Carole Anson*

Art Director: *Jayne Conte*

Cover Designer: *Bruce Kenselaar*

Art Editor: *Greg Dulles*

Manufacturing Manager: *Trudy Piscioti*

Manufacturing Buyer: *Lynda Castillo*

Marketing Manager: *Holly Stark*



© 2004 by Pearson Education, Inc.

Pearson Prentice Hall

Pearson Education, Inc.

Upper Saddle River, NJ 07458

All rights reserved. No part of this book may be reproduced, in any form or by any means, without permission in writing from the publisher.

Pearson Prentice Hall® is a trademark of Pearson Education, Inc.

The author and publisher of this book have used their best efforts in preparing this book. These efforts include the development, research, and testing of the theories and programs to determine their effectiveness. The author and publisher make no warranty of any kind, expressed or implied, with regard to these programs or the documentation contained in this book. The author and publisher shall not be liable in any event for incidental or consequential damages in connection with, or arising out of, the furnishing, performance, or use of these programs.

ORCAD is a registered trademark of the Cadence Design Systems, Inc.

Mathcad is a registered trademark of the MathSoft, Inc.

IBM®PC is a registered trademark of International Business Machines Corporation.

PSPice® is a registered trademark of MicroSim Corporation.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-101140-5

Pearson Education Ltd., London

Pearson Education Australia Pty., Ltd., Sydney

Pearson Education Singapore, Pte. Ltd.

Pearson Education North Asia Ltd., Hong Kong

Pearson Education Canada, Inc., Toronto

Pearson Educación de México, S.A. de C.V.

Pearson Education—Japan, Tokyo

Pearson Education Malaysia, Pte. Ltd.

Pearson Education, Inc., Upper Saddle River, New Jersey

COMMONLY USED FUNCTIONS

	$-A$	$90 \pm A$	$180 \pm A$	$270 \pm A$	$360 k \pm A$
sin	$-\sin A$	$\cos A$	$\mp \sin A$	$-\cos A$	$\pm \sin A$
cos	$\cos A$	$\mp \sin A$	$-\cos A$ *	$\pm \sin A$	$\cos A$

$$\sin(A \pm B) = \sin A \cos B \pm \cos A \sin B$$

$$\cos(A \pm B) = \cos A \cos B \mp \sin A \sin B$$

$$\sin 2A = 2 \sin A \cos A$$

$$\cos 2A = 1 - 2 \sin^2 A = 2 \cos^2 A - 1$$

$$\sin A + \sin B = 2 \sin \frac{A+B}{2} \cos \frac{A-B}{2}$$

$$\sin A - \sin B = 2 \cos \frac{A+B}{2} \sin \frac{A-B}{2}$$

$$\cos A + \cos B = 2 \cos \frac{A+B}{2} \cos \frac{A-B}{2}$$

$$\cos A - \cos B = 2 \sin \frac{A+B}{2} \sin \frac{B-A}{2}$$

$$\sin A \sin B = \frac{1}{2} [\cos(A-B) - \cos(A+B)]$$

$$\cos A \cos B = \frac{1}{2} [\cos(A-B) + \cos(A+B)]$$

$$\sin A \cos B = \frac{1}{2} [\sin(A-B) + \sin(A+B)]$$

$$\int \sin nx \, dx = -\frac{\cos nx}{n}$$

$$\int \sin^2 nx \, dx = \frac{x}{2} - \frac{\sin 2nx}{4n}$$

COMMONLY USED FUNCTIONS

$$\int \sin mx \sin nx \, dx = \frac{\sin (m - n)x}{2(m - n)} - \frac{\sin (m + n)x}{2(m + n)} \quad \text{for } m \neq n$$

$$\int \cos nx \, dx = \frac{\sin nx}{n}$$

$$\int \cos^2 nx \, dx = \frac{x}{2} + \frac{\sin 2nx}{4n}$$

$$\int \cos mx \cos nx \, dx = \frac{\sin (m - n)x}{2(m - n)} + \frac{\sin (m + n)x}{2(m + n)} \quad \text{for } m \neq n$$

$$\int \sin nx \cos nx \, dx = \frac{\sin^2 nx}{2n}$$

$$\int \sin mx \cos nx \, dx = \frac{\cos (m - n)x}{2(m - n)} - \frac{\cos (m + n)x}{2(m + n)} \quad \text{for } m \neq n$$

SOME UNITS AND CONSTANTS

Quantity	Units	Equivalent
Length	1 meter (m)	3.281 feet (ft) 39.36 inches (in)
Mass	1 kilogram (kg)	2.205 pounds (lb) 35.27 ounces (oz)
Force	1 newton (N)	0.2248 force pounds (lbf)
Torque	1 newton-meter (N.m.)	0.738 pound-feet (lbf.ft)
Moment of inertia	1 kilogram-meter ² (kg.m ²)	23.7 pound-feet ² (lb.ft ²)
Power	1 watt (W)	0.7376 foot-pounds/second 1.341 × 10 ⁻³ horsepower (hp)
Energy	1 joules (J)	1 watt-second 0.7376 foot-pounds 2.778 × 10 ⁻⁷ kilowatt-hours (kWh)
Horsepower	1 hp	746 watts
Magnetic flux	1 weber (Wb)	10 ⁸ maxwells or lines
Magnetic flux density	1 tesla (T)	1 weber/meter ² (Wb/m ²) 10 ⁴ gauss
Magnetic field intensity	1 ampere-turn/meter (At/m)	1.257 × 10 ² oersted
Permeability of free space	μ ₀ = 4π × 10 ⁷ H/m	

POWER ELECTRONICS CIRCUITS, DEVICES, AND APPLICATIONS

Third Edition

*To my parents, my wife Fatema, and
my family: Faeza, Farzana, Hasan and Hussain*

Preface

The third 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 16 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 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, 2.7, 2.10 to 2.13	2
3	Diode rectifiers	3.1 to 3.9	5
4	Power transistors	4.2, 4.10, 4.11	2
5	DC–DC converters	5.1 to 5.7	5
6	PWM inverters	6.1 to 6.6, 6.8 to 6.11	7
7	Thyristors	7.1 to 7.5, 7.9, 7.10	2
8	Resonant pulse inverters	8.1 to 8.5	3
10	Controlled rectifiers	10.1 to 10.6	6
11	AC voltage controllers	11.1 to 11.5	3
12	Static switches	12.1 to 12.8	2
	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 1.12	2
2	Power semiconductor diodes and circuits	2.1 to 2.4, 2.7, 2.10 to 2.13	2
3	Diode rectifiers	3.1 to 3.8	4
4	Power transistors	4.2, 4.10, 4.11	1
5	DC–DC converters	5.1 to 5.7	4
6	PWM inverters	6.1 to 6.6, 6.8 to 6.11	5
7	Thyristors	7.1 to 7.5, 7.9, 7.10	1
10	Controlled rectifiers	10.1 to 10.7	5
11	AC voltage controllers	11.1 to 11.5	2
Appendix	Magnetic circuits	B 1.6 to 16.6	1
15	DC drives	15.1 to 15.7	5
Appendix	Three-phase circuits	A 1.6 to 16.6	1
14	AC drives	16.1 to 16.6	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 conversion techniques first and then applications. It emphasizes the fundamental principles of power conversions. This third edition of *Power Electronics* is a complete revision of the second edition, and (i) features bottom-up approach rather than top-down approach; (ii) introduces the state-of-the-art advanced Modulation Techniques; (iii) presents three new chapters on “Multilevel Inverters” (Chapter 9), “Flexible AC Transmission Systems” (Chapter 13), and “Gate Drive Circuits” (Chapter 17) and covers state-of-the-art techniques; (iv) integrates the industry standard software, SPICE, and design examples that are verified by SPICE simulation; (v) examines converters with RL-loads under both continuous and discontinuous current conduction; and (vi) has expanded sections and/or paragraphs to add explanations. The book is divided into five parts:

1. Introduction—Chapter 1
2. Devices and gate-drive circuits—Chapters 2, 4, 7, and 17
3. Power conversion techniques—Chapters 3, 5, 6, 8, 9, 10, and 11
4. Applications—Chapters 12, 13, 14, 15, and 16
5. Protection and thermal modeling—Chapter 18

Topics like three-phase circuits, magnetic circuits, switching functions of converters, DC transient analysis, and Fourier analysis 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 -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. 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. Within the next 20 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 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 and Director
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 circuits, PSpice schematics, Orcad capture, and Mathcad files for use with this book.

Important Note: The PSpice circuit files (with an extension .CIR) are self-contained and each file contains any necessary device or component models. However, 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, ***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*
 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*
 George Gela, *Ohio State University*
 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*
 Shahidul I. Khan, *Concordia University, Canada*
 Hussein M. Kojabadi, *Sahand University of Technology, Iran*
 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*
 H. Rarnezani-Ferdowsi, *University of Mashhad, Iran*
 Prasad Enjeti, *Texas A&M University*
 Saburo Mastsusaki, *TDK Corporation, Japan*
 Vedula V. Sastry, *Iowa State University*
 Elias G. Strangas, *Michigan State University*
 Selwyn Wright, *The University of Huddersfield, Queensgate, UK*
 S. Yuvarajan, *North Dakota State University*

It has been a great pleasure working with the editor, Alice Dworkin and the production editor, Donna King. Finally, I would thank my family for their love, patience, and understanding.

MUHAMMAD H. RASHID
Pensacola, Florida

About the Author

Muhammad H. Rashid received the B.Sc. degree in electrical engineering from the Bangladesh University of Engineering and Technology and the M.Sc. and Ph.D. degrees from the University of Birmingham, UK.

Currently, he is a Professor of electrical engineering with the University of Florida and the Director of the UF/UWF Joint Program in Electrical and Computer Engineering. Previously, he was a Professor of electrical engineering and the Chair of the Engineering Department at Indiana University–Purdue University at Fort Wayne. In addition, he was a 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 also been employed as a design and development engineer with Brush Electrical Machines Ltd. (UK), as a Research Engineer with Lucas Group Research Centre (UK), and as a Lecturer and Head of Control Engineering Department at the Higher Institute of Electronics (Malta). He is actively involved in teaching, researching, and lecturing in power electronics. He has published 14 books and more than 100 technical papers. His books have been adopted as textbooks all over the world. His book *Power Electronics* has been translated into Spanish, Portuguese, Indonesian, Korean and Persian. His book *Microelectronics* has been translated into Spanish in Mexico and Spain. He has had many invitations from foreign governments and agencies to be a keynote lecturer and consultant, from foreign universities to serve as an external Ph.D. examiner, and from funding agencies to serve as a research proposal reviewer. His contributions in education have been recognized by foreign governments and agencies. He has previously lectured and consulted for NATO for Turkey in 1994, UNDP for Bangladesh in 1989 and 1994, Saudi Arabia in 1993, Pakistan in 1993, Malaysia in 1995 and 2002, and Bangkok in 2002, and has been invited by foreign universities in Australia, Canada, Hong Kong, India, Malaysia, Singapore to serve as an external examiner for undergraduate, master's and Ph.D. degree examinations, by funding agencies in Australia, Canada, United States, and Hong Kong to review research proposals, and by U.S. and foreign universities to evaluate promotion cases for professorship. He has previously authored seven books published by Prentice Hall: *Power Electronics—Circuits, Devices, and Applications* (1988, 2/e 1993), *SPICE For Power Electronics* (1993), *SPICE for Circuits and Electronics Using PSpice*

(1990, 2/e 1995), *Electromechanical and Electrical Machinery* (1986), and *Engineering Design for Electrical Engineers* (1990). He has authored five IEEE self-study guides: *Self-Study Guide on Fundamentals of Power Electronics*, *Power Electronics Laboratory Using PSpice*, *Selected Readings on SPICE Simulation of Power Electronics*, and *Selected Readings on Power Electronics* (IEEE Press, 1996) and *Microelectronics Laboratory Using Electronics Workbench* (IEEE Press, 2000). He also wrote two books: *Electronic Circuit Design using Electronics Workbench* (January 1998), and *Microelectronic Circuits—Analysis and Design* (April 1999) by PWS Publishing). He is editor of *Power Electronics Handbook* published by Academic Press, 2001.

Dr. Rashid is a registered Professional Engineer in the Province of Ontario (Canada), a registered Chartered Engineer (UK), a Fellow of the Institution of Electrical Engineers (IEE, UK) and a 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.*” He was the recipient of the 1991 *Outstanding Engineer Award* from The Institute of Electrical and Electronics Engineers (IEEE). 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 was also an ABET program evaluator for electrical engineering from 1995 to 2000 and he is currently an engineering evaluator for the Southern Association of Colleges and Schools (SACS, USA). He has been elected as an IEEE-Industry Applications Society (IAS) Distinguished Lecturer. He is the Editor-in-Chief of the *Power Electronics and Applications Series*, published by CRC Press.

Contents

Preface

About the Author

xix
xxiii

Chapter 1 Introduction 1

- 1.1 Applications of Power Electronics 1
 - 1.1.1 History of Power Electronics 2
- 1.2 Power Semiconductor Devices 5
 - 1.2.1 Power Diodes 5
 - 1.2.2 Thyristors 6
 - 1.2.3 Power Transistors 9
- 1.3 Control Characteristics of Power Devices 10
- 1.4 Characteristics and Specifications of Switches 16
 - 1.4.1 Ideal Characteristics 16
 - 1.4.2 Characteristics of Practical Devices 17
 - 1.4.3 Switch Specifications 18
 - 1.4.4 Device Choices 19
- 1.5 Types of Power Electronic Circuits 20
- 1.6 Design of Power Electronics Equipment 23
- 1.7 Determining the Root-Mean-Square Values of Waveforms 24
- 1.8 Peripheral Effects 24
- 1.9 Power Modules 26
- 1.10 Intelligent Modules 26
- 1.11 Power Electronics Journals and Conferences 28
 - Summary 29
 - References 29
 - Review Questions 30

Chapter 2 Power Semiconductor Diodes and Circuits 31

- 2.1 Introduction 31
- 2.2 Semiconductor Basics 31
- 2.3 Diode Characteristics 33

2.4	Reverse Recovery Characteristics	35
2.5	Power Diode Types	38
2.5.1	General-Purpose Diodes	38
2.5.2	Fast-Recovery Diodes	38
2.5.3	Schottky Diodes	39
2.6	Silicon Carbide Diodes	39
2.7	Spice Diode Model	40
2.8	Series-Connected Diodes	42
2.9	Parallel-Connected Diodes	45
2.10	Diodes with RC and RL Loads	46
2.11	Diodes with LC and RLC Loads	49
2.12	Freewheeling Diodes	56
2.13	Recovery of Trapped Energy with a Diode	58
	Summary	62
	References	63
	Review Questions	63
	Problems	64

Chapter 3 Diode Rectifiers 68

3.1	Introduction	68
3.2	Single-Phase Half-Wave Rectifiers	68
3.3	Performance Parameters	69
3.4	Single-Phase Full-Wave Rectifiers	77
3.5	Single-Phase Full-Wave Rectifier with RL Load	82
3.6	Multiphase Star Rectifiers	87
3.7	Three-Phase Bridge Rectifiers	92
3.8	Three-Phase Bridge Rectifier with RL Load	95
3.9	Comparison of Diode Rectifiers	101
3.10	Rectifier Circuit Design	101
3.11	Output Voltage with LC Filter	112
3.12	Effects of Source and Load Inductances	116
	Summary	119
	References	119
	Review Questions	119
	Problems	120

Chapter 4 Power Transistors 122

4.1	Introduction	122
4.2	Bipolar Junction Transistors	123
4.2.1	Steady-State Characteristics	124
4.2.2	Switching Characteristics	128
4.2.3	Switching Limits	135
4.3	Power MOSFETs	137
4.3.1	Steady-State Characteristics	141
4.3.2	Switching Characteristics	142

4.4	COOLMOS	144
4.5	SITs	145
4.6	IGBTs	147
4.7	Series and Parallel Operation	150
4.8	di/dt and dv/dt Limitations	151
4.9	SPICE Models	155
	4.9.1 BJT SPICE Model	155
	4.9.2 MOSFET SPICE Model	155
	4.9.3 IGBT SPICE Model	158
4.10	Comparisons of Transistors	160
	Summary	160
	References	162
	Review Questions	163
	Problems	164
Chapter 5	DC–DC Converters	166
5.1	Introduction	166
5.2	Principle of Step-Down Operation	166
	5.2.1 Generation of Duty Cycle	170
5.3	Step-Down Converter with RL Load	171
5.4	Principle of Step-Up Operation	176
5.5	Step-Up Converter with a Resistive Load	179
5.6	Performance Parameters	181
5.7	Converter Classification	182
5.8	Switching-Mode Regulators	186
	5.8.1 Buck Regulators	186
	5.8.2 Boost Regulators	190
	5.8.3 Buck–Boost Regulators	194
	5.8.4 Cúk Regulators	198
	5.8.5 Limitations of Single-Stage Conversion	204
5.9	Comparison of Regulators	205
5.10	Multioutput Boost Converter	206
5.11	Diode Rectifier-Fed Boost Converter	208
5.12	Chopper Circuit Design	211
5.13	State–Space Analysis of Regulators	217
	Summary	221
	References	221
	Review Questions	223
	Problems	224
Chapter 6	Pulse-Width-Modulated Inverters	226
6.1	Introduction	226
6.2	Principle of Operation	227
6.3	Performance Parameters	230
6.4	Single-Phase Bridge Inverters	232

6.5	Three-Phase Inverters	237
6.5.1	180-Degree Conduction	237
6.5.2	120-Degree Conduction	246
6.6	Voltage Control of Single-Phase Inverters	248
6.6.1	Single-Pulse-Width Modulation	248
6.6.2	Multiple-Pulse-Width Modulation	250
6.6.3	Sinusoidal Pulse-Width Modulation	253
6.6.4	Modified Sinusoidal Pulse-Width Modulation	257
6.6.5	Phase-Displacement Control	258
6.7	Advanced Modulation Techniques	260
6.8	Voltage Control of Three-Phase Inverters	264
6.8.1	Sinusoidal PWM	265
6.8.2	60-Degree PWM	268
6.8.3	Third-Harmonic PWM	268
6.8.4	Space Vector Modulation	271
6.8.5	Comparison of PWM Techniques	279
6.9	Harmonic Reductions	280
6.10	Current-Source Inverters	285
6.11	Variable DC-Link Inverter	288
6.12	Boost Inverter	289
6.13	Inverter Circuit Design	294
	Summary	299
	References	299
	Review Questions	300
	Problems	301

Chapter 7 Thyristors 304

7.1	Introduction	304
7.2	Thyristor Characteristics	304
7.3	Two-Transistor Model of Thyristor	307
7.4	Thyristor Turn-On	309
7.5	Thyristor Turn-Off	311
7.6	Thyristor Types	313
7.6.1	Phase-Controlled Thyristors	314
7.6.2	BCTs	314
7.6.3	Fast-Switching Thyristors	315
7.6.4	LASCRs	316
7.6.5	Bidirectional Triode Thyristors	316
7.6.6	RCTs	317
7.6.7	GTOs	318
7.6.8	FET-CTHs	322
7.6.9	MTOs	323
7.6.10	ETOs	323
7.6.11	IGCTs	324
7.6.12	MCTs	325