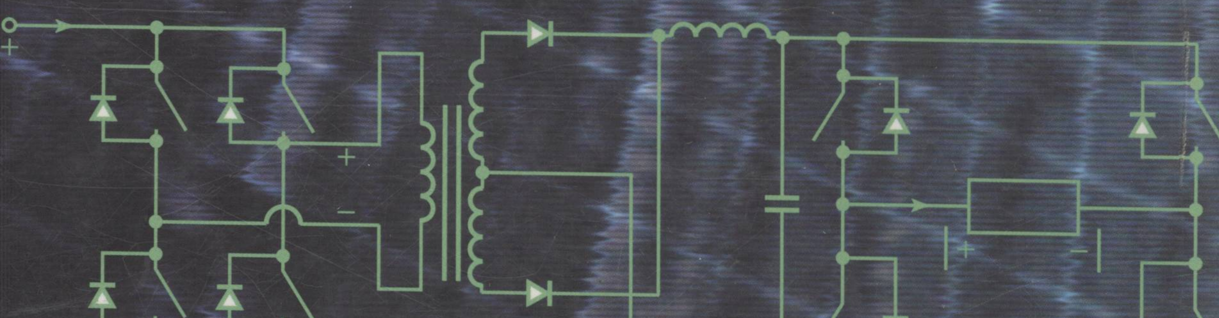
POWER ELECTRONICS

CIRCUITS, DEVICES, AND APPLICATIONS

THIRD EDITION



MUHAMMAD H. RASHID

POWER ELECTRONICS CIRCUITS, DEVICES, AND APPLICATIONS

Third Edition

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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

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

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

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

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

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

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

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	$\mu_0 = 4\pi \times 10^7$ 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.

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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.

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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.

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