

POWER-SWITCHING CONVERTERS

Medium and High Power

By Dorin O. Neacsu



Taylor & Francis

Taylor & Francis Group

Boca Raton London New York

CRC is an imprint of the Taylor & Francis Group,
an Informa business

Published in 2006 by
CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2006 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group

No claim to original U.S. Government works
Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-10: 0-8247-2625-1 (Hardcover)
International Standard Book Number-13: 978-0-8247-2625-6 (Hardcover)

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. A wide variety of references are listed. Reasonable efforts have been made to publish reliable data and information, but the author and the publisher cannot assume responsibility for the validity of all materials or for the consequences of their use.

No part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC) 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.



Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>

and the CRC Press Web site at
<http://www.crcpress.com>

Preface

Power electronics represents a branch of electronics dedicated to the controlled conversion of electrical energy. This conversion includes the adaptation of power to diverse applications such as voltage or current power sources, electrical drives, active filtering in power systems, electrochemical processes, inductive heating, lighting and cooking control, distributed generation, and naval or automotive electronics. This very broad range of applications has stimulated research and development, and new control methods of power hardware are suggested each day. Because of this great number of technical solutions with many variations of the same concepts, it is somehow difficult for the practicing engineer or for a student to keep track of new developments or to find the most appropriate solution in the given time. Furthermore, medium- and high-power converter systems require interdisciplinary knowledge of basic power electronics, digital control and hardware, sensors, analog preprocessing of signals, protection devices, and mathematical calculus.

Libraries and bookstores offer a great number of books on power electronics, but the dynamics of this field sometimes makes them obsolete. This requires new publications able to systematize the information from research in a better way. This field has a slow incremental development with new ideas on hardware implementation and more comprehensive views on existing methods. The challenge of a first-rate book on power electronics is, therefore, to find the simplest and most concise but complete explanation for a group of methods already proved by both academia and industry.

This book is a digest of the latest research results in the field of medium- and high-power converters presented in a precise manner, with a fair amount of examples and references. From the numerous papers, patents, and research notes published throughout the world during the last 20 years, only those methods accepted by the industry have been selected. The most incisive focus of this book is dedicated to the PWM algorithms, and I hope that this book presents this concept at its best.

The presentation flows from simple facts to advanced research topics, and readers require only a minimal background in electrical engineering or power electronics. Each chapter ends with problems to help the readers improve their understanding of the field. This combination of theory and examples is the result of several years of teaching at different universities as well as vast industrial “hands-on” experience.

This book begins with an industrial overview of power converters and power semiconductors dedicated to medium- and high-power operation, including aspects about the market. After a brief review of power semiconductors in [Chapter 2](#),

[Chapters 3–5](#) define the basics of operating a conventional three-phase inverter with pulse width modulation. [Chapters 6–8](#) are dedicated to the practical aspects of implementation with many examples from the well-known digital platforms used by industry. [Chapters 9–11](#) are dedicated to other special three-phase topologies and their control. [Chapter 12](#) introduces a solution that has been used more frequently during the past few years to achieve higher power from the conventional lower-power converters. The parallel or interleaved operation of conventional three-phase inverters helps increase the power capacity by the addition of multiple low-power units already available on the market.

This book covers the entire field of medium- and high-power converters used nowadays in three-phase DC/AC or AC/DC conversion and can serve as a textbook for graduate students or as a reference book for design engineers working in industry.

Author



Dorin O. Neacsu was born in Suceava, Romania, in 1964. He received M.S. and Ph.D. degrees in electronics from the Technical University of Iasi, Iasi, Romania, in 1988 and 1994, respectively. He also holds an M.Sc. in engineering management from the prestigious Gordon Institute of Tufts University, Medford, Massachusetts. Since 1988, he has been with TAGCM-SUT Iasi, Romania; Technical University of Iasi, Romania; Universite du Quebec a Trois Rivieres, Canada; Delphi-Energy and Engine Management Systems, Indianapolis, Indiana; International Rectifier, El Segundo, California; SatCon

Technology, Cambridge, Massachusetts; and Solecatria Corporation, Woburn, Massachusetts.

Dr. Neacsu has published more than 70 papers and research notes in *IEEE Transactions*, conferences, proceedings, and other international journals; he has presented five tutorials at IEEE conferences and holds one U.S. patent. He has co-written several university textbooks in Canada and Romania and a book on simulation-modeling of power converters. He is a senior member of IEEE, has served as a reviewer for several *IEEE Transactions*, and has been a member of the technical program committees or organizing committees at various IEEE conferences. His research activities are in static power converters, power semiconductor devices, PWM algorithms, microprocessor control, modeling, and simulation of power converters.

Acknowledgments

I would like to thank all the professors, managers, and colleagues who helped in my personal development as an engineer and also in acquiring the knowledge shared in this book. Their leadership and vision in power electronics helped me depict the cutting-edge trends in modern high-power switching converters, and I hope that this book will aid engineers in the field of power electronics to a great extent. “It is the role of leaders to find leaders and to unlock for them the possibility that they can make a positive impact.”

I am grateful to Professors Mihai Lucanu and Dimitrie Alexa, who encouraged me during the initial years at the Technical University of Iasi, Romania. Many of the research results published in this book are the results of the educational programs I attended under their guidance. Special thanks go to Professors Ventakachari Rajagopalan (Canada) and Frede Blaabjerg (Denmark), who introduced me to the IEEE and the world of highly competitive modern technologies.

I would like to thank all my colleagues from the U.S. industry, including Kaushik Rajashekara, James Walters, T.V. Sriram, Fani Gunawan, and Balarama Murty of Delphi Automotive; Toshio Takahashi, David Tam, Brian Pelly, and Eric Person of International Rectifier; Ted Lesser, Bogdan Borowy, William Bonnice, and Evgeny Humansky of SatCon Technology Corporation; and James Worden, Viggo Selchau-Hansen, Lance Haines, Beat Arnet, Lu Jiang, and Don Lucas of Solecstria/Azure Dynamics.

Table of Contents

Chapter 1	Introduction to Medium- and High-Power Switching Converters	1
1.1	Market for Medium- and High-Power Converters	1
1.2	Adjustable Speed Drives	6
1.2.1	AC/DC Converter	6
1.2.2	Intermediate Circuit	7
1.2.3	DC Capacitor Bank	8
1.2.4	Soft-Charge Circuit	8
1.2.5	DC Reactor	9
1.2.6	Brake Circuit	9
1.2.7	Three-Phase Inverter	10
1.2.8	Protection Circuits	10
1.2.9	Sensors	10
1.2.10	Motor Connection	10
1.2.11	Controller	11
1.3	Grid Interfaces or Distributed Generation	12
1.3.1	Grid Harmonics	13
1.3.2	Power Factor	13
1.3.3	DC Current Injection	13
1.3.4	Electro-Magnetic Compatibility and Electro- Magnetic Inference	14
1.3.5	Frequency and Voltage Variations	15
1.3.6	Maximum Power Connected at Low-Voltage Grid	15
1.4	Multi-Converter Power Electronic Systems	16
1.5	Conclusion	17
	References	17
Chapter 2	High-Power Semiconductor Devices	19
2.1	A View of the Power Semiconductor Market	19
2.2	Power MOSFETs	21
2.2.1	Operation	21
2.2.2	Control	26
2.3	Insulated Gate Bipolar Transistors	27
2.3.1	Operation	27
2.3.2	Control, Gate-Drivers	28
2.3.3	Protection	30

2.3.4	Power Loss Estimation	31
2.3.5	Active Gate-Drivers	33
2.4	Gate Turn-Off Thyristors	36
2.5	Advanced Power Devices	36
2.6	Problems	37
	References	37
Chapter 3	Basic Three-Phase Inverters	39
3.1	High-Power Devices Operated as Simple Switches	39
3.2	Inverter Leg with Inductive Load Operation	40
3.3	What Is a PWM Algorithm?	41
3.4	Basic Three-Phase Voltage Source Inverter: Operation and Functions	44
3.5	Performance Indices: Definitions and Terms Used in Different Countries	49
3.5.1	Frequency Analysis	49
3.5.2	Modulation Index for Three-Phase Converters	55
3.5.3	Performance Indices	55
3.5.3.1	Content in Fundamental (z)	55
3.5.3.2	Total Harmonic Distortion (THD) Coefficient	55
3.5.3.3	Harmonic Current Factor (HCF)	55
3.5.3.4	Current Distortion Factor	57
3.6	Direct Calculation of Harmonic Spectrum from Inverter Waveforms	57
3.6.1	Decomposition in Quasi-Rectangular Waveforms	58
3.6.2	Vectorial Method	59
3.7	Preprogrammed PWM for Three-Phase Inverters	60
3.7.1	Preprogrammed PWM for Single-Phase Inverter	61
3.7.2	Preprogrammed PWM for Three-Phase Inverter	64
3.7.3	Binary-Programmed PWM	66
3.8	Modeling a Three-Phase Inverter with Switching Functions	67
3.9	Braking Leg in Power Converters for Motor Drives	68
3.10	DC Bus Capacitor within an AC/DC/AC Power Converter	69
3.11	Conclusion	72
3.12	Problems	72
	References	73
Chapter 4	Carrier-Based Pulse Width Modulation and Operation Limits	75
4.1	Carrier-Based Pulse Width Modulation Algorithms: Historical Importance	75
4.2	Carrier-Based PWM Algorithms with Improved Reference	77

4.3	PWM Used within Volt/Hertz Drives: Choice of Number of Pulses Based on the Desired Current Harmonic Factor	83
4.3.1	Operation in the Low-Frequencies Range (Below Nominal Frequency)	84
4.3.2	High Frequencies (>60 Hz)	86
4.4	Implementation of Harmonic Reduction with Carrier PWM	86
4.5	Limits of Operation: Minimum Pulse Width	89
4.5.1	Avoiding Pulse Dropping by Harmonic Injection	95
4.6	Limits of Operation	101
4.6.1	Deadtime	101
4.6.2	Zero Current Clamping	105
4.6.3	Overmodulation	106
	4.6.3.1 Voltage Gain Linearization	107
4.7	Conclusion	108
4.8	Problems	109
	References	109

Chapter 5	Vectorial Pulse Width Modulation for Basic Three-Phase Inverters	113
5.1	Review of Space Vector Theory	113
5.1.1	History and Evolution of the Concept	113
5.1.2	Theory: Vectorial Transforms and Advantages	114
5.1.2.1	Clarke Transform	116
5.1.2.2	Park Transform	117
5.1.3	Application to Three-Phase Control Systems	118
5.2	Vectorial Analysis of the Three-Phase Inverter	119
5.2.1	Mathematical Derivation of the Current Space Vector Trajectory in the Complex Plane for Six-Step Operation (with <i>Resistive</i> and <i>Resistive-Inductive</i> Loads)	119
5.2.2	Definition of Flux of a (Voltage) Vector and Ideal Flux Trajectory	124
5.3	SVM Theory: Derivation of the Time Intervals Associated to the Active and Zero States by Averaging	126
5.4	Adaptive SVM: DC Ripple Compensation	128
5.5	Link to Vector Control: Different Forms and Expressions of Time Interval Equations in the (d, q) Coordinate System	129
5.6	Definition of the Switching Reference Function	132
5.7	Definition of the Switching Sequence	135
5.7.1	Continuous Reference Function: Different Methods	135
5.7.1.1	Direct-Inverse SVM	135
5.7.2	Discontinuous Reference Function for Reduced Switching Loss	138

5.8	Comparison between Different Vectorial PWM	141
5.8.1	Loss Performance	141
5.8.2	Comparison of Total Harmonic Distortion/HCF	141
5.9	Overmodulation for SVM	143
5.10	Volt-per-Hertz Control of PWM Inverters	144
5.10.1	Low-Frequencies Operation Mode	146
5.10.2	High-Frequency Operation Mode	147
5.11	Conclusion	150
5.12	Problems	150
	References	151

Chapter 6 Practical Aspects in Building Three-Phase Power Converters 155

6.1	Selection of the Power Devices in a Three-Phase Inverter	155
6.1.1	Motor Drives	155
6.1.1.1	Load Characteristics	155
6.1.1.2	Maximum Current Available	155
6.1.1.3	Maximum Apparent Power	155
6.1.1.4	Maximum Active (Load) Power	155
6.1.2	Grid Applications	156
6.2	Protection	156
6.2.1	Overshoot	156
6.2.2	Fuses	159
6.2.3	Overttemperature	162
6.2.4	Oversupply	162
6.2.5	Snubber Circuits	163
6.2.5.1	Theory	163
6.2.5.2	Component Selection	167
6.2.5.3	Undeland Snubber Circuit	168
6.2.5.4	Regenerative Snubber Circuits for Very Large Power	168
6.2.5.5	Resonant Snubbers	169
6.2.5.6	Active Snubbing	172
6.2.6	Gate Driver Faults	173
6.3	System Protection Management	173
6.4	Reduction of Common-Mode EMI through Inverter Techniques	173
6.5	Typical Building Structures of Conventional Inverters	
	Depending on Power Level	177
6.5.1	Packages for Power Semiconductor Devices	177
6.5.2	Converter Packaging	179
6.6	Thermal Management	180
6.6.1	Transient Thermal Impedance	182
6.7	Conclusion	183
6.8	Problems	184
	References	185

Chapter 7	Implementation of Pulse Width Modulation Algorithms	187
7.1	Analog Pulse Width Modulation Controllers	187
7.2	Mixed-Mode Motor Controller ICs	188
7.3	Digital Structures with Counters: FPGA Implementation	190
7.3.1	Principle of Digital PWM Controllers	190
7.3.2	Bus Compatible Digital PWM Interfaces	192
7.3.3	FPGA Implementation of Space Vector Modulation Controllers	192
7.3.4	Deadtime Digital Controllers	196
7.4	Markets for General-Purpose and Dedicated Digital Processors	197
7.4.1	History of Using Microprocessors/Microcontrollers in Power Converter Control	197
7.4.2	DSPs Used in Power Converter Control	200
7.4.3	Parallel Processing in Multi-Processor Structures	202
7.5	Software Implementation in Low-Cost Microcontrollers	203
7.5.1	Software Manipulation of Counter Timing	203
7.5.2	Calculation of Time Interval Constants	204
7.6	Microcontrollers with Power Converter Interfaces	209
7.7	Motor Control Co-Processors	210
7.8	Using the Event Manager within Texas Instrument's DSPs	210
7.8.1	Event Manager Structure	210
7.8.2	Software Implementation of Carrier-Based PWM	211
7.8.3	Software Implementation of SVM	212
7.8.4	Hardware Implementation of SVM	213
7.8.5	Deadtime	215
7.8.6	Individual PWM Channels	216
7.9	Conclusion	216
	References	216
Chapter 8	Practical Aspects of Implementing Closed-Loop Current Control	219
8.1	Role and Schematics	219
8.2	Current Measurement: Synchronization with Pulse Width Modulation	219
8.2.1	Shunt Resistor	219
8.2.2	Hall-Effect Sensors	221
8.2.3	Current-Sensing Transformer	222
8.2.4	Synchronization with PWM	222
8.3	Current Sampling Rate: Oversampling	222
8.4	Current Control in (a, b, c) Coordinates	224
8.5	Current Transforms (3->2): Software Calculation of Transforms	225
8.6	Current Control in (d, q) Models: PI Calibration	226
8.7	Antiwind-Up Protection: Output Limitation and Range Definition	228

8.8	Conclusion	229
	References	229
Chapter 9	Resonant Three-Phase Converters	231
9.1	Reducing Switching Losses through Resonance vs. Advanced Pulse Width Modulation Devices	231
9.2	Do We Still Get Advantages from Resonant High-Power Converters?	234
9.3	Zero Voltage Transition of IGBT Devices	237
9.3.1	Power Semiconductor Devices under Zero Voltage Switching	237
9.3.2	Step-Down Conversion	240
9.3.3	Step-Up Power Transfer	245
9.3.4	Bi-Directional Power Transfer	247
9.4	Zero Current Transition of IGBT Devices	249
9.4.1	Power Semiconductor Devices under Zero Current Switching	249
9.4.2	Step-Down Conversion	252
9.4.3	Step-Up Conversion	255
9.5	Possible Topologies of Quasi-Resonant Converters	258
9.5.1	Pole Voltage	258
9.5.2	Resonant DC Bus	258
9.6	Special PWM for Three-Phase Resonant Converters	260
9.7	Problems	261
	References	261
Chapter 10	Component-Minimized Three-Phase Power Converters	263
10.1	Solutions for Reduction of Number of Components	263
10.1.1	New Inverter Topologies	263
10.1.2	Direct Converters	267
10.2	Generalized Vector Transform	272
10.3	Vectorial Analysis of the B4 Inverter	276
10.4	Definition of PWM Algorithms for the B4 Inverter	281
10.4.1	Method 1	281
10.4.2	Method 2	282
10.4.3	Comparative Results	282
10.5	Influence of DC Voltage Variations and Method for Their Compensation	284
10.6	Two-Leg Converter Used in Feeding a Two-Phase Induction Machine	285
10.7	Conclusion	286
10.8	Problems	287
	References	287

Chapter 11	AC/DC Grid Interface Based on the Three-Phase Voltage Source Converter	291
11.1	Particularities, Control Objectives, and Active Power Control	291
11.2	PWM in the Control System	294
11.2.1	Single-Switch Applications	294
11.2.2	Six-Switch Converters	307
11.3	Closed-Loop Current Control Methods	310
11.3.1	Introduction	310
11.3.2	PI Current Loop	311
11.3.3	Transient Response Times	312
11.3.4	Limitation of the (v_d, v_q) Voltages	313
11.3.5	Minimum Time Current Control	314
11.3.6	Cross-Coupling Terms	314
11.3.7	Application of the Whole Available Voltage on the d -Axis	316
11.3.8	Switch Table and Hysteresis Control	318
11.3.9	Phase Current Tracking Methods	319
11.4	Grid Synchronization	325
11.6	Problems	327
	References	328
Chapter 12	Parallel and Interleaved Power Converters	331
12.1	Comparison between Converters Built of High-Power Devices and Solutions Based on Multiple Parallel Lower-Power Devices	331
12.2	Hardware Constraints in Paralleling IGBTs	333
12.3	Gate Control Designs for Equal Current Sharing	338
12.4	Advantages and Disadvantages of Paralleling Inverter Legs in Respect to Using Parallel Devices	338
12.4.1	Inter-Phase Reactors	339
12.4.2	Control System	340
12.4.3	Converter Control Solutions	340
12.4.4	Current Control	342
12.4.5	Small-Signal Modeling for (d, q) Control in a Parallel Converter System	343
12.4.6	(d, q) versus ($d, q, 0$) Control	346
12.5	Interleaved Operation of Power Converters	347
12.6	Circulating Currents	349
12.7	Selection of the PWM Algorithm	351
12.8	System Controller	352
12.9	Conclusion	354

12.10 Problems	354
References	355