

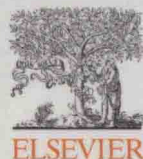
Power Electronics Applied to Industrial Systems and Transports

Nicolas Patin

volume 2

Power Converters and their Control

**ISTE
PRESS**



Series Editor
Bernard Multon

Power Electronics Applied to Industrial Systems and Transports

Volume 2
Power Converters and their Control

Nicolas Patin



First published 2015 in Great Britain and the United States by ISTE Press Ltd and Elsevier Ltd

Apart from any fair dealing for the purposes of research or private study, or criticism or review, as permitted under the Copyright, Designs and Patents Act 1988, this publication may only be reproduced, stored or transmitted, in any form or by any means, with the prior permission in writing of the publishers, or in the case of reprographic reproduction in accordance with the terms and licenses issued by the CLA. Enquiries concerning reproduction outside these terms should be sent to the publishers at the undermentioned address:

ISTE Press Ltd
27-37 St George's Road
London SW19 4EU
UK

Elsevier Ltd
The Boulevard, Langford Lane
Kidlington, Oxford, OX5 1GB
UK

www.iste.co.uk

www.elsevier.com

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

For information on all Elsevier publications visit our website at
<http://store.elsevier.com/>

© ISTE Press Ltd 2015

The rights of Nicolas Patin to be identified as the author of this work have been asserted by him in accordance with the Copyright, Designs and Patents Act 1988.

MATLAB[®] is a trademark of The MathWorks, Inc. and is used with permission.

The MathWorks does not warrant the accuracy of the text or exercises in this book.

This book's use or discussion of MATLAB[®] software or related products does not constitute endorsement or sponsorship by The MathWorks of a particular pedagogical approach or particular use of the MATLAB[®] software.

British Library Cataloguing in Publication Data

A CIP record for this book is available from the British Library

Library of Congress Cataloging in Publication Data

A catalog record for this book is available from the Library of Congress
ISBN 978-1-78548-001-0

Power Electronics Applied to Industrial
Systems and Transports 2

Preface

Volume 2 of this series gives an overview of electronic power converters (DC/DC, DC/AC, AC/DC and AC/AC) as used in industrial and transport applications, notably in variable speed drives. Existing works used in teaching on the subject have paid little attention to the detailed analysis of vector pulse width modulation (PWM) for three-phase inverters, including their impact on the DC power bus. We will attempt to provide this analysis, alongside a presentation of matrix converters (AC/AC conversion) and an introduction to multi-level converters. This volume will also include a case study of the design of a variable speed drive, which constitutes a synthesis of the other subjects tackled in the book (with the exception of direct AC/AC conversion).

This volume also contains two appendices, providing a general formula for electrical engineering and power electronics, and a relatively thorough discussion of the spectrum analysis tools used in power electronics. The formulas supplied in Appendix 1 use elements of electromagnetism which are not covered in this volume; this appendix is, in fact, intended for use with all four volumes of the book. Volume 4 [PAT 15c] is particularly concerned with electromagnetic compatibility, providing a presentation of

radiation disturbances, which requires the use of certain electromagnetic notions. Generally speaking, all chapter references in the appendices specify the volume in question.

Nicolas PATIN
Compiègne, France
February 2015

Contents

PREFACE	ix
CHAPTER 1. DC/DC CONVERTERS	1
1.1. DC motors	1
1.1.1. Electromechanical model	1
1.1.2. Applications	3
1.2. Step-down chopper	3
1.2.1. Structure and general equation model	3
1.2.2. Continuous conduction	4
1.2.3. Discontinuous conduction	9
1.3. Step-up choppers	12
1.3.1. Structure and general equation model	12
1.3.2. Continuous conduction study	13
1.3.3. Discontinuous conduction	17
1.4. Two-quadrant current-reversible chopper	22
1.4.1. Structure and general equation model	22
1.4.2. Step-up and step-down operation	23
1.5. Two-quadrant voltage-reversible chopper	25
1.5.1. Structure and general equation model	25
1.5.2. Operating principle	26
1.6. Four-quadrant chopper	29
1.6.1. Structure and general equation model	29
1.6.2. Control strategy	31

CHAPTER 2. DC/AC CONVERTERS	35
2.1. Single phase inverter and choppers	35
2.2. Control strategies and spectra	36
2.2.1. Full wave modulation	36
2.2.2. Intersective strategies	38
2.2.3. Precalculated PWM	44
2.3. “Value” half-bridge inverters	48
2.4. Three-phase inverter	50
2.4.1. Structure and modeling	50
2.4.2. Modulation by intersective PWM	55
2.4.3. “Full wave” modulation	58
2.4.4. Vector PWM modulation	61
2.4.5. Geometric analysis of the inverter and PWMs	69
2.4.6. Summary of modulation techniques	72
2.5. Impact of the inverter on the DC bus	73
2.5.1. Single-phase inverters	73
2.5.2. Three-phase inverters	75
2.6. Classification of PWM strategies: overview	78
2.7. Closed-loop control	84
2.7.1. Definitions and classification	84
2.7.2. Non-optimal controls	86
2.7.3. Optimal control	95
 CHAPTER 3. AC/DC CONVERTERS	 101
3.1. Non-controlled rectifiers	101
3.1.1. Half-wave rectifiers	101
3.1.2. Full-wave bridges	107
3.2. Rectifier DC output filters	113
3.2.1. LC filters	113
3.2.2. Capacitor filters	118
3.3. Controlled rectification	125
3.3.1. Half-wave bridges	125
3.3.2. Double bridges	126
3.4. Overlap phenomenon	132
3.4.1. Description and model	132
3.4.2. Other rectifier voltage drop-offs	139

3.5. Association of rectifier assemblies	140
3.5.1. Parallel associations and interphase windings	140
3.5.2. Series association	143
3.6. Power factor correction	146
3.6.1. Single-phase PWM rectifier	146
3.6.2. Three-phase rectifier	147
3.6.3. Single-phase rectifier without power reversal	148
3.6.4. Three-phase rectifier without power reversal	153
CHAPTER 4. AC/AC CONVERTERS	161
4.1. Two categories	161
4.2. Dimmers	161
4.2.1. Basic principles	161
4.2.2. Single-phase dimmer	162
4.2.3. Three-phase situation	170
4.2.4. STATCOM	171
4.2.5. PWM dimmers	174
4.3. Choice between PWM, phase angles and wave trains	176
4.4. Cycloconverters	178
4.5. Matrix converters	179
4.5.1. Basic structure	179
4.5.2. Operating principle	183
4.5.3. Switch commutation	187
4.5.4. Switch protection	189
CHAPTER 5. INTRODUCTION TO MULTI-LEVEL CONVERTERS	193
5.1. Context and scope of the study	193
5.2. Cascaded power converters	194
5.2.1. Diode-clamped cells	196
5.3. Imbricated cell converters	199
5.4. Control structures	201
5.4.1. “Unipolar” intersective PWM	202

5.4.2. Interleaved PWM	204
5.4.3. Spectrum comparison of the two strategies	205
5.4.4. Voltage balancing	207
5.5. Note on vector PWM	210
CHAPTER 6. CASE STUDY – THE VARIABLE SPEED DRIVE	215
6.1. Objective	215
6.2. Adequacy of the source/load	216
6.2.1. Source and rectifier	216
6.2.2. Inverter and load	217
6.2.3. Summary	217
6.3. Inverter	218
6.3.1. Current/voltage characteristics	218
6.3.2. Switching frequency	222
6.3.3. Gate drivers	225
6.4. Rectifier and filter	228
6.4.1. Behavior of the rectifier	228
6.4.2. Choke dimensioning	229
6.4.3. Capacitance calculation (rectifier)	230
6.4.4. Inverter/capacitor interactions	231
6.4.5. Capacitor life expectancy	233
6.4.6. Brake chopper	236
6.5. Losses and thermal aspects	241
6.5.1. Summary of losses in the inverter	242
6.5.2. Summary of losses in the brake chopper	244
6.5.3. Calculation of losses in the rectifier	245
6.5.4. Summary of losses	246
6.5.5. Thermal model and heatsinks	246
6.5.6. Transient study	248
APPENDIX 1	253
APPENDIX 2	273
BIBLIOGRAPHY	311
INDEX	319

DC/DC Converters

1.1. DC motors

1.1.1. *Electromechanical model*

A direct current (DC) machine consists of two distinct elements:

- an armature containing a coil, located at the rotor;
- a field coil (or magnets fulfilling the same function) at the stator.

The presence of the field coil means that the armature coil operates within a magnetic flux of ψ_f . When a current i_a is supplied to the armature, is enabled electromechanical energy conversion by creating a motor torque of the form:

$$t_m = k \cdot \psi_f \cdot i_a \quad [1.1]$$

where k is a constant which is characteristic of the machine. Furthermore, we note that the flux ψ_f is:

- either a function of the current i_{exc} circulating in the field coil, if this exists (more precisely, a linear function for a non-saturated machine: $\psi_f = K_\phi \cdot i_{exc}$);
- or a constant $\psi_f = \Psi_f$ in the case of an inductor using permanent magnets.

Due to energy conversion, it is possible to establish that the mechanical and electrical instantaneous powers are identical. Consequently, the machine holds an electromotive force (e.m.f.) e_a such that:

$$e_a \cdot i_a = t_m \cdot \omega \quad [1.2]$$

where ω is the rotation speed of the machine expressed in rad/s. Thus, we obtain:

$$e_a = k \cdot \psi_f \cdot \omega \quad [1.3]$$

As the armature contains a wound coil, we inevitably encounter a resistance R_a and an inductance L_a : consequently, the equivalent electrical model of the DC motor is a series circuit (R_a, L_a, e_a) . For the purposes of our study in the remainder of this chapter, we will use the hypothesis of negligible resistance; consequently, the model of the machine is reduced to a series circuit (L_a, e_a) , and the mechanical inertia J_m of the motor is such that, on the scale of the switching period T_d of the converter (i.e. operating period of the switch), the speed ω may be considered constant (slow evolution across a high number of switching periods – typically, the mechanical time constant of the machine will be around 100 times larger than T_d). Finally, all of our converter studies will be carried out in a steady state, i.e. all of the electrical values (currents and voltages) will be periodical. This hypothesis allows us to postulate that as the voltage V_L at the terminals of inductance L is written as a function of current I_L as follows:

$$V_L(t) = L \frac{dI_L}{dt} \quad [1.4]$$

then we must have

$$\langle V_L \rangle_{T_d} = \frac{1}{T_d} \int_{(T_d)} V_L(t) dt = 0. \quad [1.5]$$

1.1.2. Applications

Mechanical applications are characterized in terms of mechanical couple and speed reversibility; operations are qualified by the number of quadrants used in the torque/speed reference frame. As we see from equations [1.1] and [1.3], there is a direct correspondence between the torque/speed and current/voltage reference frames.

The cases encountered in practice correspond to five different types of converters (choppers):

- one-quadrant chopper, with a single rotation direction in a motor function (step-down chopper);
- one-quadrant chopper, with a single rotation direction in a generating function (step-up chopper);
- two-quadrant chopper, with a single rotation direction for motor or generator functions (current-reversible two-quadrant chopper);
- two-quadrant chopper, with two rotation directions but only one torque – motor or generator direction (voltage-reversible two-quadrant chopper);
- four-quadrant chopper, with two rotation directions and two torques – motor or generator directions (four quadrant, i.e. full bridge chopper).

1.2. Step-down chopper

1.2.1. Structure and general equation model

The structure of a step-down chopper is shown in Figure 1.4. This is a single quadrant converter, used to operate a DC motor in rotor mode with a single rotation direction.

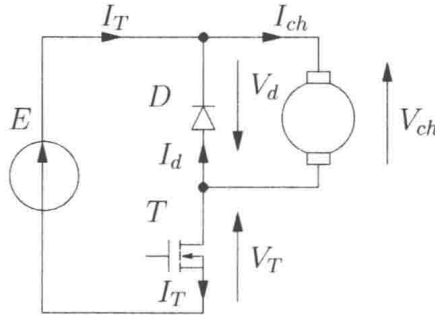


Figure 1.1. *Single quadrant chopper (step-down chopper)*

The equation model of the circuit is based on two independent loops and one node:

$$\begin{cases} E = V_T - V_d \\ -V_d = V_{load} \\ I_{load} = I_T + I_d \end{cases} \quad [1.6]$$

1.2.2. Continuous conduction

In the case of continuous conduction, the operation of the converter over a switching period T_d is split into two distinct phases, with durations of $\alpha.T_d$ (T ON, D OFF) and $(1 - \alpha).T_d$ (T OFF, D ON), respectively.

During the first phase, we control transistor switch-off. Consequently,

$$V_T = 0 \quad [1.7]$$

hence:

$$V_d = -E \quad [1.8]$$

As the voltage at the diode terminals is negative, the diode is switched off:

$$I_d = 0 \quad [1.9]$$

hence:

$$I_T = I_{load} \quad [1.10]$$

This also gives us:

$$V_{load} = E \quad [1.11]$$

In the case of an (L_a, e_a) modeling of the DC motor, supposing that $e_a = E_a = cte$, we may note:

$$L_a \frac{dI_{load}}{dt} = E - E_a \quad [1.12]$$

hence:

$$I_{load}(t) = I_{load}(0) + \frac{E - E_a}{L_a}(t) \quad [1.13]$$

At the end of this phase, we may write:

$$I_{load}(\alpha.T_d) = I_{load}(0) + \frac{E - E_a}{L_a}(\alpha.T_d) \quad [1.14]$$

and the value of $I_{load}(0)$ is, in accordance with the definition of continuous conduction, non-null.

During the second phase, we control transistor switch-on. Hence:

$$I_T = 0 \quad [1.15]$$

At the start of this phase, as I_{load} is non-null and cannot be subject to discontinuity, the diode is switched on:

$$I_d = I_{load} \quad [1.16]$$

We, therefore, write:

$$V_d = 0 \quad [1.17]$$

and, in the load:

$$V_{load} = 0 \quad [1.18]$$

and:

$$V_T = E \quad [1.19]$$

The evolution of the current in the load is, therefore, written as:

$$I_{load}(t) = I_{load}(\alpha.T_d) - \frac{E_a}{L_a}(t - \alpha.T_d) \quad [1.20]$$

Given that the circuit is operating in permanent mode, we note that the voltage at the terminals of the inductance L_a of the machine $V_{load} - E_a$ presents an average value of zero for the switching period T_d ; hence:

$$\begin{aligned} \langle V_{load} - E_a \rangle_{T_d} &= \frac{1}{T_d} \left(\int_0^{\alpha.T_d} (E - E_a) dt + \int_{\alpha.T_d}^{T_d} (-E_a) dt \right) \\ &= \frac{1}{T_d} (\alpha.T_d.(E - E_a) - (1 - \alpha).T_d.(E_a)) = 0 \end{aligned} \quad [1.21]$$

hence:

$$E_a = \alpha.E \quad [1.22]$$