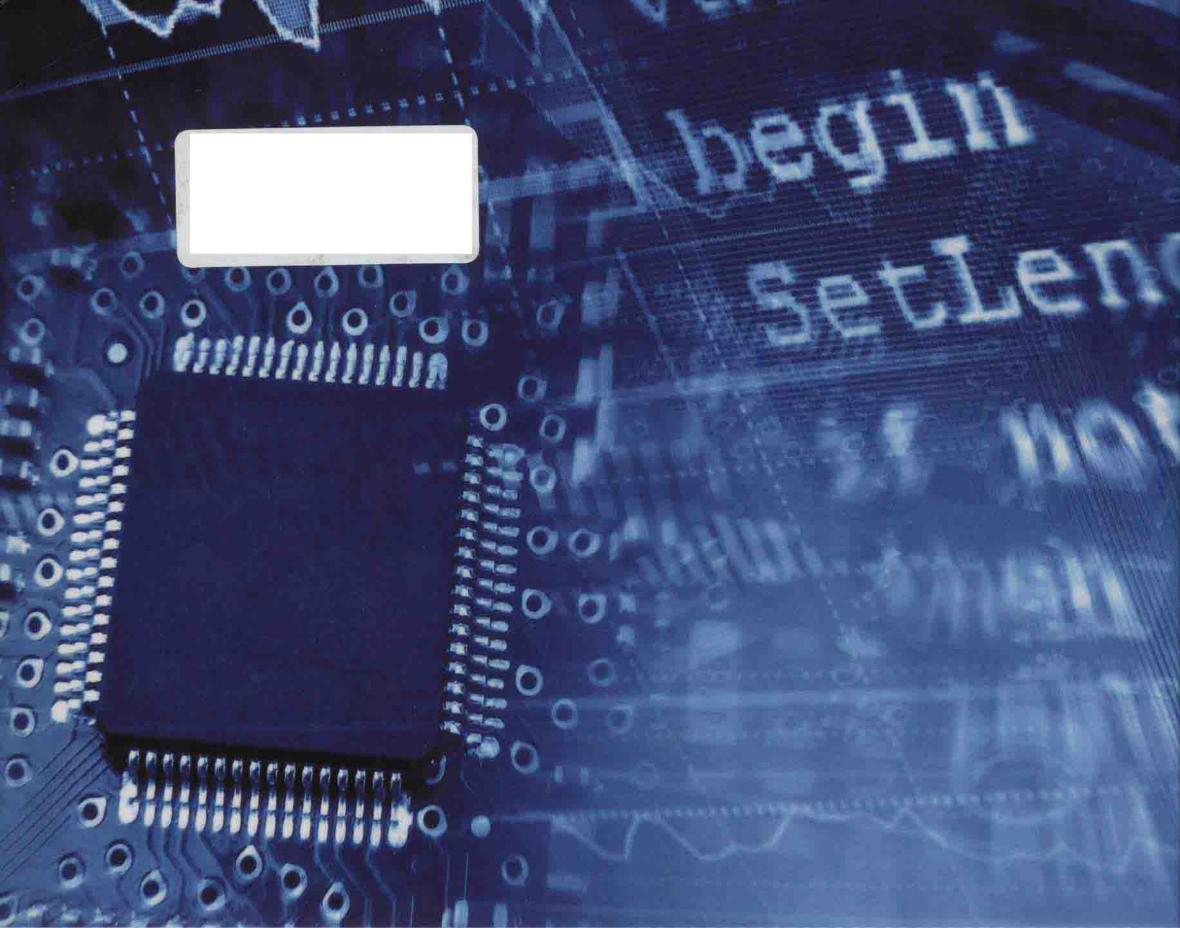

Power Electronics Applied to Industrial Systems and Transports

Nicolas Patin

volume 2

Power Converters and their Control

ISTE PRESS

ELSEVIER

Series Editor
Bernard Multon

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

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

www.iste.co.uk

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

www.elsevier.com

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

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

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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:

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

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: $\psi_f = K_\phi.i_{exc}$);

– 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:

$$e_a.i_a = t_m.\omega \tag{1.2}$$

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

$$e_a = k.\psi_f.\omega \tag{1.3}$$

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:

$$V_L(t) = L\frac{dI_L}{dt} \tag{1.4}$$

then we must have

$$\langle V_L \rangle_{T_d} = \frac{1}{T_d}\int_{(T_d)} V_L(t)\,dt = 0. \tag{1.5}$$

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.

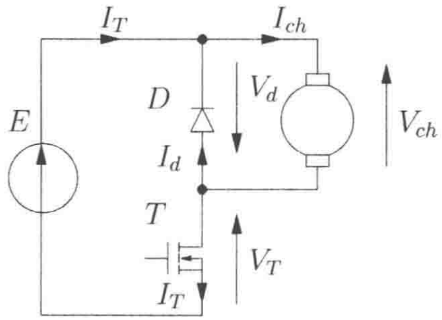

Figure 1.1. *Single quadrant chopper (step-down chopper)*

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:

$$I_d = 0 \tag{1.9}$$

hence:

$$I_T = I_{load} \tag{1.10}$$

This also gives us:

$$V_{load} = E \tag{1.11}$$

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

$$L_a \frac{dI_{load}}{dt} = E - E_a \tag{1.12}$$

hence:

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

At the end of this phase, we may write:

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

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:

$$I_T = 0 \tag{1.15}$$

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:

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

hence:

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