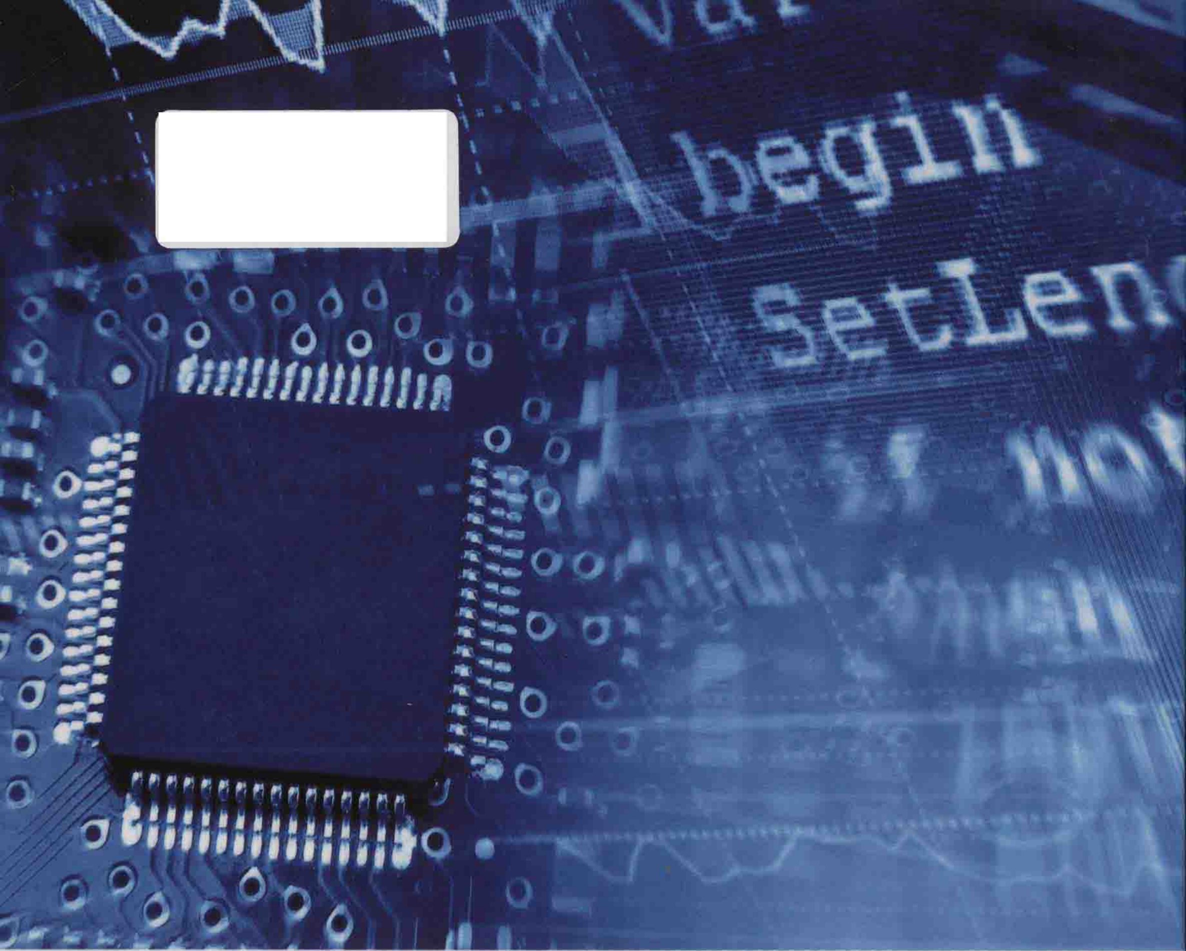

Power Electronics Applied to Industrial Systems and Transports

Nicolas Patin

volume 4

Electromagnetic Compatibility

iSTE PRESS

ELSEVIER

Series Editor
Bernard Multon

Power Electronics Applied to Industrial Systems and Transports

Volume 4
Electromagnetic Compatibility

Nicolas Patin

ISTE PRESS

ELSEVIER

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 978-1-78548-003-4

Printed and bound in the UK and US

Power Electronics Applied to Industrial Systems and Transports 4

Preface

Volume 4 in this book series presents a damaging consequence of switching in converters used in power electronics, studied in the context of a domain known as "electromagnetic compatibility" (EMC). In Volume 1 [PAT 15a], we saw that the switching mode used in converters may seem simplistic in terms of degrees of freedom when controlling the power flowing between a power supply and a load. However, this mode was seen to be satisfactory as long as the load presented an inertia sufficient to avoid effects from voltage of current switching. Once this conceptual difficulty is overcome, the gains in terms of energy efficiency and loss reduction (with associated gains regarding the volume and weight of the converter) are considerable. Unfortunately, this is not the full picture as it does not include electromagnetic interference produced by electronic switches in switching mode as switching occurs very quickly and at an increasingly high speed (switching times lower – sometimes much lower – than 1 microsecond and switching frequencies from a few hundred hertz in high power applications to several megahertz in some low power highly miniaturized switch mode power supplies). In these conditions, the great variation in (potentially high) voltages and currents over time results in the production of variable electrical and magnetic fields, which can generate interference in nearby electronic equipment (including subsystems in the converter itself). EMC can be seen as the study of the interference mechanisms which may exist between equipment creating interference (the source) and equipment subject to interference (the victim). Rules for coexistence are established on this basis in order to guarantee successful operation of elements in proximity to one another. This volume will not focus on the standardization approach (which will, nevertheless, be mentioned in Chapter 1), but will concentrate on the study of disturbance mechanisms and tools used to combat these difficulties.

Sources of interference will be presented in Chapter 1, including artificial sources (such as electronic switches in switching mode) but also natural interference (lightning and static electricity carried by the human body). Clearly, the key element in this chapter will be the pulse width modulation (PWM) waveform, which is the most common source of interference in an electronic power converter. Detailed consideration will, therefore, be given to spectral modeling of the PWM waveform using an innovative approach, not widely used in power electronics, based on the Heisenberg uncertainty principle; this principle is widely used in quantum mechanics and signal theory to analyze the duality between notions of temporal and frequency dispersion of a signal.

Chapters 2 and 3 will focus on the paths taken by electromagnetic disturbances between the emitter and the receiver. In Chapter 2, conducted interference will be discussed and, more generally, interference using electrical couplings with lumped elements will be presented. In this case, propagation may be modeled using an equivalent electrical diagram (potentially including parasitic capacitances or mutual inductances, along with common impedances in cases where circuits are galvanically connected). In Chapter 3, we will discuss propagation mechanisms for which the spatiotemporal dimension cannot be reduced (except by the introduction of a cascade of elementary electrical circuits to take account of the non-infinite speed of field and/or voltage propagation, traveling through the length of the propagation channel). This context clearly includes the case of radiated interference, although the division between Chapters 2 and 3 does not fully conform to the classic separation of conducted and radiated interference generally used when studying the EMC.

Finally, this volume includes two appendices, also included in the previous volumes. Appendix 1 provides general formulas for electrical engineering, and was included in Volumes 1, 2 and 3 [PAT 15a, PAT 15b, PAT 15c]. In this volume, the appendix is particularly useful with regard to the Maxwell equations. Appendix 2 is concerned with spectral analysis, as presented in Volume 2. The Fourier transform, in particular, is an important tool used in Chapter 1 of this volume.

Nicolas PATIN
Compiègne, France
March 2015

Contents

1

Introduction to EMC

1.1. Problems and definitions

All operational electrical or electronic devices produce interference, which may affect the operation of the device itself and/or that of nearby electrical or electronic equipment. Electromagnetic compatibility (EMC) is a domain which is concerned with the coupling of devices and aims to use all possible means to guarantee the "harmonious" operation of a set of nearby, or coupled, equipment. EMC may be compared to a set of rules for "peaceful coexistence", and is based on a set of standards that must be respected. EMC includes both a scientific aspect, which consists of studying the way in which a device interferes with (or pollutes) its environment, via different types of connections to the "victims", and a standardization aspect, concerning the specification of acceptable thresholds for interference emission, and of sensitivity thresholds at victim level.

The nature of interacting equipment is highly variable. In some cases, elements are truly separate (for example, a television and a telephone); however, they may also form part of the same device (for example, the power supply and motherboard of a personal computer (PC)). Generally speaking, interference may propagate along electric wires (or

PCB tracks): this is known as conducted interference. It may also propagate through empty space (i.e. air or a vacuum) in the case of radiated interference.

"Low-frequency" interference is essentially propagated toward victims by conduction, while higher frequencies are mostly propagated by radiation, as the use of filters allows us to prevent their propagation by conduction. This method is relatively cheap (or natural, given the inductive behavior of connection wires and, for example, the capacitive character of PCB tracks with ground and power supply planes). However, further study is required, as components (inductances and capacitors) are not always able to operate at the frequencies in question.

Conducted and radiated interference will be covered in detail in Chapters 2 and 3; in the case of conducted interference, particular attention will be given to the spectral breakdown of interference (notably for applications connected to the 50 Hz) network:

– electrostatic interference (static electricity, a type of interference often ignored in power electronics);

– very low-frequency interference (flicker, $<$10 Hz);

– "low-frequency" harmonic interference, of the order of a few multiples of 50 Hz;

– "medium-frequency" interference, linked to the switching frequency (and to its first multiples, for example, from 10 to 100 kHz for industrial speed variation drives);

– high-frequency (HF) interference, linked to the switching time in the switches ($>$1 MHz);

– environmental interference (cosmic or solar radiation, lightning).

Static interference and very low-frequency interference are specific elements, not directly linked to the switching mechanism; flicker, for example, is linked to variable use (on a human time scale) of electrical energy. "Low-frequency" interference is limited to current switching converters (diodes, thyristors and triacs), and thus also belongs to a specific category.

We will, therefore, focus on the two types of interferences which are most widespread in transistor-based converters (choppers, inverters and switch-mode power supplies) used in forced switching, i.e. "medium and high-frequency" interferences.

Environmental interference and the associated protection equipment will be covered in two specific chapters: one in Chapter 2, in relation to conducted interference, and the other in Chapter 3, concerning radiated interference.

The remainder of this chapter is devoted to sources of interference encountered in power electronics: both "natural" interference (lightning and electrostatic discharge) and artificial interference, created by switching, which is at the heart of the EMC problem for electronic power converters.

1.2. "Natural" interference

1.2.1. *Static electricity*

When two different materials are rubbed together, static electricity may be produced. This is particularly true in relation to the human body and certain fabrics; as the body behaves in a capacitive manner, discharge may occur on contact with electronic circuits. Fragile and/or poorly protected components may be damaged by this phenomenon, so preventive measures should be taken.

The human body has a surface equivalent to that of a sphere with a diameter of 1 m. Considering the capacitance of a spherical capacitor (with two concentric frames of radius r_1

and r_2, where $r_1 < r_2$), direct application of the Gauss formula gives us an expression of the capacitance C as follows:

$$C = \frac{4\pi\varepsilon_0\varepsilon_r}{\frac{1}{r_1} - \frac{1}{r_2}} \qquad [1.1]$$

In this case, regarding the intrinsic capacitance of the human body, the external frame of radius r_2 must be considered to extend to infinity. This gives us the following expression:

$$C_\infty = 4\pi\varepsilon_0\varepsilon_r r_1 \qquad [1.2]$$

As we live in air, $\varepsilon_r = 1$, giving a capacitance of 56 pF for $r_1 = 0.5$ m.

This capacitance is clearly affected by proximity to the ground, which adds around 100 pF, and additional capacitances may be added, linked to walls or furniture located close to the body (varying from approximately 50 to 100 pF). This gives an overall parallel association of capacitances of around 200 pF. Note, moreover, that this capacitance is not the only element in the equivalent model of the body when charging or discharging: skin contact is resistive, with a value varying from 500 Ω to 10 kΩ for different individuals and according to the contact surface (the end of a finger or the palm of a hand); this value is also affected by the humidity of the skin. Thus, the human body can be assimilated to a series R, C circuit (an inductance may even be included, with a value of less than 100 nH).

Electrostatic charge can easily reach very high values without the individual in question being aware of it, as voltages under 3.5 kV cannot be felt. Table 1.1 shows two examples of charges produced by walking on two different materials and for two different levels of air humidity.