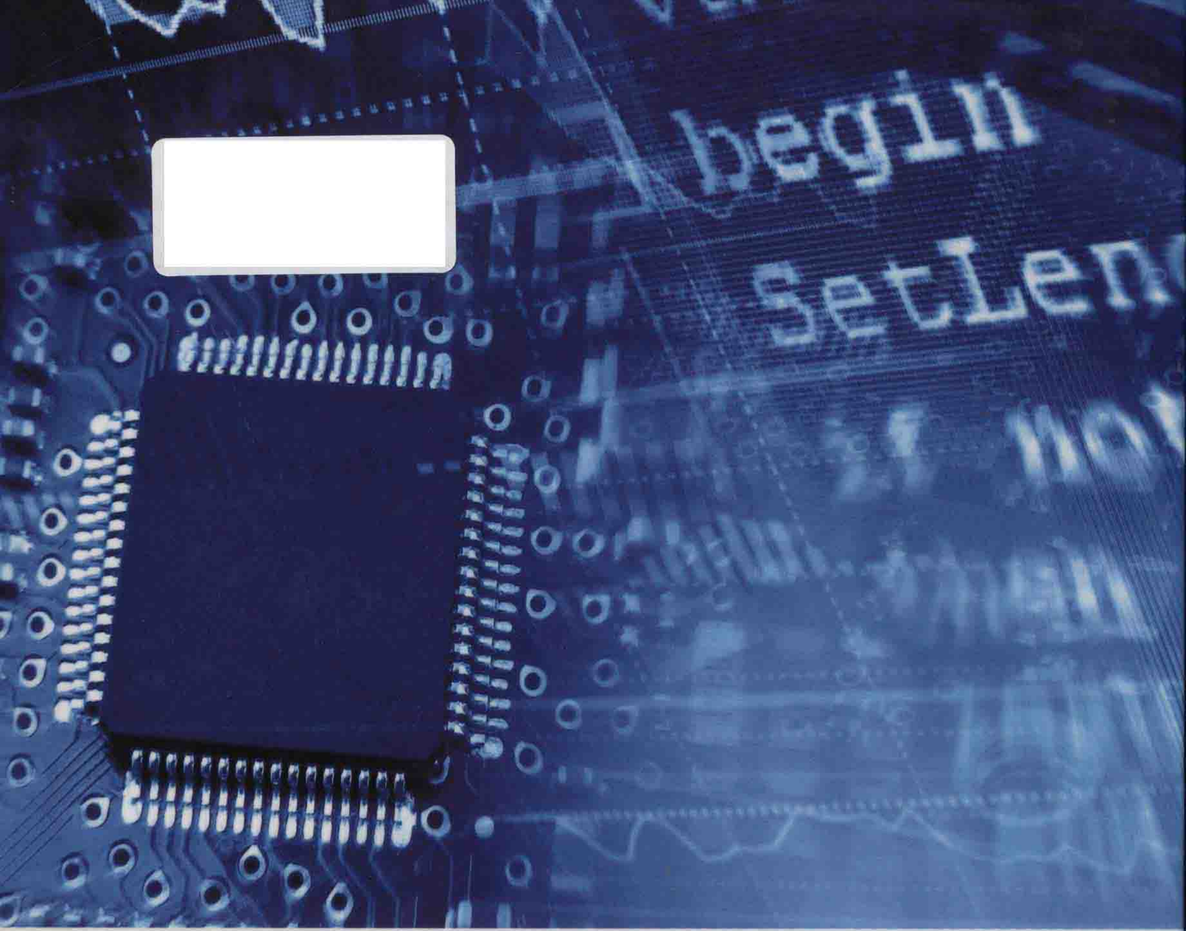

Power Electronics Applied to Industrial Systems and Transports

Nicolas Patin

volume 1

Synthetic Methodology to Converters and Components Technology

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Power Electronics Applied to Industrial Systems and Transports 1

Preface

The purpose of this series of books is to give an in-depth presentation of the field of power electronics. It will be split into four volumes, comprising a total of 21 chapters (plus appendices).

Volume 1 is aimed at introducing essential notions in power electronics from both theoretical and technological perspectives, with a focus on source connection rules, reversibility and the impact on the choice of switches for converter synthesis. Concerning technological aspects, the standard active components will be presented from a "user" perspective, and include certain elements regarding their packaging and thermal characteristics, with electrical modelings which are equivalent in terms of both permanent and transient modes. This aspect will be presented from a "user" perspective with a focus on the selection and dimensioning of cooling equipment. We will also consider component control (transistors, thyristors, triacs, etc.) and snubbers. The local environment of electronic switches will therefore be covered in some detail. A separate chapter is devoted to passive components (capacitors and magnetic components – inductors and transformers), highlighting the criteria involved in the choice of capacitors based on the technologies and limitations of each option. We will provide a more detailed discussion of magnetic components, with a guide to the choice of magnetic circuits (materials and layout) and the dimensions of windings (number of turns, use of Litz wires, etc.). The final chapter will consider the elements involved in the design and production of printed circuits.

Volume 2 [PAT 15a] will deal with industrial applications, notably those linked to transporting electronic power converters, with a focus on power supplies for electrical machinery. We will consider different types of DC/DC, DC/AC, AC/DC and AC/AC converters. We will also provide an introduction to multi-level converters (primarily in the context of inverters). The final chapter of this volume presents a case study involving full dimensioning of an industrial variable-speed drive.

Volume 3 [PAT 15b] is concerned with converters (essentially of the DC/DC variety) in the context of switch-mode power supplies, another key area in which power electronics is used is in the supply of energy to a variety of electronic equipment for signal and information processing. We will also discuss the dimensioning of inductors and HF transformers. Volume 3 also provides an introduction to soft switching, using the specific example of a DC/DC converter using a resonant inverter. A further chapter in this volume is devoted to modeling in the context of controlling switch-mode power supplies, based on Middlebrook's equivalent average models. Finally, as in Volume 2, a case study will be used to provide a thorough overview of the design of a digitally-controlled Flyback power supply, used for practical exercises at the UTC.

Volume 4, [PAT 15c] the last volume in the series, is devoted to electromagnetic compatibility, and is divided into three chapters. In Chapter 1, we will introduce and discuss the modeling of common sources of disturbances before considering case studies in Chapters 2 and 3 in order to gain an understanding of the pathways taken by these disturbances to reach their targets. This chapter structure does not fully conform to the usual notions of conducted and radiated disturbances, but distinguishes between "circuit" couplings (i.e. localized constant models – Chapter 2) and those involving propagation phenomena (i.e. distributed constant models – Chapter 3).

The case study chapters should not be considered simply as applications of the theoretical concepts developed in other chapters: certain concepts (both technological and practical) are introduced using these examples, in situations where these specific cases are sufficiently representative of a wide range of applications.

Finally, three appendices cover the usual formulas used in power electronics and electrical engineering (Appendix 1, see Volumes 1–4), a detailed presentation of spectrum analysis for periodic and non-periodic signals (Appendix 2, see Volumes 2 and 4) and a compilation of technical documentation for the components discussed elsewhere in the book (Appendix 3, see Volume 3).

This book forms the basis for power electronics teaching at the *Université de Technologie de Compiègne* (UTC, or Compiègne Technological University), in France. The first of the two modules on offer exclusively covers power electronics, including all of the families of converters presented in Volume 2. The main focus of this module is on power supplies for electrical apparatus, both in industry and for transportation. The module is offered exclusively to students in the Mechanical Engineering Department at the UTC, specifically to those following the Mechatronics, Actuators, Robotics and Systems (MARS) course. Switch-mode power supplies (Volume 3) are covered as part of a general module on electronic functions for engineering, with a lecture, seminar and practical session devoted to the subject, based on a flyback-type power supply. This more general module has a wider audience and is also offered to students in biological engineering with a specialization in biomedical sciences. This series of books therefore takes a broad approach to the elements covered in the second module, covering both the different converter topologies used in designing switch-mode power supplies and the design methodology involved (notably through a case study). We also cover certain aspects of control, more specifically control-based modeling, in order to produce usable models using automatic methods to regulate the output voltage independently of variations in load consumption. EMC (Volume 4) is also covered as part of this more general module, but is only touched on briefly.

Nicolas PATIN
Compiègne, France
December 2014

Introduction

I.1. Generic structure of an industrial variable-speed drive

A variable-speed drive such as the one shown in Figure I.1 is a useful subject for study as it allows us to include most of the functions involved in power electronics; furthermore, devices of this type are widely used in an industrial context. Factories are generally powered by a fixed-frequency alternating network (230–400 V/50 Hz in France), and most of the electrical machines (robots, conveyors, machine tools, etc.), which are used in production lines, with a power requirement of greater than or equal to 1 kW (the most widespread), use a three-phase alternating current (AC) (these are usually induction machines with squirrel cage rotors, or, more rarely, permanent magnet synchronous machines).

In the cases where a variable speed function is required, these machines require a power supply with a variable frequency (and amplitude). However, the electrical network provides a fixed frequency. As we will see, it is easier to produce voltages of variable frequency (and amplitude) using a continuous source (using an *inverter*) than to transform an AC of frequency f_1 into a new AC with frequency $f_2 \neq f_1$ (the device used for this purpose is known as a *cycloconverter* and will be presented in Chapter 1, but will not be studied in detail as they are no longer widely used). The following chapters will highlight the *modular nature of electronic power converters*, as in the case of the variable speed-drive shown in Figure I.1. This device uses a *rectifier*, which allows us to pass from the *AC with fixed amplitude and frequency* provided by the power network to the continuous supply required by the *inverter* to produce a network with an *AC with variable amplitude and frequency* for the electrical device in question. The insulated gate bipolar transistors (IGBT) inverter acts as a rectifier (during machine braking phases), but the diode rectifier used here is unable to return this electrical energy to the network. This means that a *brake chopper* is needed to consume this excess energy. These different converters will be covered, in turn, over the course of the following chapters.

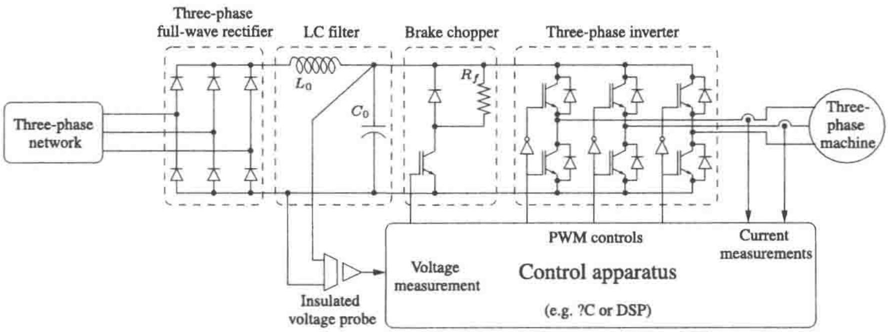

Figure I.1. *"Typical" power design of an industrial variable-speed drive*

Before beginning our study of different converter layouts, it is important to consider the specificities of power electronics. This domain involves the control of electrical power, from the power supply to the powered load. The uses of this function are evident, but the methods used need to be covered in more detail.

I.2. Specificities of power electronics

I.2.1. *Distinction between signals and energy*

Unlike the branch of electronics that concerns *information processing* equipment (whether analog or digital, using operational amplifiers, A/D or D/A converters, microprocessors, microcontrollers or other programmable or non-programmable digital circuits), power electronics focuses on *constructions that process and transform electrical energy to respond to a need.* Nevertheless, there are certain similarities between the processing of digital information (digital electronics) and power electronics, due to the way in which electronic components function in switching operations. In power electronics, transistors (among other components) are used in turned off/saturated mode, which renders them equivalent to open or closed switches. While these modes of operation are similar, they do not however concern the same objectives. In digital electronics, this type of function serves multiple purposes. Examples include:

– noise immunity in digital circuits;

– programming new functions in an unmodified physical circuit[1];

– improved integration (smaller circuits).

In power electronics, however, the sole aim of using switch functions in components is to *maximize efficiency* (and therefore *minimize loss*) in the converter.

I.2.2. *Commutations and losses*

The interest of switching-based functions may be observed by studying the (simple) construction shown in Figure I.2.

1 Note that programmable analog circuits do exist, but these too use switches – see *switched capacitor filters* [GHA 03].

This construction is made up of an input voltage source E (e.g. a battery) connected to an association in series with a resistance R (modeling, e.g. a lamp, a heating element, etc.) and a transistor T (in this case, an NPN bipolar transistor).

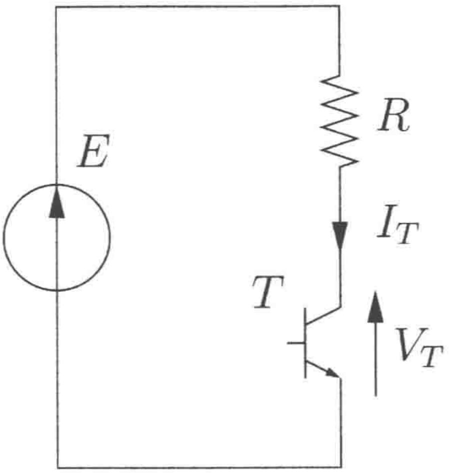

Figure I.2. *"Simple" power modulation circuit*

The equation of this simple single-loop circuit is easy to establish:

$$E = R.I_T + V_T \quad [I.1]$$

The operating point of this circuit is (graphically) the intersection between the characteristic $V_T(I_T)$ of the transistor T and the load line $V_T = E - R.I_T$ produced by equation [I.1], as shown in Figure I.3. Note that the characteristic of the transistor is linked to the command signal applied at the base. For example, the operating point M corresponds to a base/emitter voltage $V_{BE} = V_{BE5}$: we thus obtain a voltage of V_{T0} between the collector and the emitter of the transistor, and the current I_T traveling through the transistor is equal to I_{T0}. The power dissipation of any dipole is the product of voltage $\times$ current, in this case $V_T.I_T$. The temperature of a component is directly linked to the power dissipation, and constructor documentation for electronic components specifies a maximum junction temperature for operation without damaging the component. Consequently, an electronic component (associated with correctly dimensioned cooling equipment) may be characterized by a maximum power $P_{\max}$. The *isopower curve* $P_T = V_T.I_T = P_{\max}$ is shown in dotted lines in Figure I.3. We see that point M lies above this curve, and cannot therefore be accessed in steady state. In fact, use of the transistor in the linear zone leads to significant overdimensioning in relation to the power required by the load. This is generally the case for low-power requirements (e.g. class A audio amplifiers) but is not possible for high powers when a high yield is required, notably for equipment with integrated energy, where priority is given to autonomy and/or compactness (using smaller, lighter thermal dissipation elements).

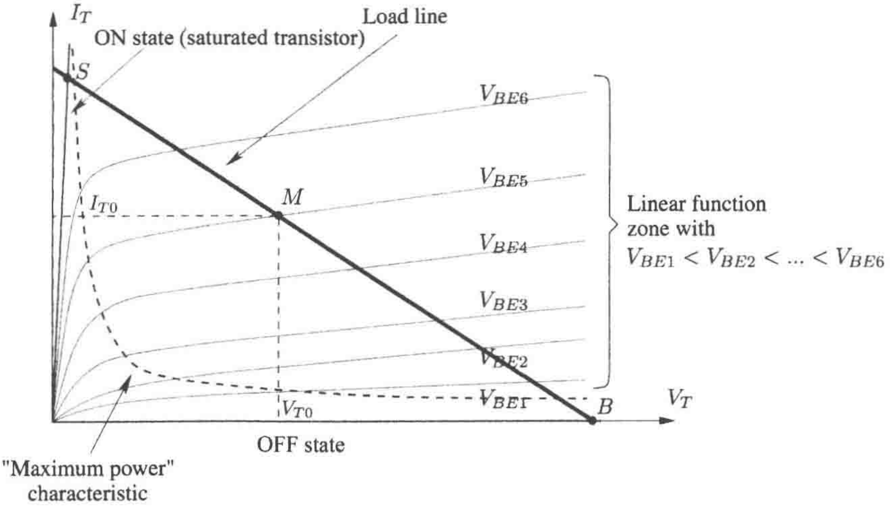

Figure I.3. *Operating point of the circuit*

However, the use of the "turned off" and "saturated" transistor modes alone seems to be limiting in terms of the dosage of the power supplied to the load, in which we must either provide no power, in cases where the transistor is operating as an open switch (point B), or maximum power, practically equal to E^2/R, if the transistor is saturated (closed switch – point S).

I.2.3. *Load inertia and average model*

The disadvantage presented by the ON/OFF operating mode for transistors, as discussed above, does not pose significant problems in practice for most applications, due to the *inertia of the powered load*. The transistor is assimilated to a switch, but, unlike in electromechanical models, this switch may operate using very short open/closed cycles (duration denoted as T_d, the *switching period*) without incurring damage. It is thus possible to make cycles sufficiently short for the powered load to be perfectly insensitive to commutation; it therefore behaves in a manner that is *equivalent to a linear power supply with a voltage equal to the average voltage supplied by the switching circuit*. The period T_d must be short in relation to the time constant of the load:

– thermal time constant for a heating element (generally high – from a number of seconds to a number of minutes in the case of ovens);

– thermal time constant, again, for the filament of an incandescent light bulb (tens or hundredths of a millisecond);

– biological time constant of persistence of vision for a rapid light source[2] such as white LEDs[3]($T_d < 40$ ms).

An LED powered with a nominal voltage/current 50% of the time will produce a light flow equal to 50% of the nominal flow.

This very general principle also applies to electrical machines, and progress in the design of electronic

2 This is necessary in order to avoid flickering that may be uncomfortable for the user of the light source.

3 LED = light emitting diode

components means that we can now attain frequencies of the order of around 10 kHz for industrial variable-speed drives with power levels greater than or equal to 1 kW. Evidently, switches commutating low-power levels can reach higher switching frequencies than high-power switches: these components themselves are subject to the same inertia problems as the loads they power. Note, for example, that switching frequencies are often lower than 1 kHz for motors with power levels measured in megawatts, such as those used in railway engines.

I.3. Families of converters

I.3.1. *Classification of structures*

The most obvious classification system for a first analysis of electronic power converters consists of differentiating between contexts of use. Sources, in the broadest sense (including loads), which are interconnected by converters, may be split into two main families:

– direct current (DC) sources;

– AC sources.

Consequently, when imagining a converter involving two different sources, we can identify $2^2 = 4$ distinct types (plus a fifth type due to the two available types of AC/AC converter):

– DC/DC converter, known as a *chopper*;

– DC/AC converter, known as an *inverter*;

– AC/DC converter, known as a *rectifier*;

– AC/AC converters, known as *dimmers* if the input and output frequencies are the same, or *cycloconverters* if this is not the case.

These different configurations are shown in Figure I.4.

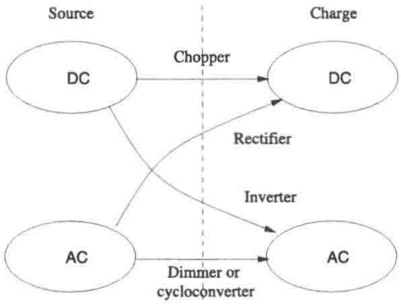

Figure I.4. *Converter structures*

I.3.2. *Typical waveforms*

Before going into detail analyzing the structures of electronic power converters, we should illustrate their operation using the waveforms of the voltages they may supply to a load in order to show their ability to modulate the transmitted energy. Figure I.5 shows the possible output waveforms of a chopper, while Figure I.6 shows the voltage waveforms produced by an inverter. Figures I.7 show the waveforms generated by dimmers commanded, respectively, by "phase angles" (e.g. for lighting) and "wave trains" (for high-power levels, e.g. for heating).

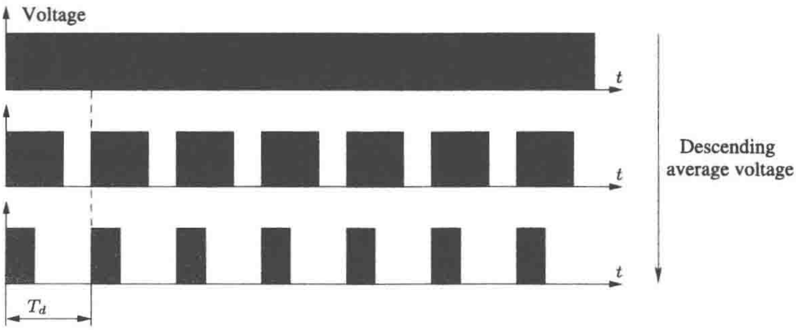

Figure I.5. *Output voltage waveforms from a chopper*