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Introduction to Modern Power Electronics

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PREFACE

This book is primarily intended for a one-semester introductory course in power electronics at the undergraduate level. However, containing a comprehensive overview of modern tools and techniques of electric power conversion, it can also be used in more advanced classes, at least as a complementary text. Practicing engineers wishing to refresh their knowledge of power electronics or interested in branching into that area are also envisioned as potential readers. The students are assumed to have the working knowledge of electric circuit analysis (dc, ac, and transient) and basic electronics.

Following recent trends in electrical power conversion, more stress has been placed on pulse width modulated (PWM) converters than in any other existing textbook. Coupled with the description of such seldom-covered concepts as matrix converters or multilevel inverters, it should make the reader well acquainted with the realm of modern power electronics.

In contrast with most books that begin with a general introduction devoid of detailed information, Chapter 1 constitutes a very important part of the teaching process. Employing a hypothetical generic power converter, basic principles and methods of power electronics are thoroughly explained. Therefore, whatever content sequence an instructor wants to adopt, Chapter 1 should be covered first.

Chapters 2 and 3 provide description of semiconductor power switches and complementary components and systems of power electronic converters. The reader should be aware of the existence and function of those auxiliary but important parts, omitted from consideration in the subsequent chapters.

The four fundamental types of electrical power conversion: ac to dc, ac to ac, dc to dc, and dc to ac, are covered in Chapters 4 through 7, respectively. Chapter 7, on power inverters, is the longest in the book, reflecting the great importance of those converters in modern power electronics. Chapter 8 is devoted to switching dc power supplies. Each chapter begins with an abstract and, after the main body, includes a brief summary. Numerical examples, homework problems, and computer assignments complement most chapters. A few relevant and easily available references are provided after each of them. Three appendices conclude the book.

The textbook is accompanied by a series of forty-eight PSpice circuit files constituting a virtual power electronics laboratory, and available on the Internet at *ftp://ftp.wiley.com/public/sci_tech_med/power_electronics*. The files contain models of most power electronics converters covered in the book, and they form a valuable teaching tool, giving the reader an opportunity to "tinker" with the converters and visualize their operation. Instructors are also encouraged to use catalogs of power electronic converters, switches, and other components, to provide the students with up-to-date samples of contemporary commercial technologies and products. Such catalogs are easy to acquire at professional conferences and exhibitions, or directly from distributors.

Compared with most of the contemporary engineering textbooks, the book is quite concise. Still, covering the whole material in a single-semester course will be difficult, unless the students are expected (and willing) to carry a heavy home-study burden. Therefore, selection of the topics to be taught in detail is left to the instructor. The suggested approach would consist in presenting the basic issues in class and letting the students broaden their knowledge through reading assignments, homework problems, and PSpice simulations.

I want to express my gratitude to Dr. Frede Blaabjerg of the Aalborg University and Dr. Stanislaw Legowski of the University of Wyoming, both my long-time research collaborators, for fruitful discussions that have enriched the book. The unknown Reviewers have greatly enhanced the quality of the text, and their most valuable comments and suggestions are warmly appreciated. Finally, my wife, Dorota, and my children, Bart and Nicole, receive apologies for my long preoccupation, and many thanks for their unwavering support.

CONTENTS

1 Principles and Methods of Electric Power Conversion

This introductory chapter provides a background for the subject of the book. The scope, tools, and applications of power electronics are briefly described. The concept of generic power converter is introduced to illustrate the principles of operation of power electronic converters and types of power conversion performed. Components of voltage and current waveforms and the related figures of merit are defined. Two basic magnitude control methods, the phase control and pulse width modulation, are presented. Determination of output current waveforms is explained. Single-phase diode rectifiers are used as simple examples of practical power converters.

1.1 WHAT IS POWER ELECTRONICS?

Modern society with its conveniences strongly relies on the ubiquitous availability of electric energy. Electricity performs most of the physical labor, provides the heating and lighting, activates electrochemical processes, and facilitates the information gathering, processing, storage, and exchange.

Contemporary power electronics can be defined as a *branch of electrical engineering devoted to conversion and control of electric power using electronic converters based on semiconductor power switches*. The existing power systems deliver an ac voltage of fixed frequency and magnitude. Typically, homes, offices, stores, and similar facilities are supplied from single-phase, low-voltage power lines, while three-phase supply systems with various voltage levels are available in industrial plants. The 60-Hz (50-Hz in most other parts of the world) fixed-voltage electric power can be thought of as a *raw power* that, for many applications, must be *conditioned*. The power conditioning involves *conversion*, from ac to dc or vice versa, and *control* of the magnitude and/or frequency of voltages and currents. Using electric lighting as a simple example, an incandescent bulb can directly be supplied with the raw power. However, a fluorescent lamp requires an electronic ballast that starts the arc and controls the current to maintain the desired light output. The ballast is thus a power conditioner, necessary for proper operation of the lamp. The same incandescent bulb mentioned before, if used in a movie theater, is supplied from an ac voltage controller that allows gradual dimming of the light just before the movie begins. This controller represents again an example of a power conditioner, or *power converter*.

Although the birth of power electronics can be traced back to the dawn of this century when the first mercury-arc rectifiers were invented, *rotating electromachine converters* were primarily used for the conversion and control of electric power in the past. An electromachine converter was simply an electric generator driven by an electric motor. If, for instance, an adjustable dc voltage was to be obtained from a fixed ac voltage, an ac motor was used to operate a dc generator with controlled output voltage. Conversely, if an ac voltage was required and the supply energy came from a battery pack, a speed-controlled dc motor and an ac synchronous generator were employed. Clearly, the convenience, efficiency, and reliability of such converters are inferior in comparison with their *static,* power electronic equivalents, in which no mechanical motion or multistage energy conversion take place.

Today's power electronics began with the development by the General Electric Company of the *silicon-controlled rectifier* (SCR), also called a *thyristor*, in 1958. The SCR is a unidirectional semiconductor power switch that can be turned on (closed) by a low-power electric pulse applied to its controlling electrode, the gate. The voltage and current ratings of SCRs are the highest available of all types of semiconductor power switches. However, the SCR is inconvenient for use in dc-input power electronic converters because, when conducting a current, it cannot be turned off (opened) by controlling the gate. Thus, the SCR is a *semicontrolled* switch. Several kinds of *fully controlled* semiconductor power switches, turned on and off by an electric signal, have been introduced to the market, especially within the last two decades. These switches, as well as the SCR, are described in detail in Chapter 2.

A widespread introduction of power electronic converters to most areas of distribution and usage of electric energy is common for all developed countries. The converters condition the electric power for a variety of applications, such as electric motor drives, uninterruptable power supplies, heating and lighting, electrochemical and electrothermal processes, electric arc welding, high-voltage dc transmission lines, active power filters and reactive power compensators in power systems, and regulated supply sources for computers and other electronic equipment.

It is estimated that by the end of the century as much as 60% of the electric power generated in the USA will flow through power electronic converters, with a raise of this share to almost 100% in the following few decades. In particular, a thorough revamping of the existing U.S. power system is envisioned under the FACTS program initiated by the Electric Power Research Institute. Introduction of power electronic converters to all stages of power generation, transmission, and distribution will allow a dramatic increase of the system's capability without investment in new power plants and transmission lines. The important role of power electronics in electric vehicles is also worth stressing. Therefore, it is safe to predict that practically every electrical engineer will encounter some power electronic converters in his or her professional career.

Types of the electric power conversion and the corresponding converters employed in contemporary power electronics are presented in Figure 1.1. For instance,

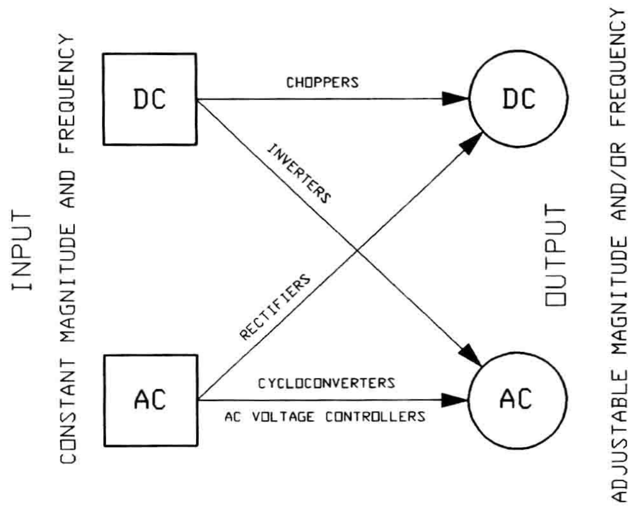

Figure 1.1 Types of electric power conversion and corresponding power electronic converters.

ac to dc conversion is accomplished using rectifiers, which are supplied from an ac source and whose output voltage contains a significant, fixed or adjustable, dc component. Individual kinds of power electronic converters are described and analyzed in Chapters 4 through 8. Basic principles of power conversion and control are explained in the following sections of this chapter.

1.2 GENERIC POWER CONVERTER

The hypothetical *generic power converter*, shown in Figure 1.2, although not a practical apparatus, is a useful teaching tool for illustration of the principles of electric power conversion and control. It is a two-port network of five switches. Switches S1 and S2 provide *direct connection* between the input (supply) terminals, I1 and I2, and the output (load) terminals, O1 and O2, respectively, while switches S3 and S4 allow *cross connection* between the input and output terminals. A supply source, typically a voltage source, either dc or ac, feeds electric power to a load through the converter. Practical loads usually contain a significant inductive component and, therefore, a resistive-inductive load (RL load) is assumed in the subsequent considerations. To maintain a closed path for the load current, a fifth switch, S5, is connected between the output terminals of the converter, and closed when switches S1 through S4 are open. It is assumed that the switches open or close instantaneously and simultaneously.

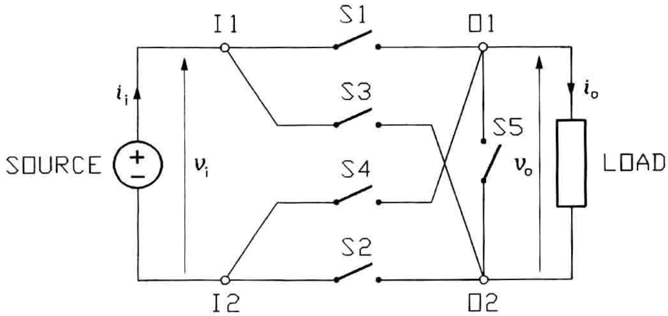

Figure 1.2 Generic power converter.

The supply source is assumed to be an ideal voltage source and as such it may not be shorted. Also, the load current may not be interrupted, for it would cause a rapid release of the electromagnetic energy accumulated in the load inductance. As a result, a high and potentially damaging overvoltage would occur. Therefore, the generic converter can only assume the following three states:

(1) State 0: Switches S1 through S4 are open and switch S5 is closed, shorting the output terminals and closing a path for the output current, if any. The output voltage is zero. The input terminals are isolated from the output terminals so that the input current is also zero.

(2) State 1: Switches S1 and S2 are closed, and the remaining ones are open. The output voltage equals the input voltage and the output current equals the input current.

(3) State 2: Switches S3 and S4 are closed, and the remaining ones are open. Now, the output voltage and current are reversed with respect to the input voltage and current, respectively.

For illustration of the voltage and current waveforms, specific values of the input voltage and RL load of the generic converter were assumed. The amplitude of the input voltage was taken as 100 V, for both the ac and dc voltage considered, and the load resistance and inductance were assumed to be 1.3 Ω and 2.4 mH, respectively. These data were needed for preparation of the subsequent figures and in example calculations in the next section. However, for generality, the waveforms will be shown without the magnitude scale.

Let us assume that the generic converter is to perform the ac to dc conversion. The sinusoidal input voltage, v_i, whose waveform is shown in Figure 1.3, is given by

$$v_i = V_{i,p}\sin(\omega t) \tag{1.1}$$

where $V_{i,p}$ denotes the peak value (amplitude) of the voltage and ω is the input radian frequency. The output voltage, v_o, of the converter should contain a possibly

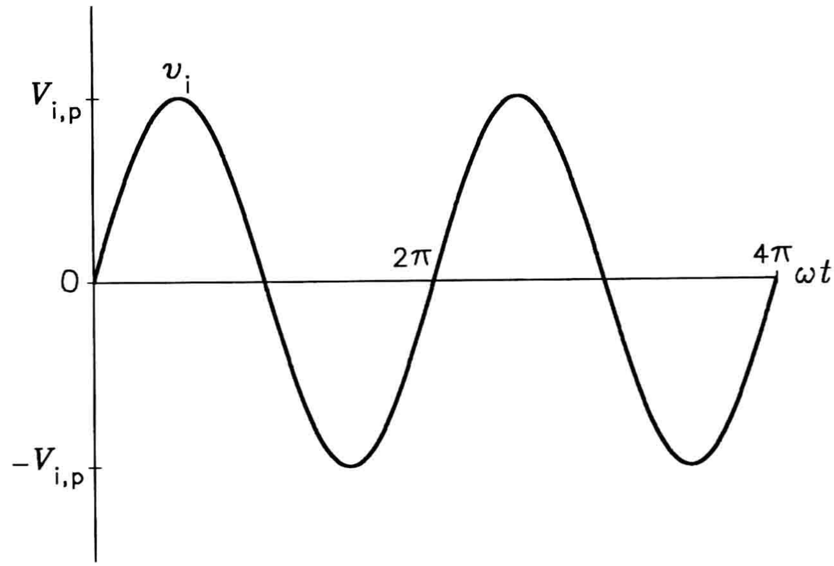

Figure 1.3 Ac input voltage waveform.

large dc component. Note that the output voltage is not expected to be of an ideal dc quality, since such voltage and current are, generally, not possible to obtain in the generic converter as well as in practical power electronic converters. The same applies to ideally sinusoidal voltages and currents in ac-output converters. If within the first half-cycle of the input voltage the converter is in State 1 and within the second half-cycle in State 2, the output voltage waveform will be such as depicted in Figure 1.4, that is,

$$v_o = |v_i| = V_{i,p}|\sin(\omega t)|. \tag{1.2}$$

The dc component represents the average value of the voltage. Power electronic converters performing the ac to dc conversion are called *rectifiers*.

The output current waveform, i_o, can be obtained as a numerical solution of the load equation

$$L\frac{di_o}{dt} + Ri_o = v_o. \tag{1.3}$$

Techniques for analytical and numerical computation of voltage and current waveforms in power electronic circuits are described at the end of this chapter. Here, only general features of the waveforms are outlined. The output current waveform of the generic rectifier under consideration is also shown in Figure 1.4, and the consecutive states of the converter are indicated there. It can be seen that this waveform is closer to an ideal dc waveform than is the output voltage waveform, because of

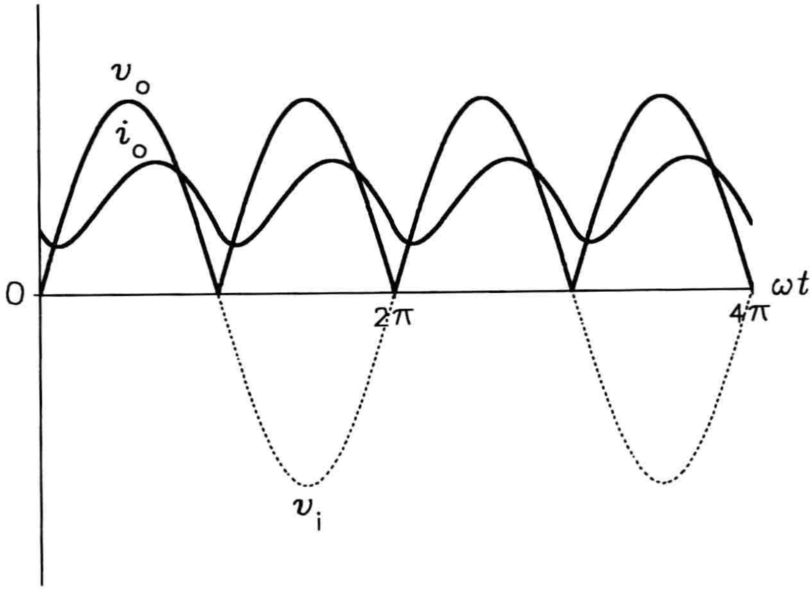

Figure 1.4 Output voltage and current waveforms in the generic rectifier.

the frequency-dependent load impedance. The k^{th} harmonic, $v_{o,k}$, of the output voltage produces the corresponding harmonic, $i_{o,k}$, of the output current such that

$$I_{o,k} = \frac{V_{o,k}}{\sqrt{R^2 + (k\omega_o L)^2}} \tag{1.4}$$

where $I_{o,k}$ and $V_{o,k}$ denote rms values of the current and voltage harmonics in question, respectively. The fundamental radian frequency, ω_o, of the output voltage is twice as high as the input frequency, ω. The load impedance for individual current harmonics, represented by the denominator at the right-hand side of Eq. (1.2), increases with the harmonic number, k. Clearly, the dc component ($k = 0$) of the output current encounters the lowest impedance, equal to the load resistance only, while the load inductance attenuates only the ac component. In other words, the RL load acts as a low-pass filter. The next section provides detailed explanation of terms related to the components and harmonic spectra of waveforms.

Interestingly, if an ac output voltage is to be produced and the generic converter is supplied from a dc source, so that the input voltage, as illustrated in Figure 1.5, is $v_i = V_i = const.$, the switches are operated in the same manner as in the previous case. Specifically, for every half-period of the desired output frequency States 1 and 2 are interchanged. In this way, the input terminals are alternately connected and cross-connected with the output terminals, and the output voltage acquires the ac, although not sinusoidal, waveform shown in Figure 1.6. The output current is

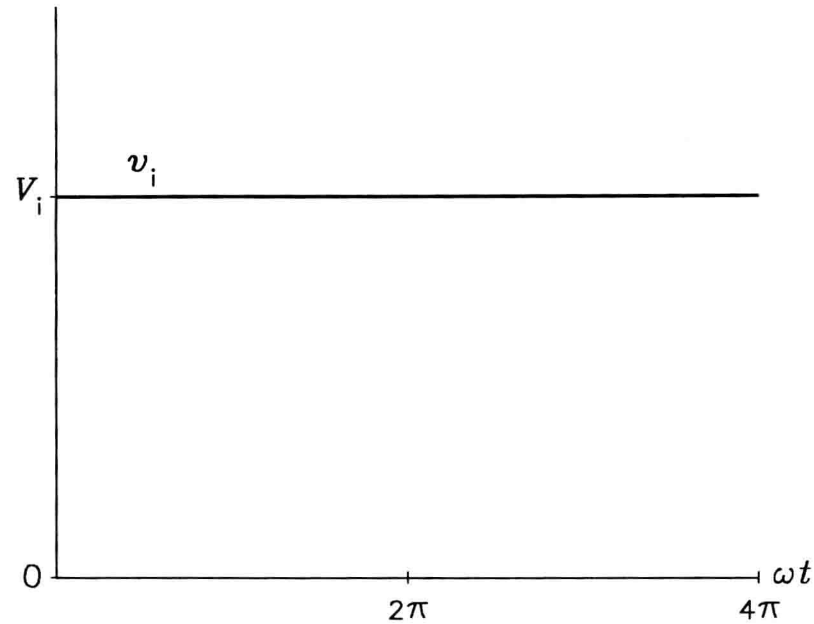

Figure 1.5 Dc input voltage waveform.

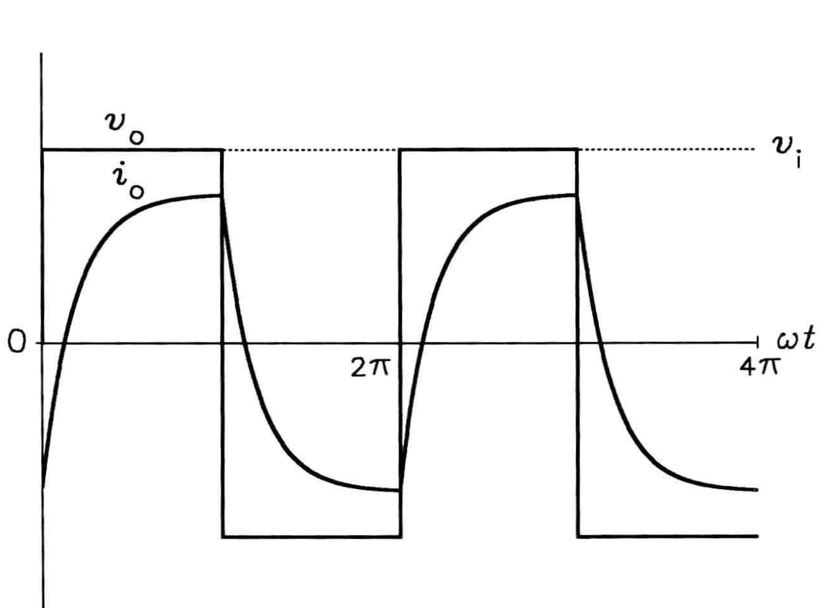

Figure 1.6 Output voltage and current waveforms in the generic inverter.

composed of growth-function and decay-function segments, typical for transient conditions of an RL circuit subjected to dc excitation. Again, thanks to the attenuating effects of the load inductance, the current waveform is closer to the desired sinusoid than is the voltage waveform. In practice, the dc to ac power conversion is performed by power electronic *inverters*. In the case described, the generic inverter is said to operate in the *square-wave mode*.

Clearly, if the input or output voltage is to be a three-phase ac voltage, the topology of the generic power converter portrayed would have to be appropriately expanded, but it still would be a network of switches. Similarly, power electronic converters are *networks of semiconductor power switches*, including power diodes. For various purposes, other elements, such as inductors, capacitors, fuses, and auxiliary circuits, are employed besides the switches in power circuits of practical power electronic converters. Yet, in most of these converters, the fundamental operating principle is the same as in the generic converter, that is, the input and output terminals are being connected, reconnected, and disconnected in a specific manner and sequence required for the given type of power conversion. Typically, as in the generic rectifier and inverter presented, the load inductance inhibits the switching-related undesirable components of the output current.

Although a voltage source has been assumed for the generic hypothetical power converter described, some practical power electronic converters are said to be supplied from current sources. In such converters, a large inductor is connected in series with the input terminals to prevent rapid changes of the input current. Analogously, voltage-source converters usually have a large capacitor connected across the input terminals to stabilize the input voltage. Inductors (often consituting a part of the load) or capacitors are also used at the output of power electronic converters to smooth the output current or voltage, respectively.

According to one of the basic principles of circuit theory, two ideal current sources may not be connected in series and two ideal voltage sources may not be connected in parallel. Consequently, the load of a current-source converter may not appear as a current source while that of a voltage-source converter may not appear as a voltage source. In practice, as illustrated in Figure 1.7, it means that in a current-source power electronic converter a capacitor should be placed in parallel with the load. Apart from smoothing the output voltage, the capacitor prevents the potentially dangerous situations in which the input inductance conducting certain current is connected in series with a load inductance conducting a different current. In contrast, in voltage-source converters, no capacitor may be connected across the output terminals, and it is the load inductance (or an extra inductor between the converter and the load) that smoothes the output current.

1.3 WAVEFORM COMPONENTS AND FIGURES OF MERIT

Terms such as "dc component," "ac component," and "harmonics" mentioned in the preceding section deserve closer examination. Knowledge of the basic components of voltage and current waveforms allows evaluation of performance of a converter.