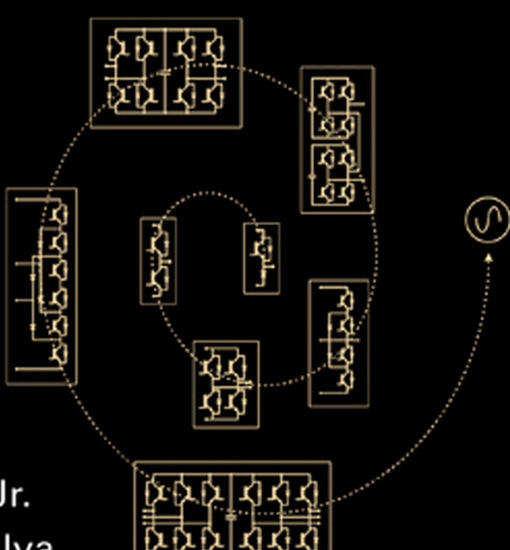
Advanced Power Electronics Converters

PWM Converters Processing AC Voltages



Euzeli Cipriano dos Santos Jr.
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PREFACE

This book deals with a new methodology to present an important class of electrical devices, that is, power electronics converters. The common approach to teaching converters is to consider each type individually, in a separate and isolated fashion. The direct consequence is that the learning process becomes passive since the power electronics configurations are presented without consideration of their origin and development. Since the teaching process is based on the topology itself, students do not develop the ability to construct new topologies from the conventional ones.

A systematic approach is taken to the presentation of multilevel and back-to-back converters, instead of showing them separately, which is normally done in a conventional presentation. Another special aspect of this book is that it covers only subjects related to the converters themselves. This will give more room for exploring the details of each topology and its concept. In this way, the method of conceptual construction of power electronics converters can be highlighted appropriately.

While presenting the basics of power devices, as well as an overview of the main power converter topologies in Chapter 2, this book focuses primarily on configurations processing ac voltage through a dc-link stage. This text is ideally suited for students who have previously taken an introductory course on power electronics. It serves as a reference book to senior undergraduate and graduate students in electrical engineering courses. However, due to the content in Chapter 2, it is expected that even students who the lack knowledge of power devices and basic concepts of converters can understand the subject.

Although the primary market for this text is heavily academic, electrical engineers working in the field of power electronics, motor drive systems, power systems, and renewable energy systems will also find this book useful.

The organization of the book is as follows: Chapter 1 is the introductory chapter. Chapter 2 presents the basics of power devices as well as an overview of the main power converter topologies. Chapter 3 provides a brief review of the main power electronics converters that process ac voltage; additionally, it furnishes the introduction to the power blocks geometry (PBG), which will be used to describe the power converters described in this book. In fact, this chapter brings up a compilation of the topologies explained throughout this book. The fundamentals of PBG and its correlation to the development of power electronics converters are presented in a general way. Multilevel configurations are presented from Chapters 4–7. Neutral-point-clamped, cascade, flying capacitor, and other multilevel configurations are presented in Chapters 4–7, respectively. Chapter 8 deals with techniques for optimization of the pulse width modulation (PWM), considering the fact that the number of pole voltages is higher than the number of voltages demanded by the load. After describing many topologies throughout Chapters 2–7, highlighting the circuits themselves, as well as PWM strategies in Chapter 8, Chapter 9 handles control actions needed to keep a specific variable of the converter under control. Chapter 9 is strategically placed before the presentation of the back-to-back converters (Chapters 10 and 11) due to their need for regulation of electrical variables. Single-phase to single-phase back-to-back converters are presented in Chapter 10, and the final chapter deals with three-phase to three-phase back-to-back converters.

Euzeli Cipriano Dos Santos Jr.
Edison Roberto Cabral Da Silva

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Power electronics may be considered a revolutionary field in electrical engineering because of the new insights obtained during its development. This has actually been the case from the beginning, when mercury arc rectifiers and thyratrons were employed in grid-controlled circuits. After this first generation of power devices and converters, power electronics with silicon power diodes and thyristors was developed to overcome many of the problems of the first generation, such as the operation in low efficiency. As mentioned in Reference 1, the so-called power electronics, with gas tube and glass-bulb electronics, was known as industrial electronics, and the power electronics with silicon-controlled rectifiers began emerging in the market in the early 1960s.

The different definitions of power electronics lead to the same concept or idea: that the control of power flow between an apparatus that furnishes electrical energy and another one that demands electrical energy. For instance, the definition given in References 2 and 3 say, respectively: " … power electronics involves the study of electronic circuits intended to control the flow of electrical energy. These circuits can handle power flow at levels much higher than the individual devices ratings … " and " … power electronics deal with conversion and control of electrical power with the help of electronic switching devices."

Power electronics involves several academic disciplines creating a complex system, including semiconductor physics, control theory, electronics, power systems, and circuit principles. The comprehensive aspect of power electronics makes the presentation of its contents difficult. The interdisciplinary nature of power electronics requires the integration of the practices and assumptions of all the academic disciplines involved, as well as calling for significant prerequisites on the part of the students enrolled for the course. Figure 1.1 illustrates this by analogy, with the prerequisite skills needed for a power electronics course being shown as the roots of a tree, the various power electronics devices as the trunk, and the resulting technologies and applications (power quality, renewable energy systems, etc.) as the branches.

Since the dawn of solid-state power electronics, the use of semiconductor devices has been the major technology to drive power processors. A comparison

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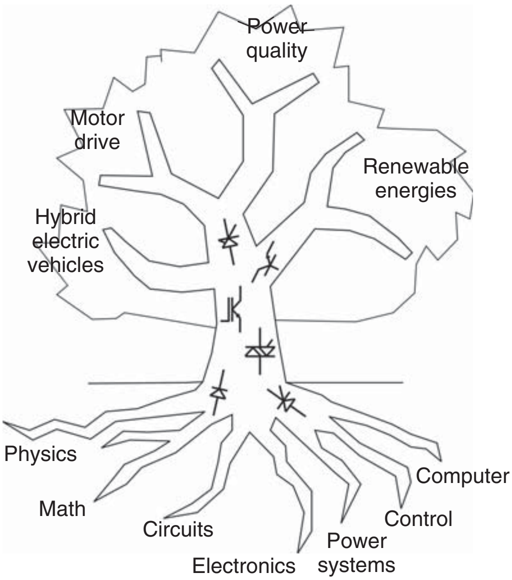

Figure 1.1 Interdisciplinary nature and new insights obtained from power electronics.

of the semiconductor devices formerly used in controlled rectifiers with new technologies underlines this dramatic development. In addition to the improvement of power switches, there has also been great activity in terms of circuit topology innovations.

A power electronic converter is the centerpiece of many electrical systems. Common applications include, but are not limited to, motor drive systems, renewable energies, robotics, electrical and hybrid vehicles, and circuits promoting power quality. These applications have required considerable research worldwide to develop semiconductor devices, configurations that process ac and dc variables, control and diagnosis, fault-tolerant systems, and the like.

In addition to the technical side mentioned already, the educational aspects have considerable importance, as students usually consider power electronics courses to be particularly difficult, perhaps because of their interdisciplinary nature. Achieving student motivation is thus a fundamental task of educators involved in the field of power electronics.

In this context, this book discusses a novel methodology for presenting an important set of power electronics converters, that is, topologies that process ac voltage. The common approach to teaching converters is to consider each type individually, in a separated and isolated manner. The direct consequence is that the learning process becomes passive as the power electronics configurations are presented without any consideration of their origin and development. Since the teaching process is based on the topology itself, students develop no ability to construct new topologies, different from the conventional ones. Section 1.2 outlines this new methodology.

1.2 BACKGROUND

Although presenting the basics of power devices as well as an overview of the main power converter topologies in Chapter 2, this book focuses primarily on configurations processing ac voltage through a dc-link stage. This book is ideally suited for students who have already taken an introductory course in power electronics. It also serves as a reference book to senior undergraduate and graduate students in electrical engineering courses. However, students can easily manage despite the lack of knowledge of power devices and basic concepts of converters, because they are explained in Chapter 2.

Systems with power electronics conversion have been used to guarantee grid and load requirements in terms of controllability and efficiency of the electrical energy demanded, especially in industrial applications. Power electronics topologies convert energy from a primary source to a load (or to another source) requiring any level of processed energy.

Classifications of the power electronics topologies can be done in terms of the type of variable under control (i.e., ac or dc), as well as the number of stages of power conversions used, as observed in Fig. 1.2. Figure 1.2(a) shows, in a general way, many of the possibilities related to energy conversion. Figure 1.2(b) highlights a direct ac–ac conversion, which converts an ac voltage (v_1) with a specific frequency (f_1) to another ac voltage with a different (or same) voltage (v_2) and frequency (f_2); this converter is normally called a cycle converter. Figure 1.2(c) depicts the ac–dc or dc–ac conversion, while Fig. 1.2(d) shows a dc–dc converter. Even admitting

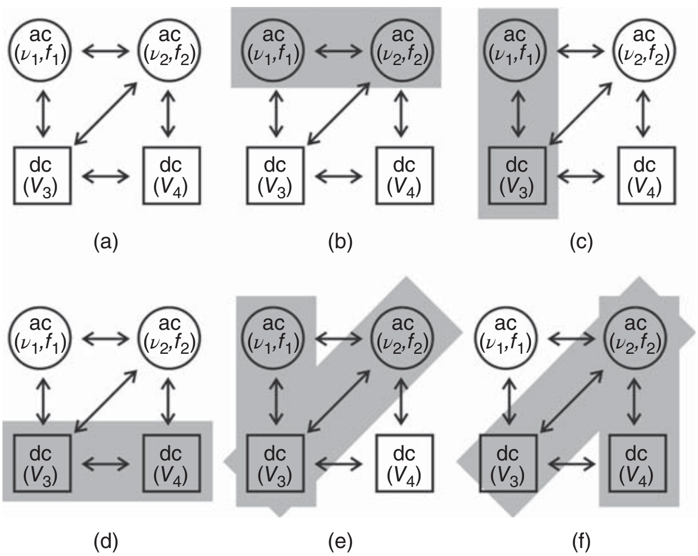

Figure 1.2 Power conversion: (a) all possibilities of conversion, (b) cycle converter, (c) rectifier or inverter, (d) chopper, (e) ac–dc–ac, and (f) dc–ac–dc.

that Fig. 1.2(e) and 1.2(f) could be considered as extended versions of the previous cases, those conversion systems (ac–dc–ac and dc–ac–dc) are presented in Fig. 1.2 because of the large use in different applications.

Special attention is given to the conversion systems presented in Fig. 1.2(c) and 1.2(e), dealing with configurations that process ac voltage (at input and/or output converter sides) with one dc stage. A systematic approach is taken for the presentation of those configurations, instead of just showing them separately, as is normally done in a conventional presentation. Another aspect of this book is that only the subjects related to the converters themselves will be considered, which means that the contents dealing with either ac filters or transformers will be omitted. This will give more room for exploring the details of each topology and its concept. In this way, the method of conceptual construction of power electronics converters can be highlighted appropriately.

1.3 HISTORY OF POWER SWITCHES AND POWER CONVERTERS

Configurations of power electronics converters have provided an attractive alternative for the applications needing energy processing, considering the acceptable level of losses associated with the conversion process itself, as well as improvement in reliability. As previously mentioned, power electronics converters must control the power flow, which means that the development of the devices used in those converters is crucial to guarantee the expected features. In this section, a historic view of the power electronics devices will be furnished, highlighting the main events that contributed to the current development.

The history of power electronics predates the development of the semiconductor devices employed nowadays. The first converters were conceived in the early 1900s, when the mercury arc rectifiers were introduced. Until the 1950s the devices used to build power electronics converters were grid-controlled vacuum tube rectifier, ignitron, phanotron, and thyratron. There were two important events in the power electronics development: (i) in 1948, when Bell Telephone Laboratories invented the silicon transistor, with applications in very low power devices such as in portable radios and (ii) in 1958, when the General Electric Company developed the thyristors or SCR, first using germaniums and later silicon. It was the first semiconductor power device.

Besides these two events, many developments have been achieved in terms of switching development. Between 1967 and 1977, the gate turnoff (GTO) (gate-controlled switch) and gate-assisted turnoff thyristor (GATT) (gate-assisted turnoff switch) were invented. Power transistors, MOSFETs (metal oxide semiconductor field-effect-transistors), MCTs (MOS-controlled thyristor) and IGBTs (insulated-gate-bipolar transistors) have been invented since the end of 1970s. In addition, it is worth mentioning that the area of power electronics was deeply influenced by microelectronics development, and the history of power electronics is closely related to advances in integrated circuits to control switching power supplies.

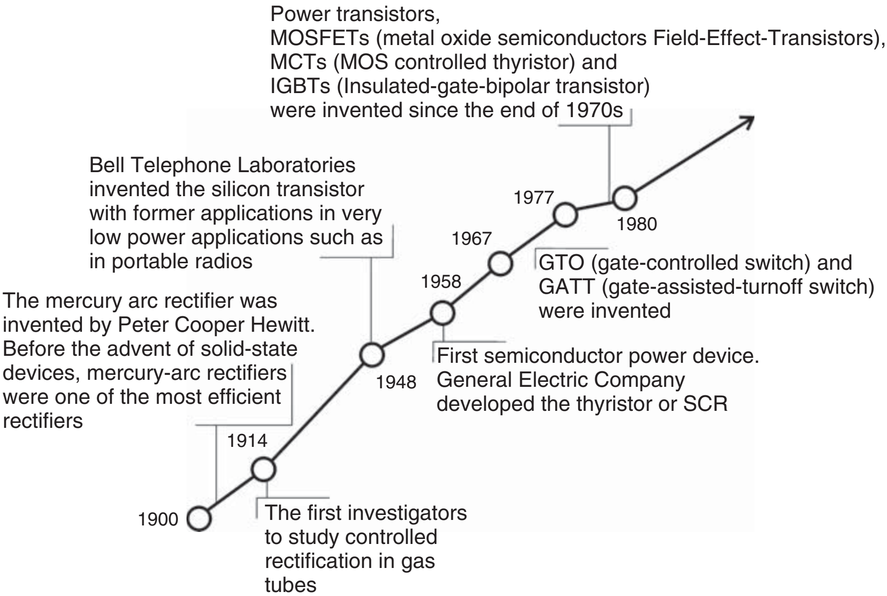

Figure 1.3 Timeline of historical events in the power electronics devices evolution.

Figure 1.3 depicts the timeline showing the development of power electronics devices.

An important chapter in the history of power electronics converters was the development of switching power suppliers. In 1958, the IBM 704 computer, which was developed for large-scale calculations, used as a switching power supplier the primitive vacuum tube-based switching regulator. But the revolution in power supplier concepts came in the late 1960s, when the switching power supplies replaced the linear ones. In a linear power supply, regulated dc voltages are obtained from the ac utility grid throughout the following sequence of steps: (i) 60 Hz power transformer, to converter 120 ac voltage at the primary transformer side to low voltage at secondary transformer side; (ii) such voltage is converted to dc with a simple diode rectifier; and (iii) a linear regulator drops the voltage to a desired value. Indeed, it is possible to identify many problems related to this technology, such as low efficiency (50–65% of the power is wasted as heat), and it was heavy and large (mainly due to the low frequency transformer, heatsink and fans to deal with the heat). The advantages are that it has a very stable output voltage and the conversion system is noise-free.

To overcome the disadvantages of the linear regulators, General Electric published a design of an early stage switching power supply in 1959.

The concept of switching power suppliers is very different from linear regulators. Instead of conducting power 100% of the time (i.e., turning excess power into heat), the switches and passive elements are connected to rapidly turn the power on and off. Unlike linear regulators, the ac utility voltage is converted directly to dc voltage, and the gating signal controls the time of the switching, regulating the average voltage desired at the output converter end.

Another important development in power electronics configurations was the controlled rectifiers, especially with the production of the silicon-controlled rectifier (SCR or thyristor). Such a device allowed the control of high power by just changing the signal applied to its gating circuit with higher efficiency rather than the older technology of employing a mercury arc rectifier.

1.4 APPLICATIONS OF POWER ELECTRONICS CONVERTERS

The range of applications for power electronics converters is so large that it goes from low power residential applications to high power transmission lines. Many of those applications can be considered as traditional ones (e.g., rectification circuits and motor drive systems). On the other hand, a few emerging applications have generated wide interest (e.g., renewable energy systems). A brief discussion matching the power electronics converters with those applications will be introduced here, with the details of those applications being presented throughout the chapters.

Figures 1.4 and 1.5 summarize some examples that demonstrate the presence of power electronics in a wide range of applications. Figure 1.4(a) shows schematically the application of power electronics in hybrid/electric vehicles. From the power

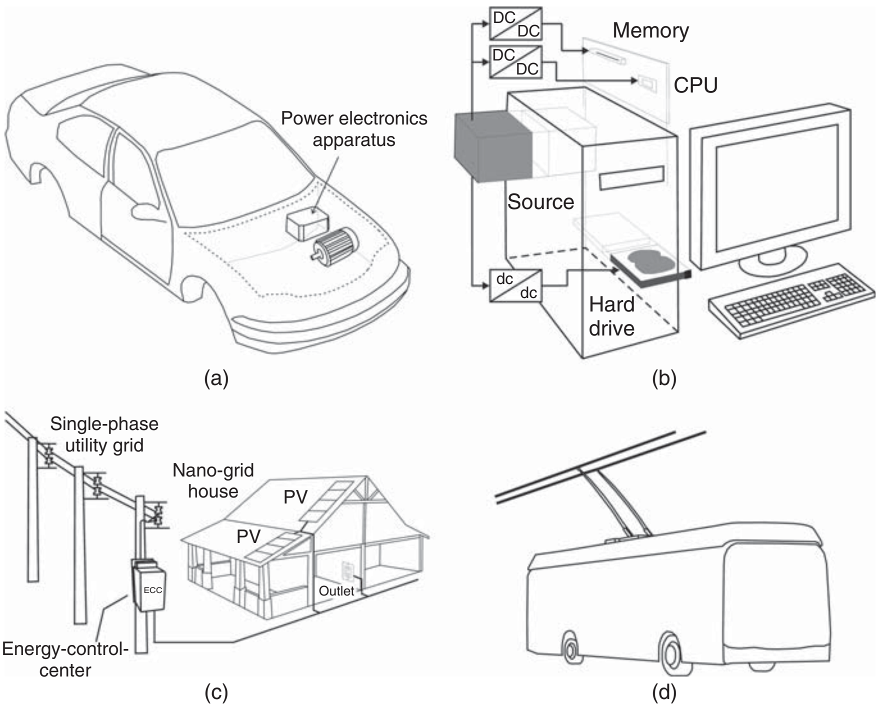

Figure 1.4 Applications of power electronics using converters that process ac voltage.

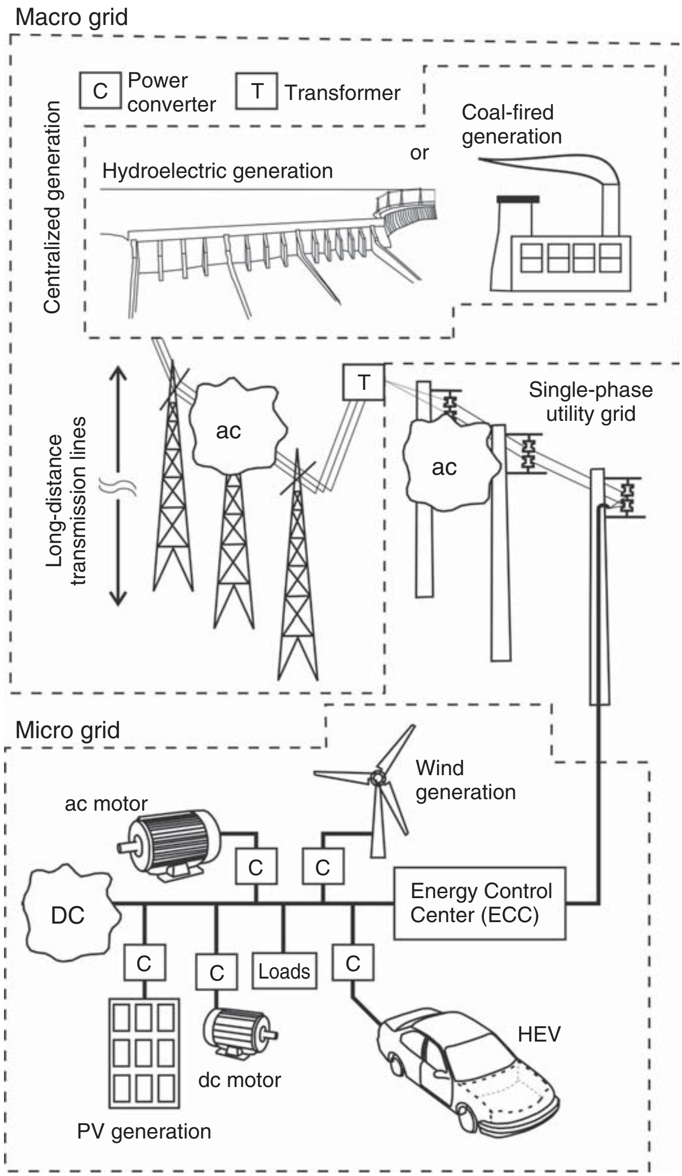

Figure 1.5 Application of power electronics in a distributed generation system. C stands for converter.

electronics point of view, the hybrid and fully electric automobiles differ one from another, mainly due to the power ratings of the inverters used. While a typical inverter rating is about 50 kW for the hybrid vehicle, the inverter rating for a fully electric vehicle is about 200 kW. The inverter motor drive system that furnishes energy to the power-train is by far the most important power electronics system used in this kind of application, but the battery charge and other peripheral systems are also crucial. The main features expected in this application are high efficiency performance, compact on-board energy storage, and low manufacturing cost for market competition with conventional thermal-engine vehicles.

Desktop and laptop computers can be considered as systems with on-board distribution schemes where different dc bus voltages are required. Inside these equipment can be found many power electronics converters, as seen in Fig. 1.4(b). An ac–dc converter produces a dc voltage bus from an ac utility grid, which will be employed by different dc–dc converters to supply the microprocessor, disk drive, memory, and so on. In the case of laptops, a battery charger is added with a power management system to control sleep modes, which guarantees extension in battery life via power consumption reduction.

Figure 1.4(c) shows the application of the power electronics converters in renewable energy systems, which nowadays is a hot topic in the political agenda of many industrialized countries, mainly due to environmental issues and as an alternative way to establish a decentralized generation system. It is worth mentioning that, besides the advantages of renewable energy, this kind of system presents a high price energy generation, especially when it is compared to conventional sources such as hydroelectric power and coal. In this sense, power electronics converters must deal with efficiency, reliability, and cost reduction, in order to make those alternative sources of energy more competitive.

Figure 1.4(d) shows a trolley bus, which is an electric bus that receives electrical energy directly from overhead wires (generally suspended from roadside posts) by using spring-loaded trolley poles.

A well-defined traditional power distribution system has a radial topology and unidirectional power flow to feed end-users. However, in the last few years, there has been research and development in replacing this paradigm by a new and complex multisource system with active functions and bidirectional power flow capability. In this new scenario, the utility grid is supposed to guarantee load management and demand side management, as well as using market price of electricity, and forecasting of energy (e.g., based on wind and solar renewable sources) in order to optimize the distribution system as a whole.

A microgrid can be defined as a localized grouping of electricity generation, energy storage, and loads that are normally connected to a traditional centralized grid (macrogrid), as seen in Fig. 1.5. Figure 1.5 shows a microgrid with a dc bus, where the power converters (represented generically by the letter C) interface distributed sources and loads with the dc bus. The point of common coupling (PCC) between micro- and macrogrid can be disconnected, which means that the microgrid can then operate autonomously. In this case, an island detection system is necessary, which safely disconnects the microgrid. The interface between micro- and macrogrid is possible due to advances made in the power electronics

The important equipment in this scenario is the Energy-Control-Center (ECC), consisting of a bidirectional ac–dc (or dc–ac) power conversion converter used to interface the utility ac grid and dc bus. The multiple dispersed generation sources and the ability to isolate the microgrid from a larger network would provide highly reliable electric power.

Another important area in which power electronics is becoming more and more common is in aerospace industry. Many loads classically powered by hydraulic networks were replaced by electrical power loads (e.g., pumps and braking). Besides facing the common challenges, the power electronics converters must deal with harsh environment constraints in terms of temperature, low pressure, humidity, and vibrations.

1.5 SUMMARY

Following the introduction, this chapter presents in Section 1.2 the background of the book, highlighting the type of configurations that this book will deal with (i.e., dc–ac and ac–dc–ac converters). Section 1.3 gives a brief history of the power electronics devices and power electronics converters, focusing on the development of switching power suppliers and SCR rectifiers. Finally, some applications are considered in Section 1.4 to show the wide range of applications of power electronics converters. Readers can find further discussion from References 4 to 13.

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CHAPTER 2

POWER SWITCHES AND OVERVIEW OF BASIC POWER CONVERTERS

2.1 INTRODUCTION

The basic principles and characteristics of the main power switches are presented in this chapter. Furthermore, an overview of the principal power electronics converters is furnished, highlighting the main characteristics for each type of topology. Semiconductor power devices are the center piece of the power electronics converters. While the knowledge about such devices is crucial to design a power converter with specific characteristics for a given application, the study of different topologies brings up new possibilities to improve the energy process system.

Before dealing specifically with pulse-width modulation (PWM) converters processing ac voltage, which is the core of this book, this chapter considers a large variety of power conversion possibilities. The converters studied in this chapter include dc–dc, dc–ac, ac–dc, and ac–ac converters, as well as voltage-, and current-source converters.

As the objective is to furnish an overview of the different types of switches and converters, a deep analysis of the converters described in this chapter is omitted. However, the following chapters present a systematic description of both power converters, called Power Block Geometry, and the advanced PWM converters processing ac voltage (e.g., multilevel converters and back-to-back converters) to the smallest detail.

This chapter is organized as follows: Section 2.2 presents the ideal characteristics of the major power switches available in the market, highlighting their static and dynamic features; Section 2.3 shows the real characteristics of such semiconductor devices, sorted in terms of dynamic characteristics; Section 2.4 describes basic power electronics converters, and finally, Section 2.5 summarizes the chapter.

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2.2 POWER ELECTRONICS DEVICES AS IDEAL SWITCHES

The design and construction of power semiconductor devices focus on how to improve their performance toward the hypothetical concept of an ideal switch. Figure 2.1 shows the power switches and the year of development of each switch. The performance of a given power switch is normally measured by its static and dynamic characteristics. An ideal switch must have the following characteristics: (i) infinite blocking voltage capability, (ii) no current while the switch is off, (iii) infinite current capability when on, (iv) drop voltage equal to zero while on, (v) no switching or conduction losses, and (vi) capability to operate at any switching frequency.

There are different ways to classify a power switch. In this book, two different ways are considered: static characteristics and dynamic controllability. The main

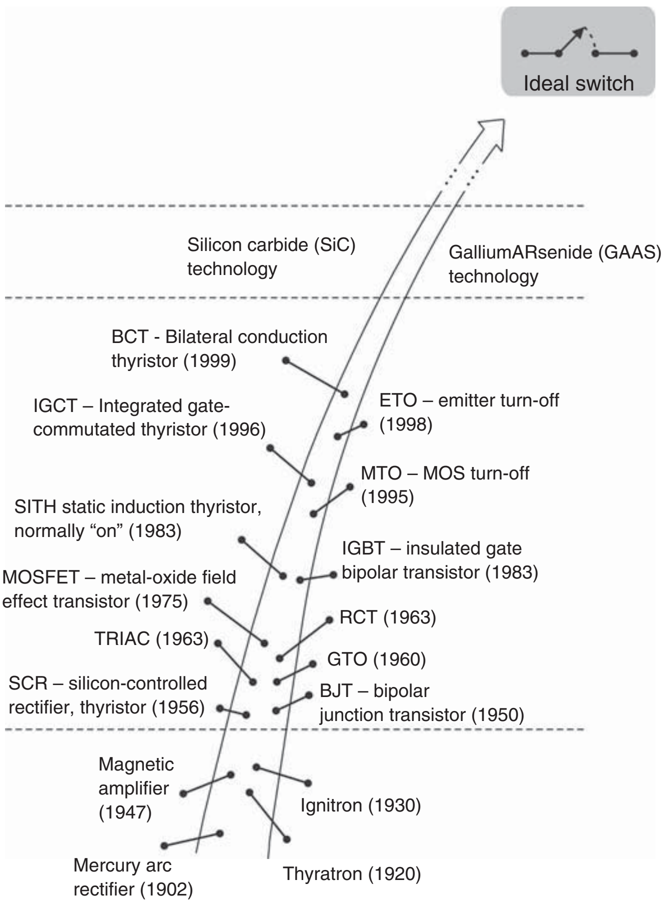

Figure 2.1 Development of the power switches toward the concept of the ideal switch.

figures of merit for the static characteristics are the graphs describing the current versus voltage behaviors ($I-V$). On the other hand, for the dynamic features, the capability to change the states on and off through either an external signal (gating command) or by the variables of the circuit in which the switch is connected is considered. For example, there is no gating signal to turn on and off a diode, its conduction or blocking depends upon the voltage and current imposed by the circuit.

2.2.1 Static Characteristics

The static characteristics of the power semiconductor devices are related to their ability to either conduct or block one or two polarities, as shown in Fig. 2.2.

Figure 2.2(a) and 2.2(b) shows the ideal $I-V$ characteristic for the blocking and conducting states, respectively. Figure 2.2(c)–2.2(g) depicts the voltage versus current ($I-V$) ideal characteristics for the main devices found in the market.

The semiconductor devices can, therefore, operate with either unidirectional or bidirectional (UniC or BidC) current, and with either unidirectional or bidirectional voltage (UniV or BidV). For example: (i) diode, bipolar junction transistor (BJT), and insulated bipolar junction transistor (IGBT) are unidirectional voltage and current type of devices, (ii) SCR is an unidirectional current and bidirectional voltage device, (iii) TRIAC and bidirectional controlled thyristor (BCT) are bidirectional in current and voltage, and (iv) MOSFET is unidirectional in voltage and bidirectional in current.

The characteristics presented in Fig. 2.2(c)–2.2(g) play an important role for the specification and design of the power electronics converters. These graphs are in fact approximations of the real $I-V$ characteristics of the device. For example, Fig. 2.2(c) is an approximation of the real characteristics of a power diode, which is presented later in this chapter.

2.2.2 Dynamic Characteristics

The dynamic characteristics of a specific device are related to the behavior of voltage and current when there is a change either from conduction to blocking state or from blocking to conduction. Such a change is known as commutation or switching. The commutation (or switching) from the blocking state to the conduction state is referred to as either turn-on or conduction. The commutation from the conduction state to the blocking state is referred to as either turn-off or blocking. For the $I-V$ characteristic curves (shown in Fig. 2.2), the commutation process corresponds to going from the operating point on an axis to another one. For example, for a switch UniC/UniV with direct voltage as in Fig. 2.2(c), the blocking procedure makes the variables of the switch (voltage and current) go from the I-axis to the V-axis.

In fact, the commutation process can be spontaneous or controlled, as shown in Fig. 2.3. Four cases are presented as follows:

- Spontaneous conduction (SC)—see Fig. 2.3(a);
- Spontaneous blocking (SB)—see Fig. 2.3(b);

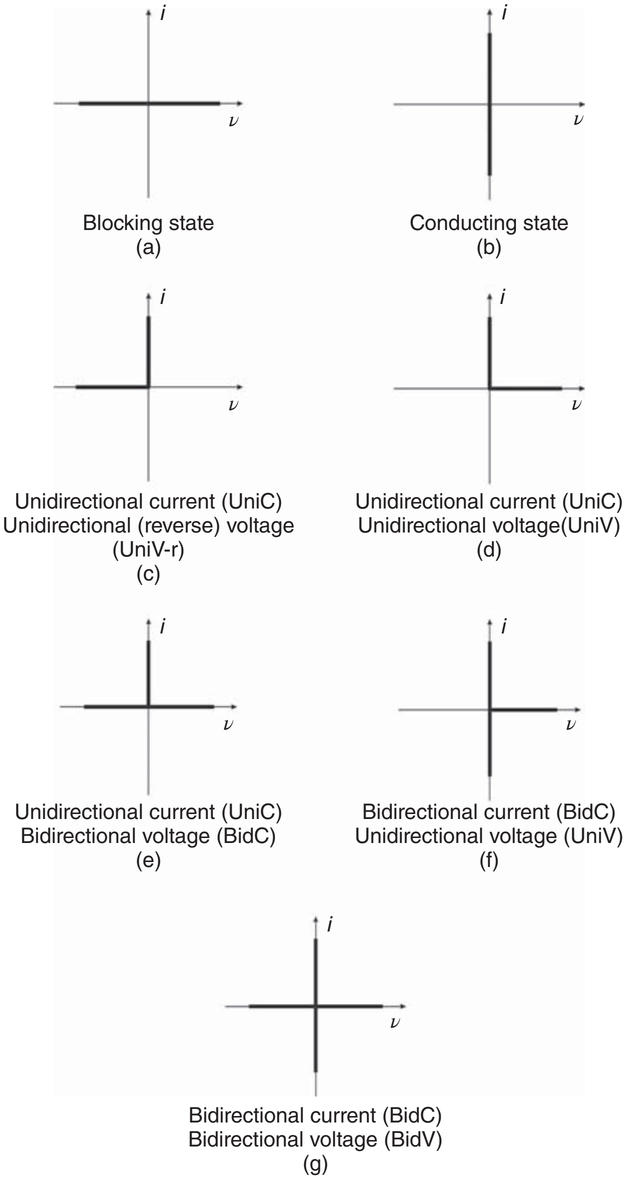

Figure 2.2 Ideal $I-V$ characteristics for blocking and conduction states of the power switches available in the market.

- Controlled conduction (CC)—see Fig. 2.3(c);
- CB—see Fig. 2.3(d).

In the case of spontaneous commutation (i.e., conduction and blocking), the change of state is defined by the variables of the power circuit, while for the controlled

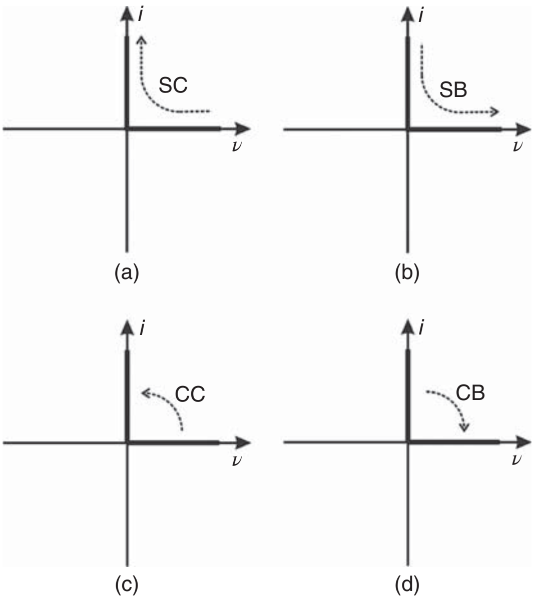

Figure 2.3 Dynamic characteristics of an ideal device considering its commutation process. (a) Spontaneous turn on, (b) spontaneous turn off, (c) controlled turn on, and (d) controlled turn off.

commutation, the change of state is guaranteed via a gating signal (command signal).

Figure 2.4 shows the behavior of the voltage and current in time-domain (left side) and dynamic characteristics (right side) for SC, SB, CC, and CB. The points (P1, P2, and P3) along with the axes in Fig. 2.4 illustrate the behavior of the variables when the switching process occurs for both spontaneous and controlled commutation. For example, in Fig. 2.4(a) P1 indicates the operation point when the switch is blocked, which means that such a device is submitted to a negative voltage while its current is zero. The operation point P2 shows the device's behavior while its voltage has been reduced. Finally, P3 shows the values of voltage and current when the switch is turned on. This commutation process occurs, for example, in a rectifier circuit with diodes where the circuit itself allows the state change from blocking to conduction. A similar analysis can be done for SB in Fig. 2.4(b).

On the other hand, a controlled commutation device must have a control electrode, usually called a gate or base, in addition to the two main terminals. A control signal applied to the gate or base, while the voltage applied between the main terminals is positive, results in change of state in a desirable manner, that is, from one axis to another, as shown in Fig. 2.4(c) and 2.4(d).

In terms of dynamic characteristics, the ideal power devices can be classified as follows:

- SC/SB;
- CC/SB;
- CC/CB;
- SC/CB.

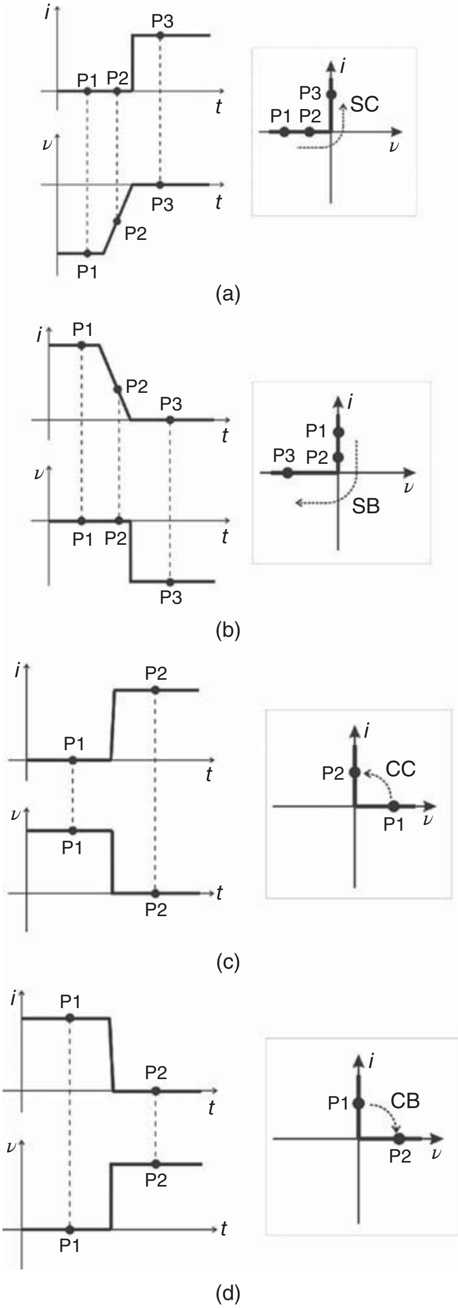

Figure 2.4 Comparison on time-domain and dynamic characteristics during the commutation process. (a) SC, (b) SB, (c) CC, and (d) CB.

2.3 MAIN REAL POWER SEMICONDUCTOR DEVICES

The most common power electronics devices are diodes, thyristors, and power transistors. Usually they have two power terminals (anode/cathode, or collector/emitter or drain/source) and one or more command terminals (gate/ base). Unlike the ideal characteristics presented earlier, real devices have practical limits for rated voltage and current, as well as for their operation frequency. Such limits are normally specified by the datasheet furnished by manufacturers. Therefore, the device characteristics and their specification are crucial to choose a particular power device instead of others.

The most common nonideal device characteristics are

(a) *The Forward and Reverse Voltage Capability*. The main limiting ratings are as follows:

  i. *Forward Blocking Voltage*. The maximum repetitive forward voltage that can be applied to the power terminals of the device (normally from anode to cathode, from collector to emitter, from drain to source) so that the device blocks the current flow (blocking state) in the direct sense, unless commanded to turn on.

  ii. *Reverse Blocking Voltage*. The maximum repetitive reverse voltage that can be applied to the power terminals of the device (from cathode to anode, for instance) so that the device blocks the current flow in the reverse sense.

  iii. *Maximum Peak Nonrepetitive Forward and Reverse Voltage*. The maximum nonrepetitive forward and reverse voltages, respectively, under transient conditions.

  iv. V_{dc} and V_R. Maximum continuous direct (forward) and reverse blocking voltages, respectively. This is the maximum dc voltage that the diode can withstand in reverse-bias mode on a continual basis.

  v. *Forward Voltage Drop*. This is the instantaneous value of the drop voltage, which is normally dependent on the temperature.

(b) The current capability while the device is on (conducting) is junction temperature-dependent. The main limiting ratings are the following:

  i. *On-State Current*. It is the average value of the conduction current.

  ii. *On-State Root Mean Square (RMS) Current*. It is the RMS value of the conduction current.

  iii. *Peak Repetitive Forward Current*. It is the maximum repetitive current that can flow through the device.

  iv. *Peak Surge Forward Current*. It is the maximum nonrepetitive forward current that can flow through the device under transient conditions.

It should be noted that when blocked, the device still conducts a leakage current that can be forward or reverse, depending on the device state.

(c) The switching is not instantaneous, so there are limits in the switching frequency, as follows:

  i. *Turn-On Time*. It is the time required to complete the turn-on process.