1 Electronic Power Conversion

1.1 INTRODUCTION

Historically, power-electronic converters have been predominantly employed in domestic, industrial, and information technology applications. However, due to advancements in power semiconductor and microelectronics technologies, their application in power systems has gained considerably more attention in the past two decades. Thus, power-electronic converters are increasingly utilized in power conditioning, compensation, and power filtering applications.

A power-electronic converter consists of a power circuit—which can be realized through a variety of configurations of power switches and passive components—and a control/protection system. The link between the two is through gating/switching signals and feedback control signals. This chapter briefly introduces power circuits of the most commonly used power-electronic converters for high-power applications. In the subsequent chapters, two specific configurations, that is, the two-level voltage-sourced converter (VSC) and the three-level neutral-point clamped (NPC) converter, are analyzed in more detail. This book focuses on the modeling and control aspects of the two-level VSC and the three-level NPC converter. However, the presented analysis techniques and the control design methodologies are conceptually also applicable to the other families of power-electronic converters introduced in this chapter.

1.2 POWER-ELECTRONIC CONVERTERS AND CONVERTER SYSTEMS

In this book we define a power-electronic (or static) converter as a multiport circuit that is composed of semiconductor (electronic) switches and can also include auxiliary components and apparatus, for example, capacitors, inductors, and transformers. The main function of a converter is to facilitate the exchange of energy between two (or more) subsystems, in a desired manner, based on prespecified performance specifications. The subsystems often have different attributes in terms of voltage/current waveforms, frequency, phase angle, and number of phases, and therefore cannot be directly

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Voltage-Sourced Converters in Power Systems, by Amirnaser Yazdani and Reza Iravani

interfaced with each other, that is, without power-electronic converters. For instance, a power-electronic converter is required to interface a wind turbine/generator unit, that is, an electromechanical subsystem that generates a variable-frequency/variable-voltage electricity, with the constant-frequency/constant-voltage utility grid, that is, another electromechanical subsystem.

In the technical literature, converters are commonly categorized based on the type of electrical subsystems, that is, AC or DC, that they interface. Thus,

- A DC-to-AC or DC/AC converter interfaces a DC subsystem to an AC subsystem.
- A DC-to-DC or DC/DC converter interfaces two DC subsystems.
- An AC-to-AC or AC/AC converter interfaces two AC subsystems.

Based on the foregoing classification, a DC/AC converter is equivalent to an AC/DC converter. Hence, in this book, the terms DC/AC converter and AC/DC converter are used interchangeably. The conventional diode-bridge rectifier is an example of a DC/AC converter. A DC/AC converter is called a *rectifier* if the flow of average power is from the AC side to the DC side. Alternatively, the converter is called an *inverter* if the average power flow is from the DC side to the AC side. Specific classes of DC/AC converters provide bidirectional power-transfer capability, that is, they can operate either as a rectifier or as an inverter. Other types, for example, the diode-bridge converter, can only operate as a rectifier.

DC/DC converter and AC/AC converter are also referred to as *DC converter* and *AC converter*, respectively. A DC converter can directly interface two DC subsystems, or it can employ an intermediate AC link. In the latter case, the converter is composed of two back-to-back DC/AC converters which are interfaced through their AC sides. Similarly, an AC converter can be direct, for example, the matrix converter, or it can employ an intermediate DC link. The latter type consists of two back-to-back DC/AC converters which are interfaced through their DC sides. This type is also known as *AC/DC/AC converter*, which is widely used in AC motor drives and variable-speed wind-power conversion units.

In this book, we define a *power-electronic converter system* (or a converter system) as a composition of one (or more) power-electronic converter(s) and a control/protection scheme. The link between the converter(s) and the control/protection scheme is established through gating signals issued for semiconductor switches, and also through feedback signals. Thus, the transfer of energy in a converter system is accomplished through appropriate switching of the semiconductor switches by the control scheme, based on the overall desired performance, the supervisory commands, and the feedback from a multitude of system variables.

This book concentrates on modeling and control of a specific class of converter systems, this is, the VSC systems. This class is introduced in Section 1.6.

1.3 APPLICATIONS OF ELECTRONIC CONVERTERS IN POWER SYSTEMS

For a long time, applications of high-power converter systems in electric power systems were limited to high-voltage DC (HVDC) transmission systems and, to a lesser extent, to the conventional static VAR compensator (SVC) and electronic excitation systems of synchronous machines. However, since the late 1980s, the applications in electric power systems, for generation, transmission, distribution, and delivery of electric power, have continuously gained more attention [1–6]. The main reasons are

- Rapid and ongoing developments in power electronics technology and the availability of various types of semiconductor switches for high-power applications.
- Ongoing advancements in microelectronics technology that have enabled realization of sophisticated signal processing and control strategies and the corresponding algorithms for a wide range of applications.
- Restructuring trends in the electric utility sector that necessitate the use of power-electronic-based equipment to deal with issues such as power line congestion.
- Continuous growth in energy demand that has resulted in close-to-the-limit utilization of the electric power utility infrastructure, calling for the employment of electronic power apparatus for stability enhancement.
- The shift toward further utilization of green energy, in response to the global warming phenomenon, and environmental concerns associated with centralized power generation. The trend has gained momentum due to recent technological developments and has resulted in economic and technical viability of alternative energy resources and, in particular, renewable energy resources. Such energy resources are often interfaced with the electric power system through power-electronic converters.

In addition, development of new operational concepts and strategies, for example, microgrids, active networks, and smart grids [7], also indicates that the role and importance of power electronics in electric power systems will significantly grow. The envisioned future roles of power-electronic converter systems in power systems include

- Enhancement of efficiency and reliability of the existing power generation, transmission, distribution, and delivery infrastructure.
- Integration of large-scale renewable energy resources and storage systems in electric power grids.
- Integration of distributed energy resources, both distributed generation and distributed storage units, primarily, at subtransmission and distribution voltage levels.

- Maximization of the depth of penetration of renewable distributed energy resources.

Power-electronic converter systems are employed in electric power systems for

- *Active Filtering:* The main function of a power-electronic-based active filter is to synthesize and inject (or absorb) specific current or voltage components, to enhance power quality in the host power system. A comprehensive treatment of the concepts and controls of active power filters is given in Ref. [8].
- *Compensation:* The function of a power-electronic (static) compensator, in either a transmission or a distribution line, is to increase the power-transfer capability of the line, to maximize the efficiency of the power transfer, to enhance voltage and angle stability, to improve power quality, or to fulfill a combination of the foregoing objectives. Various static compensation techniques have been extensively discussed in the technical literature under the general umbrella of flexible AC transmission systems (FACTS) and custom-power controllers [1–6]. The FACTS controllers include, but are not limited to, the static synchronous compensator (STATCOM), the static synchronous series compensator (SSSC), the intertie power flow controller (IPFC), the unified power flow controller (UPFC), and the semiconductor-controlled phase shifter.
- *Power Conditioning:* The main function of an electronic power conditioner is to enable power exchange between two electrical (or electromechanical) subsystems in a controlled manner. The power conditioner often has to ensure that specific requirements of subsystems, for example, the frequency, voltage magnitude, power factor, and velocity of the rotating machines, are met. Examples of electronic power conditioning systems include but are not limited to
    1. the back-to-back HVDC system that interfaces two AC subsystems that can be synchronous, asynchronous, or even of different frequencies [9];
    2. the HVDC rectifier/inverter system that transfers electrical power through a DC tie line between two electrically remote AC subsystems [10, 11];
    3. the AC/DC/AC converter system that transfers the AC power from a variable-frequency wind-power unit to the utility grid; and
    4. the DC/AC converter system that transfers the DC power from a DC distributed energy resource (DER) unit, for example, a photovoltaic (PV) solar array, a fuel cell, or a battery storage unit, to the utility grid [12, 13].

1.4 POWER-ELECTRONIC SWITCHES

Power-electronic semiconductor switches (or electronic switches) are the main building blocks of power-electronic converters. A power-electronic switch is a semiconductor device that can permit and/or interrupt the flow of current through a branch of the host circuit, by the application of a gating signal.[1] This is in contrast to the operation of a mechanical switch in which the on/off transition is achieved through a mechanical process, for example, the movement of a mechanical arm. A mechanical switch

- is slow and thus not intended for repetitive switching;
- essentially includes moving parts and therefore is subject to loss of lifetime during each switching action and thus, compared to an electronic switch, provides a limited number of on/off operations; and
- introduces relatively low power loss during conduction, such that it can be practically considered as a closer representation to an ideal switch.

By contrast, an electronic switch

- is fast and intended for continuous switching;
- includes no moving part and thus is not subject to loss of lifetime during turn-on and turn-off processes; and
- introduces switching and conduction power losses.

The above-mentioned characteristics of the mechanical and electronic switches indicate that for some applications a combination of mechanical and electronic switches can provide an optimum solution in terms of switching speed and power loss. However, the trend in the development of power semiconductor switches [14, 15] points toward ever-increasing utilization of electronic switches. The effort to increase the maximum permissible switching frequency and to minimize switching and conduction losses is the subject of major research and development programs of the power semiconductor switch industry.

1.4.1 Switch Classification

The characteristics of a power-electronic converter mainly depend on the type of its semiconductor switches. It is therefore warranted to briefly review different switch types. Further details regarding the operation and characteristics of the most commonly used switches can be found in Refs. [16, 17].

1.4.1.1 Uncontrollable Switches The power diode is a two-layer semiconductor device and the only uncontrollable switch. It is uncontrollable since the current conduction and interruption instants are determined by the host electrical circuit. Power

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[1] The only exception is diode that conducts current based on the conditions of the host circuit and not in response to a gating signal.

diodes are extensively used in power-electronic converter circuits as stand-alone components, and/or as integral parts of other switches.

1.4.1.2 Semicontrollable Switches The most widely used semicontrollable electronic switch is the thyristor or the silicon-controlled rectifier (SCR). The thyristor is a four-layer semiconductor device that is half- or semicontrollable, since only the instant at which its current conduction starts can be determined by a gating signal, provided that the device is properly voltage biased. However, the current interruption instant of the thyristor is determined by the host electrical circuit. The thyristor has been, and even currently is, the switch of choice for HVDC converters, although in recent years fully controllable switches have also been considered and utilized for HVDC applications.

1.4.1.3 Fully Controllable Switches The current conduction and interruption instants of a fully controllable switch can be determined by means of a gating command. Most widely used fully controllable switches include

- *Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET):* The MOSFET is a three-layer semiconductor device. Compared to other fully controllable power switches, current and voltage ratings of power MOSFETs are fairly limited. Consequently, the application of power MOSFETs is confined to relatively lower power converters where a high switching frequency is the main requirement.
- *Insulated-Gate Bipolar Transistor (IGBT):* The IGBT is also a three-layer semiconductor device. The power IGBT has significantly evolved since the early 1990s, in terms of the switching frequency, the current rating, and the voltage rating. At present, it is used for a broad spectrum of applications in electric power systems.
- *Gate-Turn-Off Thyristor (GTO):* The GTO is structurally a four-layer semiconductor device and can be turned on and off by external gating signals. The GTO requires a relatively large, negative current pulse to turn off. This requirement calls for an elaborate and lossy drive scheme. Among the fully controllable switches, the GTO used to be the switch of choice for high-power applications in the late 1980s and early 1990s. However, it has lost significant ground to the IGBT in the last several years.
- *Integrated Gate-Commutated Thyristor (IGCT):* The IGCT conceptually and structurally is a GTO switch with mitigated turn-off drive requirements. In addition, the IGCT has a lower on-state voltage drop and can also be switched faster compared to the GTO. In recent years, the IGCT has gained considerable attention for high-power converters due to its voltage/current handling capabilities.

In terms of voltage/current handling capability, the semicontrollable and fully controllable switches are classified as follows:

- *Unidirectional Switch:* A unidirectional switch can conduct current in only one direction. Hence, the switch turns off and assumes a reverse voltage when its current crosses zero and attempts to go negative. A unidirectional switch can be bipolar (symmetrical) or unipolar (asymmetrical). A bipolar switch can withstand a relatively large reverse voltage. The thyristor is an example of a bipolar, unidirectional switch. A unipolar switch, however, has a relatively small reverse breakdown voltage; thus, a voltage exceeding the switch reverse breakdown voltage results in a reverse in-rush current that can damage the switch. Therefore, to prevent the reverse breakdown and the consequent damage, a diode can be connected in antiparallel with the unipolar switch that also makes the switch *reverse conducting*. The GTO and the IGCT are commercially available in both unipolar and bipolar types. The current-sourced converter (CSC), described in Section 1.5.2, requires bipolar, unidirectional switches.
- *Reverse-Conducting Switch:* A reverse-conducting switch is realized when a unidirectional switch, whether unipolar or bipolar, is connected in antiparallel with a diode. Hence, a reverse-conducting switch can be regarded as a unipolar switch whose reverse breakdown voltage is approximately equal to the forward voltage drop of a diode. Thus, a reverse-conducting switch starts to conduct in the opposite direction if it is reverse biased by only a few volts. The IGBT and the power MOSFET are examples of reverse-conducting switches. Reverse-conducting IGCT switches are also commercially available. In this book, we refer to a fully controllable reverse-conducting switch also as a *switch cell*, generically illustrated in Figure 1.1(a). The VSC, defined later in this chapter, requires reverse-conducting switches (switch cells). Figure 1.1(b) shows two common symbolic representations of a switch cell in which the gate control terminal is not shown.
- *Bidirectional Switch:* A bidirectional switch can conduct and interrupt the current in both directions. Essentially, a bidirectional switch is also a bipolar switch since in the off state it must withstand both forward and reverse voltage biases. An example of a (semicontrollable) bidirectional switch are two thyristors that are connected in antiparallel. It should be pointed out that, to date, there

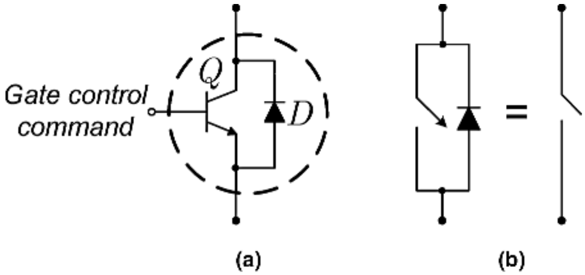

FIGURE 1.1 (a) Generic schematic diagram of a switch cell. (b) Symbolic representations of a switch cell.

exists no fully controllable bidirectional single-device switch technology. Hence, such a switch must be realized through antiparallel connection of two bipolar unidirectional switches. Fully controllable bidirectional switches are required for matrix converters [18].

1.4.2 Switch Characteristics

In the context of electronic power conversion, semiconductor switches are almost exclusively used in the switching mode, that is, the switch is either in the on state or in the off state. The steady-state and switching properties of an electronic switch are conventionally illustrated and characterized by, respectively, the switch current/voltage waveforms and the characteristic curves in the current-versus-voltage (v–i) plane. For system studies and control design purposes, especially for high-power converters where the switching frequencies are typically low, simplified switch models are often adopted. Such models retain the device features relevant to the study, while considerably reduce the modeling, analytical, and computational burden. However, depending on the objectives of a specific investigation, the accuracy of waveforms and results can be enhanced if more elaborate switch models are employed. For example, if the switching loss of a converter is of interest, the diode reverse recovery and the transistor tailing current effects [16] must be included in the model of switches.

In this book, the on- and off-state characteristics of an electronic switch are approximated by corresponding straight lines in the v–i plane. Thus, transient switching processes such as the reverse recovery, the tailing current, and so on are ignored, and transition from one state to the other is generally assumed to be instantaneous. However, to demonstrate the methodology, in Section 2.6 we employ more detailed models of switches to estimate the power loss of a DC/AC voltage-sourced converter.

1.5 CLASSIFICATION OF CONVERTERS

There are a variety of approaches to classification of power-electronic converters. This section introduces two categorization methods relevant to high-power applications.

1.5.1 Classification Based on Commutation Process

One widely used approach to the categorization of converters is based on the commutation process, defined as the transfer of current from branch i to branch j of a circuit, when the switch of branch i turns off while that of branch j turns on. Based on this definition, the following two classes of converters are identified in the technical literature:

- *Line-Commutated Converter:* For a line-commutated (naturally-commutated) converter, the electrical AC system dictates the commutation process. Thus, the commutation process is initiated by the reversal of the AC voltage polarity. The conventional six-pulse thyristor-bridge converter, widely used in HVDC transmission systems, is an example of a line-commutated converter [19]. The line-commutated converter is also known as the naturally-commuted converter.

- *Forced-Commutated Converter:* For a forced-commutated converter, the transfer of current from one switch to another one is a controlled process. Thus, in this type of converter, either the switches must be fully controllable, that is, they must have the *gate-turn-off capability*, or the turn-off process must be accomplished by auxiliary turn-off circuitry, for example, an auxiliary switch or a capacitor. A forced-commutated converter that utilizes switches with the gate-turn-off capability is also known as a *self-commutated converter*. Self-commutated converters are of great interest for power systems applications and are the main focus of this book.

It should be noted that in specific power-electronic converter configurations, switches may not be subjected to the current commutation process, in which case the converter is referred to as a *converter without commutation*. For example, the two antiparallel thyristors in the conventional SVC can be regarded as a converter without commutation.

1.5.2 Classification Based on Terminal Voltage and Current Waveforms

DC/AC converters can also be classified based on voltage and current waveforms at their DC ports. Thus, a *current-sourced converter (CSC)* is a converter in which the DC-side current retains the same polarity, and therefore, the direction of average power flow through the converter is determined by the polarity of the DC-side voltage. The DC side of a CSC is typically connected in series with a relatively large inductor that maintains the current continuity and is more representative of a current source. For example, the conventional, six-pulse, thyristor-bridge rectifier is a CSC. In a *voltage-sourced converter (VSC)*, however, the DC-side voltage retains the same polarity, and the direction of the converter average power flow is determined by the polarity of the DC-side current. The DC-side terminals of a VSC are typically connected in parallel with a relatively large capacitor that resembles a voltage source.

Compared to the VSC, the forced-commutated CSC has not been as widely used for power system applications. The reason is that a CSC requires bipolar electronic switches. However, the power semiconductor industry has not yet fully established a widespread commercial supply of fast, fully controllable bipolar switches. Although bipolar versions of the GTO and the IGCT are commercially available, they are limited in terms of switching speed and are mainly tailored for very high-power electronic converters. Unlike the CSC, a VSC requires reverse-conducting switches or switch cells. The switch cells are commercially available as the IGBT or the reverse-conducting IGCT. Prior to the dominance of the IGBT and the IGCT, each switch of the VSC was realized through antiparallel connection of a GTO with a diode.

1.6 VOLTAGE-SOURCED CONVERTER (VSC)

The focus of this book is on modeling and control of the VSC and VSC-based systems. In the next section, the most common VSC configurations are briefly introduced.

1.7 BASIC CONFIGURATIONS

Figure 1.2 shows the basic circuit diagram of a half-bridge, single-phase, two-level VSC. The half-bridge VSC consists of an upper switch cell and a lower switch cell. Each switch cell is composed of a fully controllable, unidirectional switch in antiparallel connection with a diode. As explained in Section 1.4.1.3, this switch configuration constitutes a reverse-conducting switch that is readily available, for example, in the form of commercial IGBT and IGCT. The DC system that maintains the net voltage of the split capacitor can be a DC source, a battery unit, or a more elaborate configuration such as the DC side of an AC/DC converter. The half-bridge VSC of Figure 1.2 is called a two-level converter since the switched AC-side voltage, at any instant, is either at the voltage of node p or at the voltage of node n, depending on which switch cell is on. The fundamental component of the AC-side voltage is usually controlled based on a pulse-width modulation (PWM) technique [16, 20].

If two half-bridge VSCs are connected in parallel through their DC sides, the full-bridge single-phase VSC of Figure 1.3 is realized. Thus, as shown in Figure 1.3, the AC system can be interfaced with the AC-side terminals of the two half-bridge converters. One advantage is that, for a given DC voltage, the synthesized AC voltage of the full-bridge VSC is twice as large in comparison with the half-bridge VSC, which corresponds to a more efficient utilization of the DC voltage and switch cells. The full-bridge VSC of Figure 1.3 is also known as the *H-bridge converter*.

Figure 1.4 illustrates the schematic diagram of a three-phase two-level VSC. The three-phase VSC is also an extension of the half-bridge VSC of Figure 1.2. In power system applications, the three-phase VSC is interfaced with the AC system, typically, through a three-phase transformer, based on a three-wire connection. In case a four-wire interface is required, either the VSC must permit access to the midpoint of its split DC-side capacitor, through the fourth wire (or the neutral wire), or it must

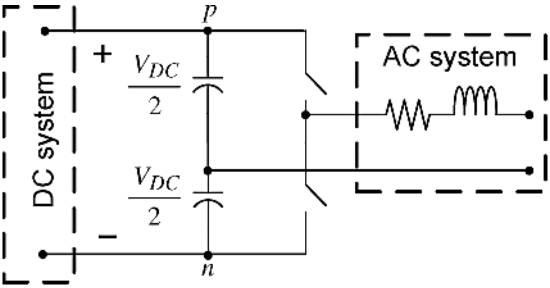

FIGURE 1.2 Schematic diagrams of the half-bridge, single-phase, two-level VSC.

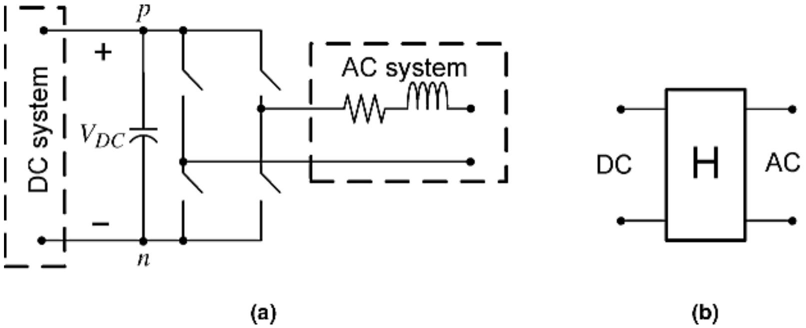

FIGURE 1.3 (a) Schematic diagram of the full-bridge, single-phase, two-level VSC (or an H-bridge converter). (b) Symbolic representation of the H-bridge converter.

be augmented with an additional half-bridge converter, to represent the fourth leg identical to the other three legs, whose AC terminal is connected to the fourth wire. Various PWM and space-vector modulation techniques for switching the three-phase two-level VSC are described in Ref. [20].

The principles of operation of the half-bridge VSC and the three-phase VSC are discussed in Chapters 2 and 5, respectively.

1.7.1 Multimodule VSC Systems

In high-voltage, high-power VSCs, the switch cell of Figure 1.2(b), which is composed of a fully controllable, unidirectional switch and a diode, may not be able to handle the voltage/current requirements. To overcome this limitation, the switch cells are connected in series and/or in parallel and form a composite switch structure which is called a *valve*. Figure 1.5 shows two valve configurations composed of parallel- and series-connected identical switch cells. In most applications, the existing power semiconductor switches meet current handling requirements. However, in

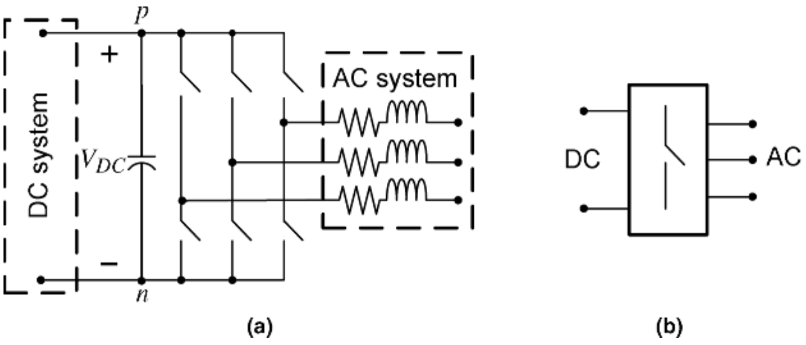

FIGURE 1.4 (a) Schematic diagram of the three-wire, three-phase, two-level VSC. (b) The symbolic representation of the three-phase VSC.

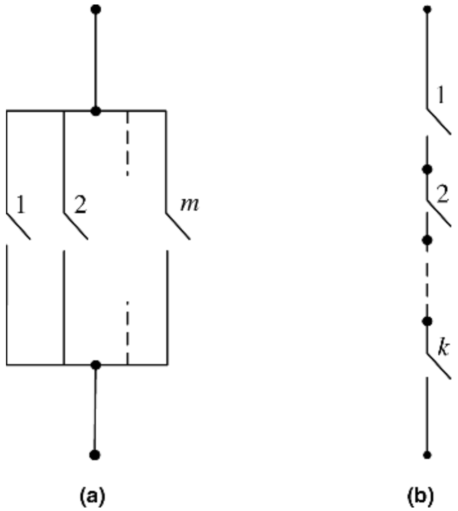

FIGURE 1.5 Symbolic representations of a valve composed of (a) m parallel-connected switch cells and (b) k series-connected switch cells.

most applications, series-connected switch cells are inevitably required to satisfy the voltage requirements. Due to various practical limitations including unacceptable form factor, unequal off-state voltage distribution, and simultaneous-gating requirements, the number of series-connected switch cells within a valve is limited. Thus, a two-level VSC unit cannot be constructed for any voltage level, and an upper voltage limit applies.

The maximum permissible voltage limit of a VSC system can be increased by series connection of identical, three-phase, two-level VSC modules, to form a multimodule VSC [21]. Figure 1.6 illustrates a schematic diagram of an n-module VSC in which n identical two-level VSC modules are connected in series and parallel, respectively, at their AC and DC ports. Thus, the VSC modules share the same DC-bus capacitor. Figure 1.7 illustrates an alternative configuration of an n-module VSC in which the two-level VSC modules are connected in series at both the AC and DC sides. In both configurations of Figures 1.6 and 1.7, the AC-side voltages of the VSC modules are added up by the corresponding open-winding transformers, to achieve the desired voltage level (and waveform) for connection to the AC system. One of the salient features of the n-module VSC configurations of Figures 1.6 and 1.7 is their modularity, as all the VSC modules and transformers are identical. Modularity is a desired feature that reduces manufacturing costs, facilitates maintenance, and permits provisions for spare parts.

The multimodule converter of Figure 1.7 can be further enhanced to acquire the AC-side voltage harmonic reduction capability of a multipulse configuration while its modularity is preserved. This is achieved through appropriate phase shift in switching patterns of the constituent VSC modules, such that a prespecified set of voltage harmonics are canceled/minimized when added up by the open-winding

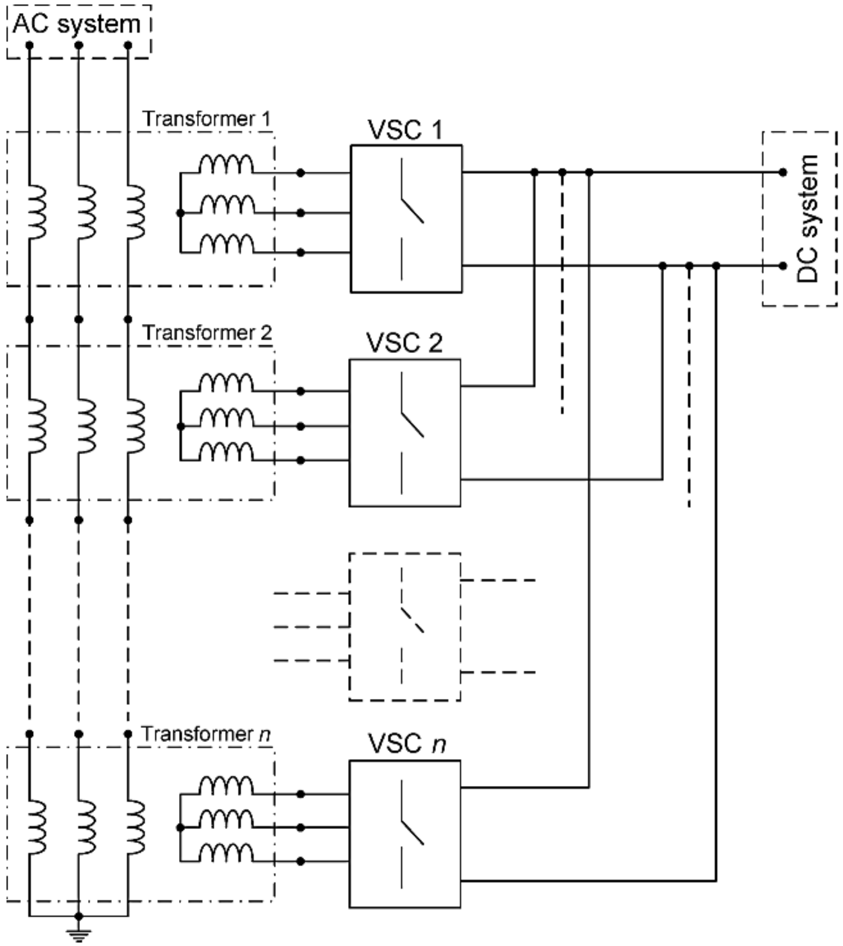

FIGURE 1.6 Schematic diagram of a multimodule VSC composed of *n* two-level VSC modules paralleled from their DC sides.

transformers. The harmonic minimization enables operation of the multimodule converter at low switching frequencies, which, in turn, results in lower switching losses; it also mitigates the need for low-frequency harmonic filters at the converter AC side [22].

The concept of multipulse conversion is another technique employed to minimize low-frequency harmonic components of the synthesized AC voltage of a VSC [23], and thus to minimize the associated filtering requirements. Figure 1.8 shows a schematic diagram of a 12-pulse, thyristor-bridge CSC system that has been extensively used in conventional HVDC transmission applications. As Figure 1.8 shows, the 12-pulse operation of the CSC requires a 30-degree phase shift between the AC-side voltages of the two CSCs. This phase shift is realized by means of two transformers

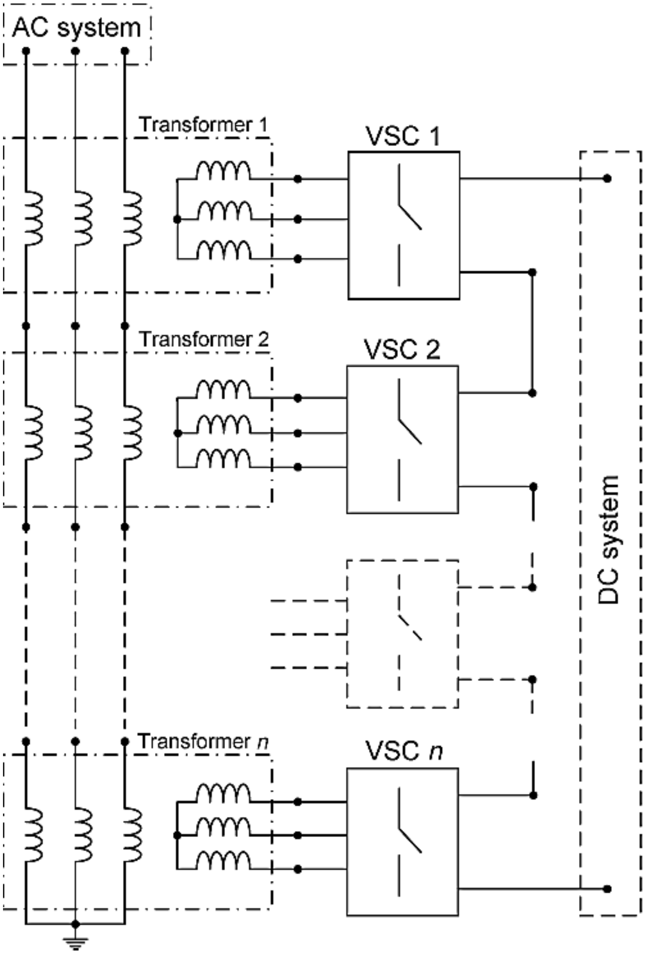

FIGURE 1.7 Schematic diagram of a multimodule VSC composed of *n* two-level VSC modules series with respect to their DC sides.

of different winding configurations. Therefore, the modularity is not fully preserved in the configuration of Figure 1.8.

1.7.2 Multilevel VSC Systems

Another option for a VSC system to accommodate the voltage requirements of a high-power application is to utilize a multilevel voltage synthesis strategy. Conceptually, the multilevel VSC configurations [17] can be divided into

- the H-bridge-based multilevel VSC;
- the capacitor-clamped multilevel VSC; and
- the diode-clamped multilevel VSC.

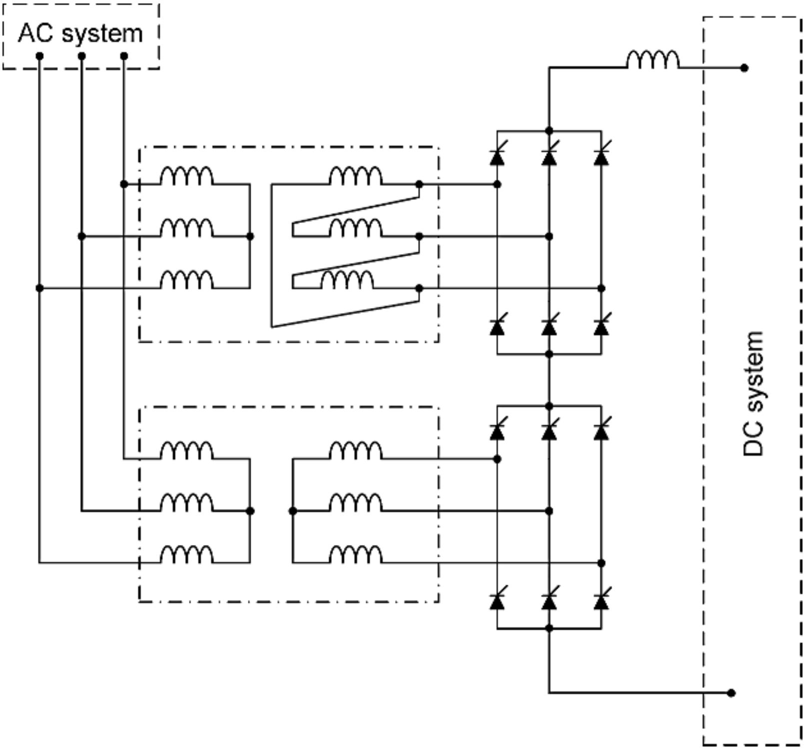

FIGURE 1.8 Schematic diagram of a 12-pulse, line-commutated, thyristor-bridge-based CSC.

The H-bridge-based multilevel VSC, also called the *cascaded H-bridge multilevel VSC*, is constructed through series connection of the H-bridge modules of Figure 1.3(b). Figure 1.9 shows a schematic diagram of a three-phase, wye-connected, H-bridge-based, multilevel VSC. For this configuration, especially if real-power exchange is involved, the DC-bus voltage of each H-bridge module must be independently supplied and regulated by an auxiliary converter system. This renders the H-bridge-based VSC of Figure 1.9 practically unattractive for general-purpose applications; rather, the H-bridge-based converter is more suitable for specific applications, for example, the STATCOM, where only reactive-power exchange is the objective.

One salient feature of the configuration of Figure 1.9 is that it permits independent control of the three legs of the converter. If a (grounded) neutral conductor is provided, the converter can also provide independent control over the zero-sequence components of the three-phase current, in addition to the positive-sequence and the negative-sequence components. It should be noted that the three-wire, three-phase VSC configurations of Figures 1.4 and 1.7 can be controlled to respond only to the positive-sequence and the negative-sequence components.

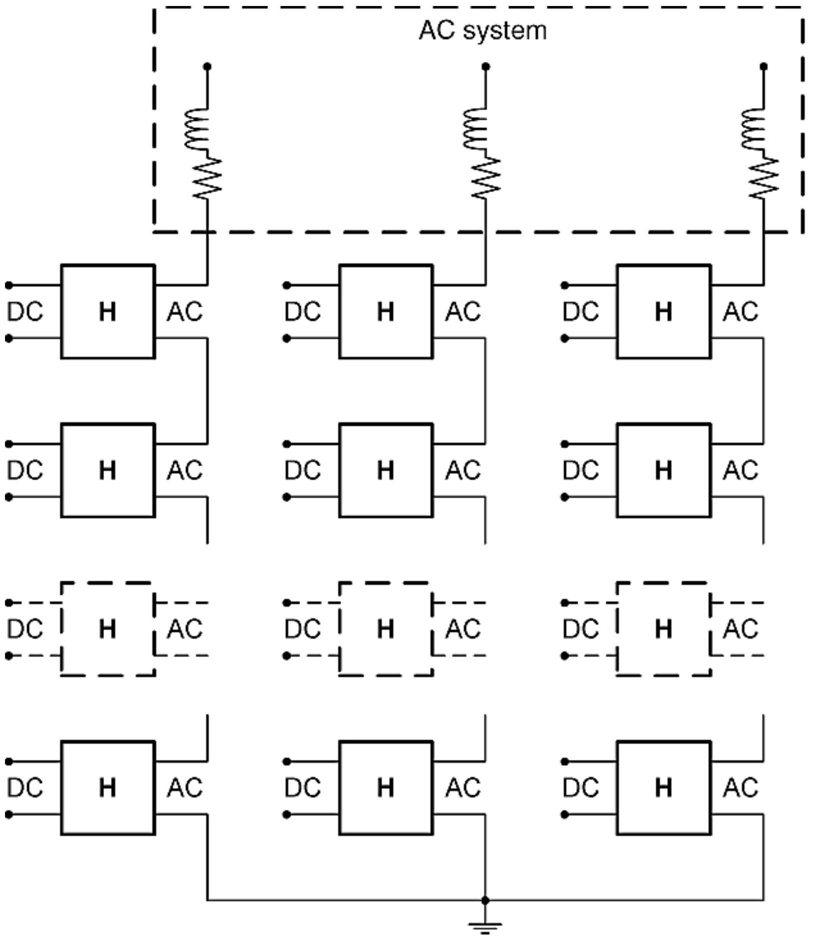

FIGURE 1.9 Schematic diagram of a wye-connected, H-bridge-based, multilevel VSC.

The capacitor-clamped multilevel VSC is another class of multilevel converter configurations. This type of converter is characterized by a large number of relatively large-size capacitors. One of the technical challenges associated with this type of converter is the regulation of its capacitors' voltages. Consequently, the application of the capacitor-clamped multilevel VSC in power systems has not been widely sought in practice and will not be discussed in this book.

The diode-clamped, multilevel, voltage-sourced converter (DCC) is a generalization of the two-level VSC of Figure 1.4(a). This configuration largely avoids the drawbacks of the other two multilevel converter configurations and is considered a promising configuration for power system applications. Figure 1.10 illustrates a conceptual diagram of an n-level DCC in which each leg of the converter is symbolically represented by a fictitious n-tuple-through switch, and the DC bus consists

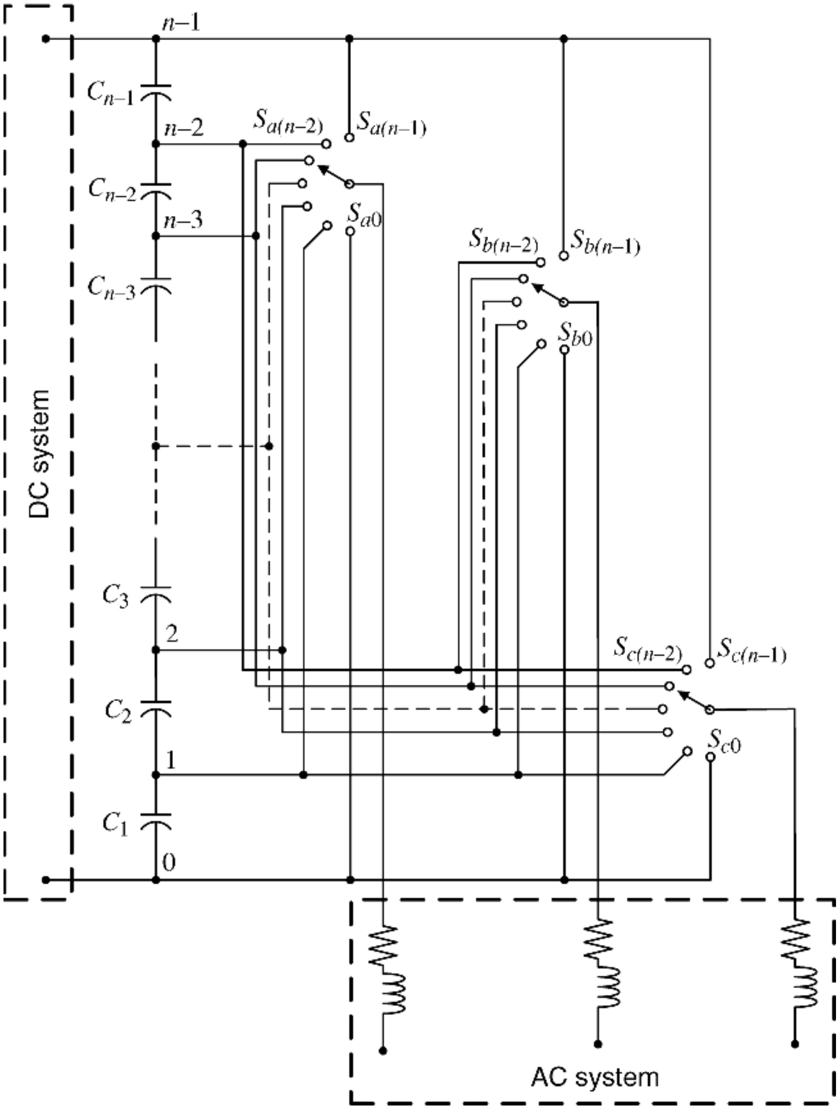

FIGURE 1.10 Conceptual representation of an n-level DCC.

of $n - 1$ nominally identical capacitors C_1 to C_{n-1}. Based on the switching strategy devised for the n-level DCC, each switch in Figure 1.10 connects the corresponding AC-side terminal to one of the nodes 0 to $n - 1$ at the converter DC side. Thus, the AC-side terminal voltage can assume one of the n discrete voltage values of the DC-side nodes. Figures 1.11 and 1.12 illustrate circuit realizations for the three-level DCC and the five-level DCC, respectively. The three-level DCC is also known as the *neutral-point diode-clamped (NPC) converter*, which is widely accepted for

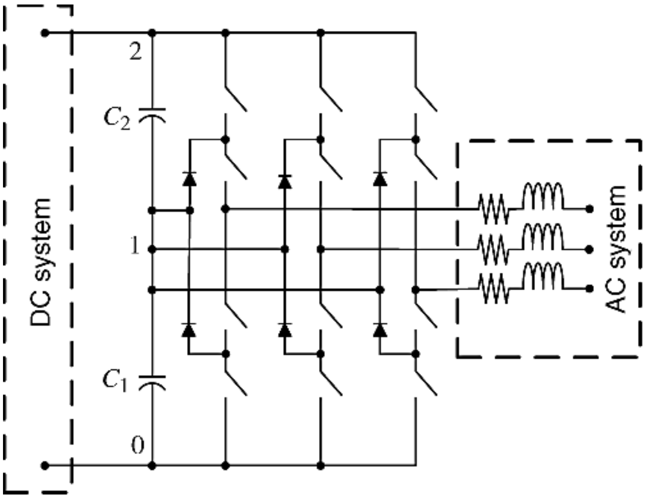

FIGURE 1.11 Schematic diagram of the three-level DCC (or the NPC converter).

high-power applications. Compared to a two-level VSC of the same rating, the three-level DCC can offer a less distorted synthesized AC voltage, lower switching losses, and reduced switch stress levels.

One main technical requirement for proper operation of an n-level DCC is to maintain the voltages of its DC-bus capacitors at their prescribed (usually equal) levels and to prevent voltage drifts during the steady-state and dynamic regimes. In a DCC, net DC-bus voltage regulation cannot guarantee proper operation of the converter system since the individual capacitor voltages may drift or even entirely collapse. This is in contrast to the case of the three-wire two-level VSC for which net DC voltage regulation guarantees proper operation. Provision of a DC-side voltage equalizing scheme is essential for the operation of the DCC.

Conceptually, there are two approaches to deal with the DC capacitor voltage drift phenomenon in a DCC. The first approach is to utilize an auxiliary power circuitry. The auxiliary circuitry can be a set of independent power supplies for capacitors, or it can be a dedicated electronic converter—of a considerably smaller capacity—that injects current into the capacitors and regulates their voltages. The approach is, however, not appealing for power systems applications due to its cost and complexity.

The second approach to equalize the voltages of the DC-side capacitors of a DCC is to enhance the converter control strategy, to modify the switching patterns of the switches such that the capacitors' voltages are regulated at their corresponding desired values. Although this approach calls for a more elaborate control strategy, it offers an economically viable and technically elegant solution to the problem.

It should be pointed out that the number of levels of the multilevel DCC can be higher than three. Therefore, the DCC can accommodate noticeably higher AC and

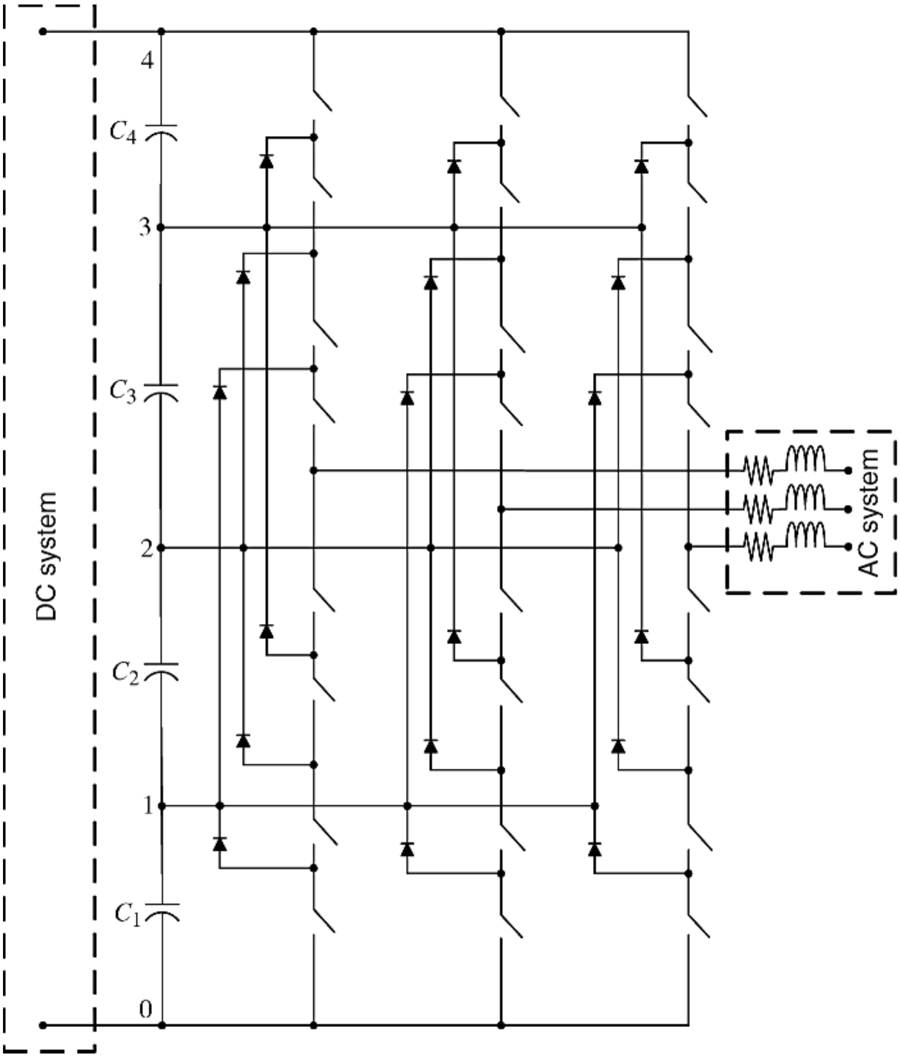

FIGURE 1.12 Schematic diagram of the five-level DCC.

DC voltages, compared to the two-level VSC. However, there is also a limit to the maximum attainable voltage level of a multilevel DCC. Thus, the application of a multilevel DCC in a high-voltage system, for example, an HVDC system, practically may require a multimodule structure similar to that of Figure 1.7, with each module being a multilevel DCC itself. Chapter 6 provides modeling and analysis techniques for the three-level DCC.

1.8 SCOPE OF THE BOOK

In a power-electronic converter system, the functions required for active filtering, compensation, and power conditioning are enabled through the proper operation of the converter control/protection scheme, which finally determines the switching instants of the converter switches. The remainder of this book discusses the mathematical modeling, transient and steady-state behavior, and control design methodologies for a number of VSC-based systems. To limit the number of pages, the methodologies are presented only for the two-level VSC and the three-level DCC. This provides the reader with a comprehensive understanding of the principles of operation, operational characteristics, and control design considerations for the two basic, yet most commonly used, VSC-based configurations. Thus, no attempt has been made in this book to present methodologies for every VSC-based configuration. However, with the understanding gained through this book, the reader should be able to extend and apply similar techniques to different VSC-based systems. Although the book primarily focuses on VSC applications in power conditioning systems, the developments are largely applicable also to compensation systems.