# VOLTAGE-SOURCED CONVERTERS IN POWER SYSTEMS

## Modeling, Control, and Applications

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*To Farzaneh and Arman,*
*and Suzan*

# CONTENTS

# PREFACE

The concept of electronic (static) power conversion has gained widespread acceptance in power system applications. As such, electronic power converters are increasingly employed for power conversion and conditioning, compensation, and active filtering. The gradual increase in the depth of penetration of distributed energy resource (DER) units in power systems and further acceptance of new trends and concepts, for example, microgirds, active distribution systems, and smart grids, also indicate a wider role for power-electronic converters in the electric power system.

While a fairly large number of books on various power-electronic converter configurations and their principles of operation do exist, there is a gap in terms of modeling, analysis, and control of power-electronic converters in the context of power systems. This book addresses this gap and concentrates on power conversion and conditioning applications and presents the analysis and control design methodologies for a specific class of high-power electronic converters, namely, the three-phase voltage-sourced converter (VSC). It provides systematic, comprehensive, unified, and detailed coverage of the relevant materials.

This book serves as a reference book for senior undergraduate and graduate students in power engineering programs, practicing engineers who deal with grid integration and operation of DER systems, design engineers, and researchers in the areas of electric power generation, transmission, distribution, and utilization. The book does not cover implementation details of controllers; however, it contains adequate details for system analysts and control designers and

- describes various functions that the VSC can perform in an electric power system,
- introduces different classes of applications of the VSC in electric power systems,
- provides a systematic approach to modeling a VSC-based system with respect to its class of application,
- presents a comprehensive and detailed control design approach for each class of applications, and
- illustrates the control design procedures and evaluates the performance, based on digital computer time-domain simulation studies.

The text is organized in 13 chapters. Chapter 1 provides a brief introduction to the most commonly used electronic switches and converter configurations in the power system. The rest of the book is divided into two parts. The first part, Chapters 2–10, provides theory and presents fundamental modeling and design methodologies. The second part, Chapters 11–13, covers applications of theory and design methodologies, through three selected application cases: the static compensator (STATCOM), the forced-commutated back-to-back HVDC converter system, and the variable-speed wind-power systems based on the doubly fed asynchronous generator. The second part could have included more application varieties. However, only three application cases have been presented to highlight the main concepts, within a limited number of pages. The PSCAD/EMTDC software package has been used to generate most of the time-domain simulation results in the text. We would like to emphasize that the main purpose of the numerical examples in this book is to highlight the concepts and design methodologies. As such, the numerical values of some parameters may not be fully consistent with the values typically adopted for specific applications.

The reader is expected to have, at least, an undergraduate-level background in electric circuits, electric machinery, electric power system fundamentals, and classical (linear) control. Familiarity with power electronics and the state-space representation of systems is a bonus but not a necessity. Relevant references are also cited throughout the book to help the reader trace back the developments to their original sources. While we have tried to be as comprehensive as possible, it is very likely that we have missed some important references due to the richness of the technical literature and the breadth of the subject matter. We would greatly appreciate any comments and feedback from the readers, for future modifications of the book.

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*January 2010*

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A. Y.

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R. I.

# ACRONYMS

| | |
|---|---|
| AC | Alternating current |
| CSC | Current-sourced converter |
| DC | Direct current |
| DCC | Diode-clamped converter |
| DER | Distributed energy resource |
| DFIG | Doubly-fed induction generator |
| DG | Distributed generation |
| DES | Distributed energy storage |
| FACTS | Flexible AC transmission systems |
| GTO | Gate-turn-off thyristor |
| HVDC | High-voltage DC |
| IGBT | Insulated-gate bipolar transistor |
| IGCT | Integrated gate-commutated thyristor |
| LHP | Left half plane |
| MIMO | Multi-input-multi-output |
| MOSFET | Metal-oxide-semiconductor field-effect transistor |
| NPC | Neutral-point clamped |
| PCC | Point of common coupling |
| PI | Proportional-integral |
| PLL | Phase-locked loop |
| PMSM | Permanent-magnet synchronous machine |
| PWM | Pulse-width modulation |
| pu | Per-unit |
| PV | Photovoltaic |
| RHP | Right half plane |
| SCR | Silicon-controlled rectifier |
| SISO | Single-input-single-output |
| SM | Synchronous machine |
| STATCOM | Static compensator |
| SVC | Static VAR compensator |
| UPS | Uninterruptible power supply |
| VCO | Voltage-controlled oscillator |
| VSC | Voltage-sourced converter |

# 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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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

[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

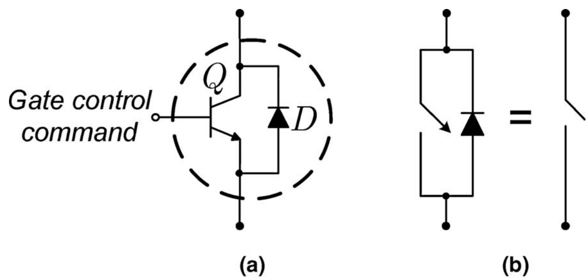


**FIGURE 1.1** (a) Generic schematic diagram of a switch cell. (b) Symbolic representations of a switch cell.

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,