HIGH-POWER CONVERTERS AND AC DRIVES

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Preface

With technology advancements in semiconductor devices such as insulated gate bipolar transistors (IGBTs) and gate commutated thyristors (GCTs), modern high-power medium voltage (MV) drives are increasingly used in petrochemical, mining, steel and metals, transportation and other industries to conserve electric energy, increase productivity and improve product quality.

Although research and development of the medium voltage (2.3 KV to 13.8 KV) drive in the 1-MW to 100-MW range are continuously growing, books dedicated to this technology seem unavailable. This book provides a comprehensive analysis on a variety of high-power converter topologies, drive system configurations, and advanced control schemes.

This book presents the latest technology in the field, provides design guidance with tables, charts and graphs, addresses practical problems and their mitigation methods, and illustrates important concepts with computer simulations and experiments. It serves as a reference for academic researchers, practicing engineers, and other professionals. This book also provides adequate technical background for most of its topics such that it can be adopted as a textbook for a graduate-level course in power electronics and ac drives.

This book is presented in five parts with fourteen chapters. Part One, Introduction, provides an overview of high-power MV drives, which includes market analysis, drive system configurations, typical industrial applications, power converter topologies and semiconductor devices. The technical requirements and challenges for the MV drive are highlighted; these are different in many aspects from those for low-voltage drives.

Part Two, Multipulse Diode and SCR Rectifiers, covers 12-, 18- and 24-pulses rectifier topologies commonly used in the MV drive for the reduction of line current distortion. The configuration of phase-shifting (zigzag) transformers and principle of harmonic cancellation are discussed.

Part Three, Multilevel Voltage Source Inverters, presents detailed analysis on various multilevel voltage source inverter (VSI) topologies, including neutral point clamped and cascaded H-bridge inverters. Carrier-based and space-vector modulation schemes for the multilevel inverters are elaborated.

Part Four, PWM Current Source Converters, deals with a number of current source inverters (CSI) and rectifiers for the MV drive. Several modulation techniques such as trapezoidal pulse width modulations, selective harmonics elimination and space vector modulations are analyzed. Unity-power factor control and active damping control for the current source rectifiers are also included.

Part Five, High-Power ac Drives, focuses on various configurations of VSI- and CSI-fed MV drives marketed by major drive manufacturers. The features and limitations of these drives are discussed. Two advanced drive control schemes, field oriented control and direct torque control, are analyzed. Efforts are made to present these complex schemes in a simple, easy to understand manner.

The Appendix at the end of the book provides a list of 12 simulation based projects for use in a graduate course. The detailed instruction for the projects and their answers are included in Instructor's Manual (published separately). Since the book is rich in illustrations, Power Point slides for each of the chapters are included in the manual.

Finally, I would like to express my deep gratitude to my colleagues at Rockwell Automation Canada; in particular, Steve Rizzo, Navid Zargari, and Frank DeWinter, for numerous discussions and 12 years of working together in developing advanced MV-drive technologies. I sincerely thank my supervisors, Drs. Shashi Dowan and Gordon Slemon for their valuable advice on high-power drive research during my graduate studies at the University of Toronto. I am also indebted to Dr. Robert Hanna at RPM Engineering Ltd. for his review of the manuscript and constructive comments. I am grateful to my postdoctoral fellows and graduate students in the Laboratory for Electric Drive Applications and Research (LEDAR) at Ryerson University for their assistance in preparing the manuscript of this book. I am thankful to my colleagues at ASI Robicon, ABB, Siemens AG, and Rockwell Automation for providing the photos of the MV drives. I also wish to acknowledge the support and inspiration of my wife, Janice, and my daughter, Linda, during the preparation of this book.

BIN WU

Toronto, Canada
December 2005

Part One

Introduction

Chapter 1

Introduction

1.1 INTRODUCTION

The development of high-power converters and medium-voltage (MV) drives started in the mid-1980s when 4500-V gate turn off (GTO) thyristors became commercially available [1]. The GTO was the standard for the MV drive until the advent of high-power insulated gate bipolar transistors (IGBTs) and gate commutated thyristors (GCTs) in the late 1990s [2, 3]. These switching devices have rapidly progressed into the main areas of high-power electronics due to their superior switching characteristics, reduced power losses, ease of gate control, and snubberless operation.

The MV drives cover power ratings from 0.4 MW to 40 MW at the medium-voltage level of 2.3 kV to 13.8 kV. The power rating can be extended to 100 MW, where synchronous motor drives with load commutated inverters are often used [4]. However, the majority of the installed MV drives are in the 1- to 4-MW range with voltage ratings from 3.3 kV to 6.6 kV as illustrated in Fig. 1.1-1.

The high-power MV drives have found widespread applications in industry. They are used for pipeline pumps in the petrochemical industry [5], fans in the cement industry [6], pumps in water pumping stations [7], traction applications in the transportation industry [8], steel rolling mills in the metals industry [9], and other applications [10,11]. A summary of the MV drive applications is given in the appendix of this chapter [12].

Since the beginning of the 21st century a few thousands of MV drives have been commissioned worldwide. Market research has shown that around 85% of the total installed drives are for pumps, fans, compressors and conveyors [13], where the drive system may not require high dynamic performance. As shown in Fig. 1.1-2, only 15% of the installed drives are nonstandard drives.

One of the major markets for the MV drive is for retrofit applications. It is reported that 97% of the currently installed MV motors operate at a fixed speed and only 3% of them are controlled by variable-speed drives [13]. When fans or pumps are driven by a fixed-speed motor, the control of air or liquid flow is normally achieved by conventional mechanical methods, such as throttling control, inlet dampers, and flow control valves, resulting in a substantial amount of energy loss.

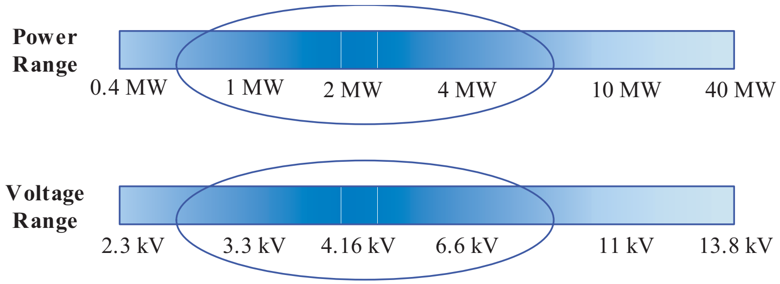

Figure 1.1-1 Voltage and power ranges of the MV drive. Source: Rockwell Automation.

The installation of the MV drive can lead to a significant savings on energy cost. It was reported that the use of the variable-speed MV drive resulted in a payback time of the investment from one to two and a half years [7].

The use of the MV drive can also increase productivity in some applications. A case was reported from a cement plant where the speed of a large fan was made adjustable by an MV drive [11]. The collected dust on the fan blades operated at a fixed speed had to be cleaned regularly, leading to a significant downtime per year for maintenance. With variable-speed operation, the blades only had to be cleaned at the standstill of the production once a year. The increase in productivity together with the energy savings resulted in a payback time of the investment within six months.

Figure 1.1-3 shows a general block diagram of the MV drive. Depending on the system requirements and the type of the converters employed, the line- and motor-side filters are optional. A phase shifting transformer with multiple secondary windings is often used mainly for the reduction of line current distortion.

The rectifier converts the utility supply voltage to a dc voltage with a fixed or adjustable magnitude. The commonly used rectifier topologies include multipulse

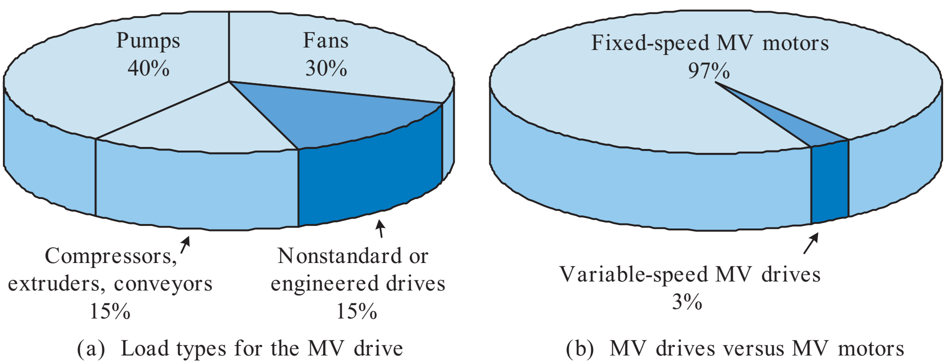

Figure 1.1-2 MV drive market survey. Source: ABB.

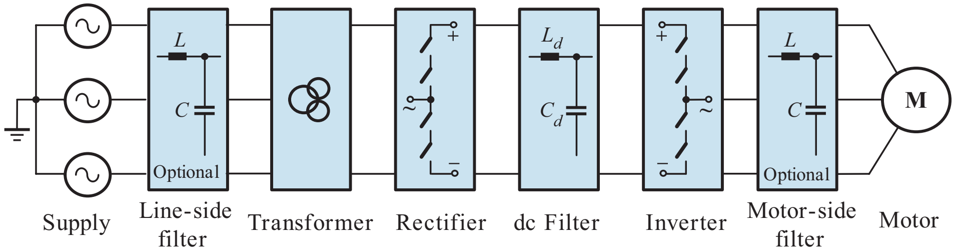

Figure 1.1-3 General block diagram of the MV drive.

diode rectifiers, multipulse SCR rectifiers, or pulse-width-modulated (PWM) rectifiers. The dc filter can simply be a capacitor that provides a stiff dc voltage in voltage source drives or an inductor that smoothes the dc current in current source drives.

The inverter can be generally classified into voltage source inverter (VSI) and current source inverter (CSI). The VSI converts the dc voltage to a three-phase ac voltage with adjustable magnitude and frequency whereas the CSI converts the dc current to an adjustable three-phase ac current. A variety of inverter topologies have been developed for the MV drive, most of which will be analyzed in this book.

1.2 TECHNICAL REQUIREMENTS AND CHALLENGES

The technical requirements and challenges for the MV drive differ in many aspects from those for the low-voltage ($\leq$ 600 V) ac drives. Some of them that must be addressed in the MV drive may not even be an issue for the low-voltage drives. These requirements and challenges can be generally divided into four groups: the requirements related to the power quality of line-side converters, the challenges associated with the design of motor-side converters, the constraints of the switching devices, and the drive system requirements.

1.2.1 Line-Side Requirements

(a) Line Current Distortion. The rectifier normally draws distorted line current from the utility supply, and it also causes notches in voltage waveforms. The distorted current and voltage waveforms can cause numerous problems such as nuisance tripping of computer-controlled industrial processes, overheating of transformers, equipment failure, computer data loss, and malfunction of communications equipment. Nuisance tripping of industrial assembly lines often leads to expensive downtime and ruined product. There exist certain guidelines for harmonic regulation, such as IEEE Standard 519-1992 [14]. The rectifier used in the MV drive should comply with these guidelines.

(b) Input Power Factor. High input power factor is a general requirement for all electric equipment. Most of the electric utility companies require their customers to have a power factor of 0.9 or above to avoid penalties. This requirement is especially important for the MV drive due to its high power rating.

(c) LC Resonance Suppression. For the MV drives using line-side capacitors for current THD reduction or power factor compensation, the capacitors form LC resonant circuits with the line inductance of the system. The LC resonant modes may be excited by the harmonic voltages in the utility supply or harmonic currents produced by the rectifier. Since the utility supply at the medium voltage level normally has very low line resistance, the lightly damped LC resonances may cause severe oscillations or overvoltages that may destroy the switching devices and other components in the rectifier circuits. The LC resonance issue should be addressed when the drive system is designed.

1.2.2 Motor-Side Challenges

(a) dv/dt and Wave Reflections. Fast switching speed of the semiconductor devices results in high *dv*/*dt* at the rising and falling edges of the inverter output voltage waveform. Depending on the magnitude of the inverter dc bus voltage and speed of the switching device, the *dv*/*dt* can well exceed 10,000 V/μs. The high *dv*/*dt* in the inverter output voltage can cause premature failure of the motor winding insulation due to partial discharges. It induces rotor shaft voltages through stray capacitances between the stator and rotor. The shaft voltage produces a current flowing into the shaft bearing, leading to early bearing failure. The high *dv*/*dt* also causes electromagnetic emission in the cables connecting the motor to the inverter, affecting the operation of nearby sensitive electronic equipment.

To make the matter worse, the high *dv*/*dt* may cause a voltage doubling effect at the rising and falling edges of the motor voltage waveform due to wave reflections in long cables. The reflections are caused by the mismatch between the wave impedance of the cable and the impedances at its inverter and motor ends, and they can double the voltage on the motor terminals at each switching transient if the cable length exceeds a certain limit. The critical cable length for 500 V/μs is in the 100-m range, for 1000 V/μs in the 50-m range, and for 10,000 V/μs in the 5-m range [15].

(b) Common-Mode Voltage Stress. The switching action of the rectifier and inverter normally generates common-mode voltages [16]. The common-mode voltages are essentially zero-sequence voltages superimposed with switching noise. If not mitigated, they will appear on the neutral of the stator winding with respect to ground, which should be zero when the motor is powered by a three-phase balanced utility supply. Furthermore, the motor line-to-ground voltage, which should be equal to the motor line-to-neutral (phase) voltage, can be substantially increased due to the common-mode voltages, leading to the premature failure of the motor winding insulation system. As a consequence, the motor life expectancy is shortened.

It is worth noting that the common-mode voltages are generated by the rectification and inversion process of the converters. This phenomenon is different from the high *dv/dt* caused by the switching transients of the high speed switches. It should be further noted that the common-mode voltage issue is often ignored in the low-voltage drives. This is partially due to the conservative design of the insulation system for low-voltage motors. In the MV drives, the motor should not be subject to any common-mode voltages. Otherwise, the replacement of the damaged motor would be very costly in addition to the loss of production.

(c) Motor Derating. High-power inverters may generate a large amount of current and voltage harmonics. These harmonics cause additional power losses in the motor winding and magnetic core. As a consequence, the motor is derated and cannot operate at its full capacity.

(d) LC Resonances. For the MV drives with a motor-side filter capacitor, the capacitor forms an LC resonant circuit with the motor inductances. The resonant mode of the LC circuit may be excited by the harmonic voltages or currents produced by the inverter. Although the motor winding resistances may provide some damping, this problem should be addressed at the design stage of the drive.

(e) Torsional Vibration. Torsional vibrations may occur in the MV drive due to the large inertias of the motor and its mechanical load. The drive system may vary from a simple two-inertia system consisting of only the motor and the load inertias to very complex systems such as a steel rolling-mill drive with more than 20 inertias. The torsional vibrations may be excited when the natural frequency of the mechanical system is coincident with the frequency of torque pulsations caused by distorted motor currents. Excessive torsional vibrations can result in broken shafts and couplings, and also cause damages to the other mechanical components in the system.

1.2.3 Switching Device Constraints

(a) Device Switching Frequency. The device switching loss accounts for a significant amount of the total power loss in the MV drive. The switching loss minimization can lead to a reduction in the operating cost when the drive is commissioned. The physical size and manufacturing cost of the drive can also be reduced due to the reduced cooling requirements for the switching devices. The other reason for limiting the switching frequency is related to the device thermal resistance that may prevent efficient heat transfer from the device to its heatsink. In practice, the device switching frequency is normally around 200 Hz for GTOs and 500 Hz for IGBTs and GCTs.

The reduction of switching frequency generally causes an increase in harmonic distortion of the line- and motor-side waveforms of the drive. Efforts should be made to minimize the waveform distortion with limited switching frequencies.

(b) Series Connection. Switching devices in the MV drive are often connected in series for medium-voltage operation. Since the series connected devices and their gate drivers may do not have identical static and dynamic characteristics, they may not equally share the total voltage in the blocking mode or during switching transients. A reliable voltage equalization scheme should be implemented to protect the switching devices and enhance the system reliability.

1.2.4 Drive System Requirements

The general requirements for the MV drive system include high efficiency, low manufacturing cost, small physical size, high reliability, effective fault protection, easy installation, self-commissioning, and minimum downtime for repairs. Some of the application-specific requirements include high dynamic performance, regenerative braking capability, and four-quadrant operation.

1.3 CONVERTER CONFIGURATIONS

Multipulse rectifiers are often employed in the MV drive to meet the line-side harmonic requirements. Figure 1.3-1 illustrates a block diagram of 12-, 18- and 24-pulse rectifiers. Each multipulse rectifier is essentially composed of a phase-shifting transformer with multiple secondary windings feeding a set of identical six-pulse rectifiers.

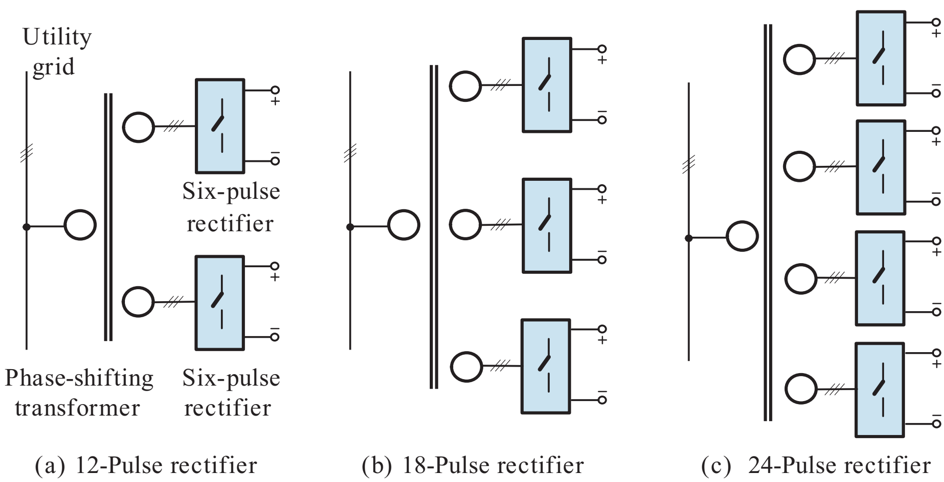

Figure 1.3-1 Multipulse diode/SCR rectifiers.

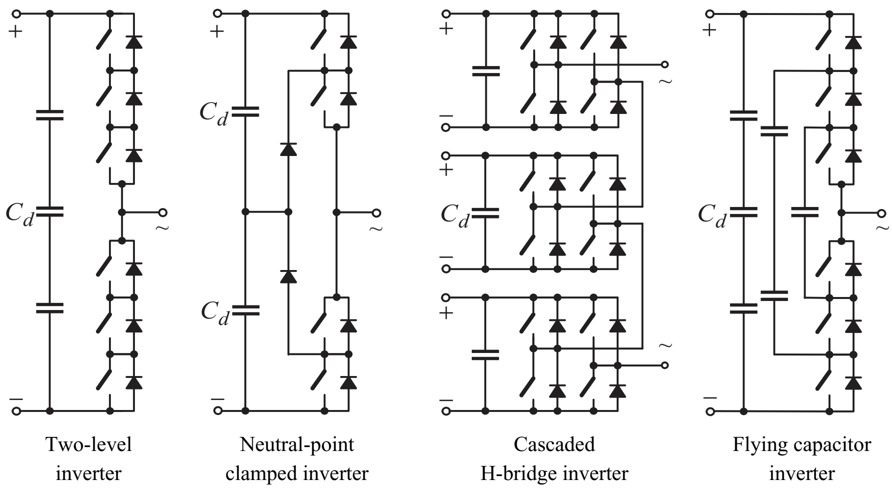

Figure 1.3-2 Per-phase diagram of VSI topologies.

Both diode and SCR devices can be used as switching devices. The multipulse diode rectifiers are suitable for VSI-fed drives while the SCR rectifiers are normally for CSI drives. Depending on the inverter configuration, the outputs of the six-pulse rectifiers can be either connected in series to form a single dc supply or connected directly to a multilevel inverter that requires isolated dc supplies. In addition to the diode and SCR rectifiers, PWM rectifiers using IGBT or GCT devices can also be employed, where the rectifier usually has the same topology as the inverter.

To meet the motor-side challenges, a variety of inverter topologies can be adopted for the MV drive. Figure 1.3-2 illustrates per-phase diagram of commonly used

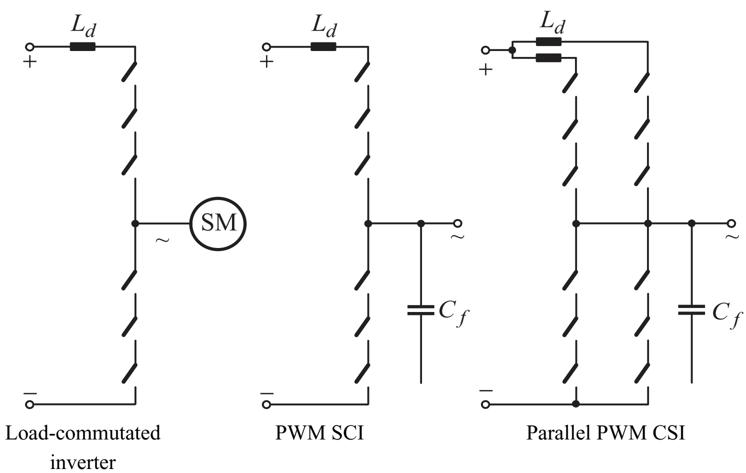

Figure 1.3-3 Per-phase diagram of CSI topologies.

three-phase multilevel VSI topologies, which include a conventional two-level inverter, a three-level neutral-point clamped (NPC) inverter, a seven-level cascaded H-bridge inverter and a four-level flying-capacitor inverter. Either IGBT or GCT can be employed in these inverters as a switching device.

Current source inverter technology has been widely accepted in the drive industry. Figure 1.3-3 shows the per-phase diagram of the CSI topologies for the MV drive. The SCR-based load-commutated inverter (LCI) is specially suitable for very large synchronous motor drives, while the PWM current source inverter is a preferred choice for most industrial applications. The parallel PWM CSI is composed of two or more single-bridge inverters connected in parallel for super-high-power applications. Symmetrical GCTs are normally used in the PWM current source inverters.

1.4 MV INDUSTRIAL DRIVES

A number of MV drive products are available on the market today. These drives come with different designs using various power converter topologies and control schemes. Each design offers some unique features but also has some limitations. The diversified offering promotes the advancement in the drive technology and the market competition as well. A few examples of the MV industrial drives are as follows.

Figure 1.4-1 illustrates the picture of an MV drive rated at 4.16 kV and 1.2 MW. The drive is composed of a 12-pulse diode rectifier as a front end and a three-level

Figure 1.4-1 GCT-based three-level NPC inverter-fed MV drive. Courtesy of ABB (ACS1000).

Figure 1.4-2 IGBT-based three-level NPC inverter-fed MV drive. Courtesy of Siemens (SIMOVERT MV).

NPC inverter using GCT devices. The drive's digital controller is installed in the left cabinet. The cabinet in the center houses the diode rectifier and air-cooling system of the drive. The inverter and its output filters are mounted in the right cabinet. The phase-shifting transformer for the rectifier is normally installed outside the drive cabinets.

Figure 1.4-2 shows an MV drive using an IGBT-based three-level NPC inverter. The IGBT–heatsink assemblies in the central cabinet are constructed in a modular fashion for easy assembly and replacement. The front end converter is a standard 12-pulse diode rectifier for line current harmonic reduction. The phase-shifting transformer for the rectifier is not included in the drive cabinet.

A 4.16-kV 7.5-MW cascaded H-bridge inverter-fed drive is illustrated in Fig. 1.4-3. The inverter is composed of 15 identical IGBT power cells, each of which can be slid out for quick repair or replacement. The waveform of the inverter line-to-line voltage is composed of 21 levels, leading to near-sinusoidal waveforms without using LC filters. The drive employs a 30-pulse diode rectifier powered by a phase-shifting transformer with 15 secondary windings. The transformer is installed in the left cabinets to reduce the installation cost of the cables connecting its secondary windings to the power cells.

Figure 1.4-4 shows a current source inverter-fed MV drive with a power range from 2.3 MW to 7 MW. The drive comprises two identical PWM GCT current

Figure 1.4-3 IGBT cascaded H-bridge inverter-fed MV drive. Courtesy of ASI Robicon (Perfect Harmony).

Figure 1.4-4 CSI-fed MV drive using symmetrical GCTs. Courtesy of Rockwell Automation (PowerFlex 7000).

Table 1.4-1 Summary of the MV Drive Products Marketed by Major Drive Manufacturers

Inverter Configuration	Switching Device	Power Range (MVA)	Manufacturer
Two-level voltage source inverter	IGBT	1.4–7.2	Alstom (VDM5000)
Three-level neutral point clamped inverter	GCT	0.3–5	ABB (ACS1000)
		3–27	(ACS6000)
	GCT	3–20	General Electric (Innovation Series MV-SP)
	IGBT	0.6–7.2	Siemens (SIMOVERT-MV)
	IGBT	0.3–2.4	General Electric-Toshiba (Dura-Bilt5 MV)
Multilevel cascaded H-bridge inverter	IGBT	0.3–22	ASI Robicon (Perfect Harmony)
		0.5–6	Toshiba (TOSVERT-MV)
		0.45–7.5	General Electric (Innovation MV-GP Type H)
NPC/H-bridge inverter	IGBT	0.4–4.8	Toshiba (TOSVERT 300 MV)
Flying-capacitor inverter	IGBT	0.3–8	Alstom (VDM6000 Symphony)
PWM current source inverter	Symmetrical GCT	0.2–20	Rockwell Automation (PowerFlex 7000)
Load commutated inverter	SCR	>10	Siemens (SIMOVERT S)
		>10	ABB (LCI)
		>10	Alstom (ALSPA SD7000)

source converters, one for the rectifier and the other for the inverter. The converters are installed in the second cabinet from the left. The dc inductor required by the current source drive is mounted in the fourth cabinet. The fifth (right most) cabinet contains drive's liquid cooling system. With the use of a special integrated dc inductor having both differential- and common-mode inductances, the drive does not require an isolation transformer for the common-mode voltage mitigation, leading to a reduction in manufacturing cost.

Table 1.4-1 provides a summary of the MV drive products offered by major drive manufacturers in the world, where the inverter configuration, switching device, and power range of the drive are listed.

1.5 SUMMARY

This chapter provides an overview of high-power converters and medium-voltage (MV) drives, including market analysis, drive system configurations, power converter topologies, drive product analysis, and major manufacturers. The technical requirements and challenges for the MV drive are also summarized. These requirements and challenges will be addressed in the subsequent chapters, where various power converters and MV drive systems are analyzed.

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