Part One

Introduction

Chapter 1

Introduction

1.1 OVERVIEW OF HIGH-POWER DRIVES

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 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, and ease of gate control.

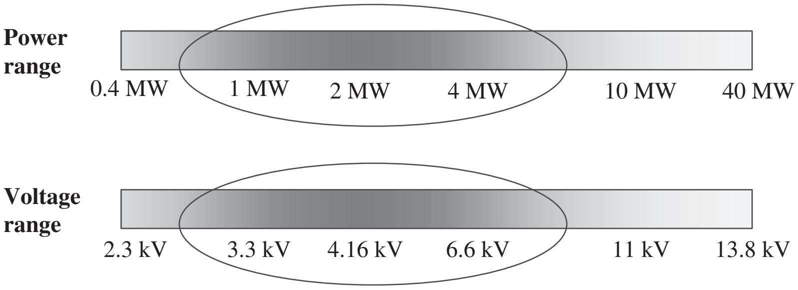
The MV drives cover power ratings from 0.4 to 40 MW at the medium voltage level of 2.3–13.8 kV. The power rating can be extended to 100 MW, where synchronous motor drives with load commutated inverters (LCIs) are often used [4]. However, the majority of the installed MV drives are in the 1–4 MW range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

The high-power MV drives have found widespread applications in industry. They can be 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].

Market research has shown that around 85% of the MV drive applications are for pumps, fans, compressors, and conveyors [13]. The technical requirements for these drives are relatively simple and can be accomplished by a standard MV drive. As shown in Fig. 1.1-2, only 15% of the total installed drives are non-standard drives.

One of the major markets for the MV drive is for retrofit applications. Although with the advancements of high-power converter technology, the variable-speed MV drives have been widely accepted in industry over the last three decades, many of the MV motors still operate in the field at a fixed speed. When large fans, pumps, or compressors are driven by a fixed-speed motor, the control of air or liquid flow is

High-Power Converters and AC Drives, Second Edition. Bin Wu and Mehdi Narimani.



Source: Rockwell Automation

Figure 1.1-1 Voltage and power ranges of the MV drive.

normally achieved by mechanical methods, such as throttling control, inlet dampers, and flow control valves, resulting in a substantial amount of energy loss. The installation of the MV drive can lead to 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 1 to 2 $\frac{1}{2}$ 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 6 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 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.

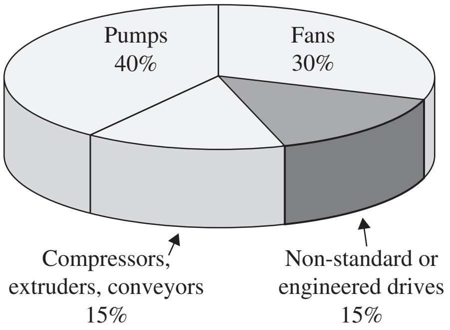


Figure 1.1-2 MV drive market survey.

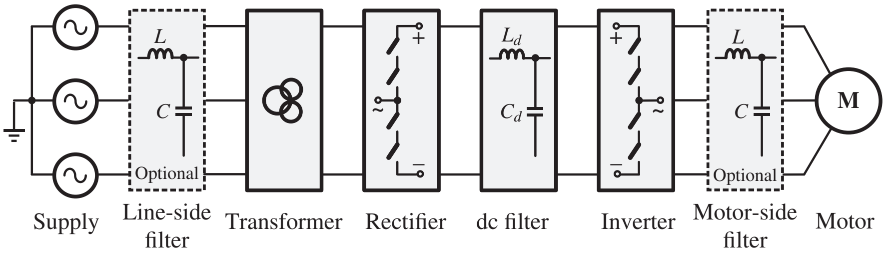


Figure 1.1-3 General block diagram of the MV drive.

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 ($\leq 600\,\mathrm{V}$) 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 produces distorted line currents and 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 European Standard IEC1000 and IEEE Standard 519-2014 [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. 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 little line resistance, the lightly damped LC resonances may cause severe oscillations or over-voltages 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 $10,000\,\mathrm{V/\mu s}$. 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 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 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 $500\,\mathrm{V/\mu s}$ is in the 100 m range, for $1000\,\mathrm{V/\mu s}$ in the 50 m range and for $10,000\,\mathrm{V/\mu s}$ 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 motor with respect to ground, which should be zero when the motor is powered by a three-phase balanced utility supply. Further, 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 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 often 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.

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 limited to 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 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

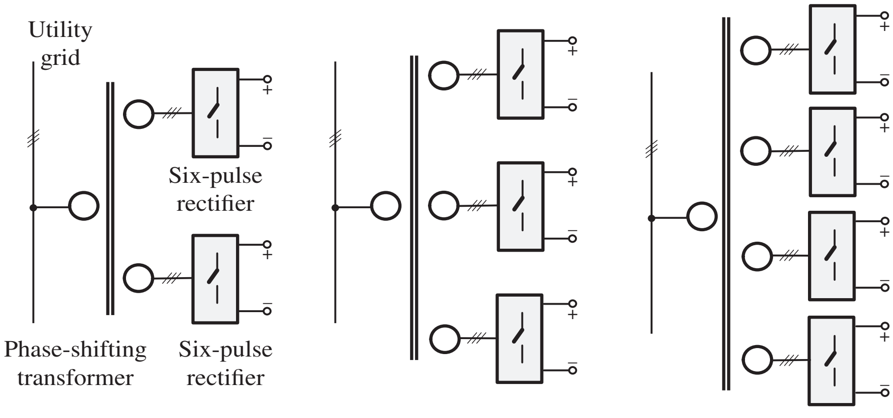
The general requirements for the MV drive system include high efficiency, low manufacturing cost, small physical size, high reliability, effective fault protection, easy installation, self-commissioning, and minimum downtime for repairs. Some of the application-specific requirements include high dynamic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

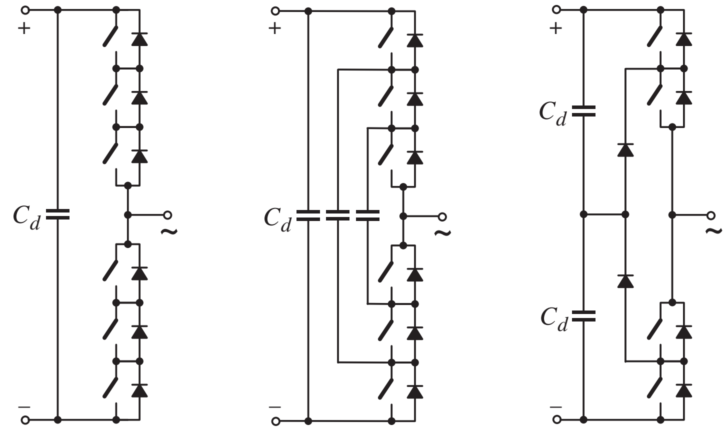
Both diode and SCR devices can be used as switching devices. The multipulse diode rectifiers are suitable for VSI fed drives while the SCR rectifiers are normally for CSI drives. Depending on the inverter configuration, the outputs of the six-pulse rectifiers can be either connected in series to form 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 three-phase multilevel VSI topologies, which include a conventional two-level (2L) VSI, a flying-capacitor(FC) inverter, a neutral point clamped (NPC) inverter, a cascaded H-bridge (CHB) inverter, and a modular multilevel inverter (MMC). For the 2L-VSI, FC, and NPC inverter topologies, either IGBT or GCT devices can be employed, while for the CHB and MMC inverters, IGBT devices are exclusively used.



(a) 12-pulse rectifier (b) 18-pulse rectifier (c) 24-pulse rectifier

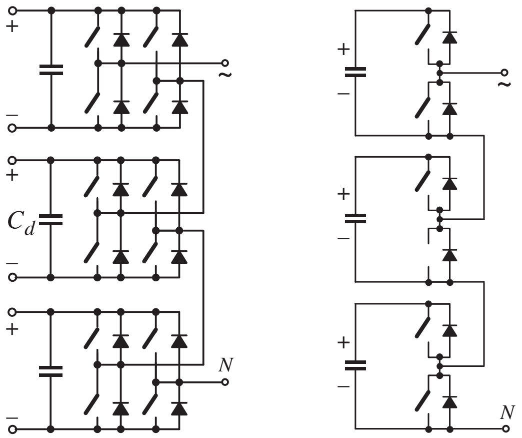
Figure 1.3-1 Multipulse diode/SCR rectifiers.



2L voltage
source inverter

Flying capacitor
inverter

Neutral point
clamped inverter



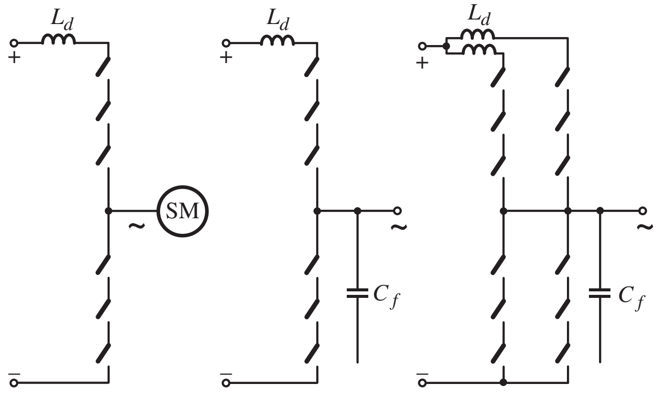
Cascaded
H-bridge inverter

Modular multilevel
inverter

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

CSI 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 LCI is specially suitable for very large synchronous motor drives while the PWM CSI 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 CSIs.

A relatively new power converter topology, cascaded matrix converter (CMC) as shown in Fig. 1.3-4, has been developed for used in commercial MV drives. Unlike the VSI and CSI topologies, the CMC converter performs direct ac–ac conversion



Load commutated inverter

PWM CSI

Parallel PWM CSI

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

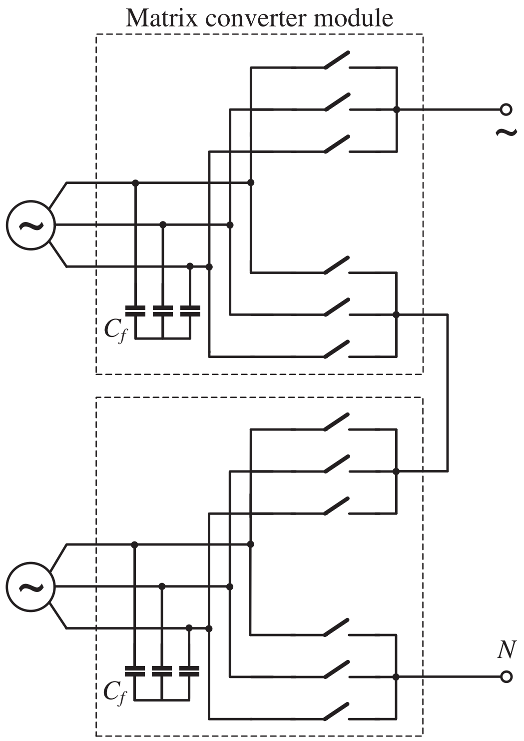


Figure 1.3-4 Per-phase diagram of cascaded matrix converter topology.

without the need of a dc link. The CMC topology is composed of a number of CMC modules per phase to produce high-quality output voltage waveforms, but requires an isolated three-phase power supply for each of the MC modules. IGBT devices are exclusively used in this topology.

1.4 INDUSTRIAL MV DRIVES

A number of MV drive products are available in 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 2.0 MW. The drive is composed of a 12-pulse diode rectifier as a front end and a three-level 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 1.4-1 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).

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.

Figure 1.4-3 shows a 6.6 kV cascaded H-bridge inverter fed MV drive with a power rating from 0.2 to 3.72 MW. The CHB inverter has 18 IGBT power cells and is installed in the middle cabinet. The inverter line-to-line voltage is composed of 25 small voltage steps, which makes the inverter output voltage waveform nearly sinusoidal. A phase-shifting transformer with 18 secondary windings is in the left cabinet. The dominant switching harmonics produced by the power cells are cancelled by the phase-shifting transformer, which makes its primary current nearly sinusoidal. The digital controller for the drive is mounted in the right cabinet.

Figure 1.4-4 shows a CSI fed MV drive with a power range from 2.3 to 7 MW. The drive comprises two identical PWM GCT current 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 (most right) cabinet contains drive's liquid-cooling

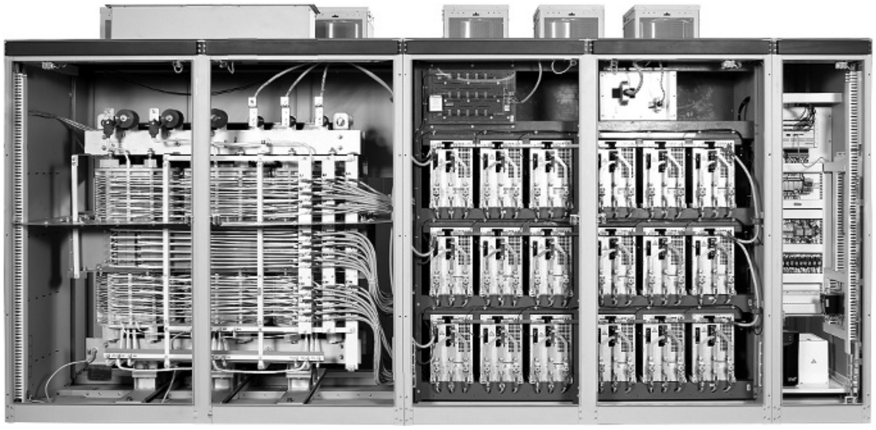


Figure 1.4-3 IGBT cascaded H-bridge inverter fed MV drive. Courtesy of Rockwell Automation (PowerFlex 6000).

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 significant 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.

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

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

Inverter Configuration	Switching Device	Power Range (MVA)	Manufacturer
Two-level voltage source inverter (VSI)	IGBT	1.4–7.2	Alstom (VDM5000)
Three-level neutral point clamped (NPC) inverter	GCT	0.3–5 3–36	ABB (ACS1000) (ACS6000)
	IGBT	3–21	GE Power Conversion (MV7000)
	IGBT	0.6–7.2	Siemens (SIMOVERT-MV)
Multilevel cascaded H-bridge (CHB) inverter	IGBT	0.2–13	θ Harvest (HARSVERT A/S/VA)
		0.3–60	Siemens (Perfect Harmony) (GH180)
		0.31–16.7	Hitachi (HIVECOL-HVI)
		0.32–5.6	Rockwell Automation (PowerFlex 6000)
Multilevel NPC/H-bridge inverter	IGBT	0.4–4.8	Toshiba (TOSVERT 300 MV)
		0.2–3.75	Yaskawa (MV1000)
Flying-capacitor (FC) inverter	IGBT	0.5–9	Alstom (VDM6000 Symphony)
PWM current source inverter (CSI)	Symmetrical GCT	0.2–25	Rockwell Automation (PowerFlex 7000)
Load commutated inverter (LCI)	SCR	>10	Siemens (SIMOVERT S)
		>10	ABB (LCI)
		>10	Alstom (ALSPA SD7000)

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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APPENDIX

A SUMMARY OF MV DRIVE APPLICATIONS

Industry	Application Examples
Petrochemical	Pipeline pumps, gas compressors, brine pumps, mixers/extruders, electrical submersible pumps, induced draft fans, boiler feed water pumps, water injection pumps
Cement	Kiln induced draft fans, forced draft fans, baghouse fans, preheat tower fans, raw mill induced draft fans, kiln gas fans, cooler exhaust fans, separator fans
Mining and Metals	Slurry pumps, ventilation fans, descaling pumps, tandem belt conveyors, baghouse fans, cyclone feed pumps, crushers, rolling mills, hoists, coilers, winders
Water / Wastewater	Raw sewage pumps, bio-roughing tower pumps, treatment pumps, freshwater pumps, storm water pumps
Transportation	Propulsion for naval vessels, shuttle tankers, icebreakers, cruisers. Traction drives for locomotives, light-track trains
Electric Power	Feed water pumps, induced draft fans, forced draft fans, effluent pumps, compressors
Forest Products	Induced draft fans, boiler feed water pumps, pulpers, refiners, kiln drives, line shafts
Miscellaneous	Wind tunnels, agitators, test stands, rubber mixers