

PART I

GENERAL ASPECTS OF CONVENTIONAL MMC

CHAPTER 1

REVIEW OF HIGH-POWER CONVERTERS

1.1 INTRODUCTION

Power converters are well known in industries and the academia as one of the preferred choices for high-efficiency, electric power conversion systems. For the past few years, several power converters were developed and commercialized in the form of standard and customized products. These converters power a wide range of industrial applications such as pumps, compressors, fans, mills, conveyors, transportation (e.g., electric vehicles and, railway traction), manufacturing, petrochemical, high-voltage direct current (HVDC) transmission, reactive power compensation, and wind energy conversion systems [1–3].

This chapter deals with state-of-the-art and recent advancements in high-power converter topologies. The classification of high-power converters is presented in Section 1.2. The first category of power converters uses an intermediate DC-link to achieve the power conversion from fixed AC to variable AC supply. Based on the type of intermediate DC-link, power converters are categorized into voltage source converters (VSC) and current source converters (CSC). A brief description of VSC and CSC topologies is presented in Sections 1.3 and 1.4, respectively. An alternative approach is the direct power conversion from fixed AC to variable AC without

any intermediate DC-link. Cycloconverters (CCV) and matrix converters (MC) belong to this category. The circuit configuration and operation of these topologies are presented in Section 1.5.

Voltage source converters have the highest market share and are widely used in industries. Several VSCs were developed in the past years. Among them, modular multilevel converter (MMC) is a highly regarded topology, which is the main focus of this book. The modular multilevel converter has several features such as modular construction, high reliability, and cost-effectiveness because it uses low-voltage, insulated gate bipolar transistor (LV-IGBT) technology to reach high-voltage (HV) operation. MMC is directly connected to medium-voltage (MV) and high-voltage (HV) grids without any step-up transformer. These features are potentially useful for a wide range of applications. This topology is commercially implemented in medium-voltage motor drives, HVDC transmission, multi-terminal HVDC systems, offshore wind farms, and static synchronous compensators (STATCOM). MMC also requires a control scheme with a more complex structure and function to manage several control objectives simultaneously. Furthermore, it requires a high-performance control platform to process a large number of gating signals. The applications and technical challenges of MMC are presented in Section 1.6. The summary of this chapter is discussed in Section 1.7.

1.2 OVERVIEW OF HIGH-POWER CONVERTERS

Most power converter topologies are available in the form of standard products for an operating voltage of 2.3–13.8 kV only. These power converter topologies require either a step-up transformer or high-voltage semiconductor devices for a high-voltage operation. The former solution is costly and increases the size and volume of the converter system. The new solution does not increase the size and volume of the converter. The main limitation of this solution is the availability of HV semiconductor devices. The available semiconductor devices and their voltage and current ratings are shown in Table 1.1. Insulated gate bipolar transistor (IGBT) devices are widely used in VSCs and matrix converters. These devices are available with a maximum voltage 6.5 kV and a maximum current of 2.4 kA. The integrated gate commutated thyristor (IGCT) is another important device technology used in voltage source converters. Other variants of the IGCT technology include asymmetrical, reverse conducting, and symmetrical types. Symmetrical gate commutated thyristors (SGCT) are used in the CSCs, which are available for a maximum voltage of 10 kV and a maximum current of 5 kA [3, 4]. These MV rated devices cannot block the higher operating voltage.

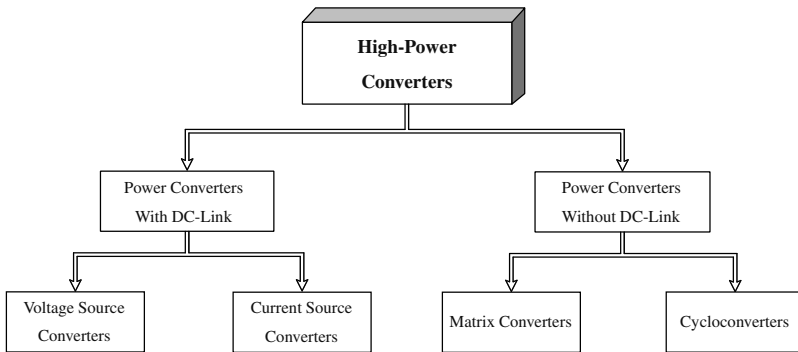
Alternatively, the medium-voltage devices are connected in series to increase the operating voltage of power converters. The series connected devices, and their gate drivers may not exhibit similar static and dynamic performance. Also, these devices may not equally share the total voltage during blocking mode or switching transients. This approach requires a voltage equalization circuit to achieve the equal voltage sharing during blocking mode. These additional circuits increase the power losses in

Table 1.1 Market overview of power semiconductor devices

Parameter	Power Diode	Thyristor	GTO	GCT/IGCT/ SGCT	LV-IGBT/ HV-IGBT
Voltage	8.5 kV@1.2 kA	12 kV@1.5 kA	6 kV@6 kA	10 kV@1.7 kA	6.5 kV@0.75 kA
Current	9.6 kA@1.8 kV	5 kA@0.4 kV	6 kA@6 kV	5 kA@4.5 kV	2.4 kA@1.7 kV

power converters. The series connection of devices does not improve output voltage and current waveform quality.

A modular approach has been developed to overcome the limitations of semiconductor device ratings and their series connection to achieve higher operating voltage. In a modular approach, the identical low-voltage submodules are connected in cascade to reach the higher operating voltage. With the modular approach, the scaling of voltage and power rating of power converters becomes easy, the complexity of assembly and maintenance of power converters is reduced, and power converters can be operated at reduced capacity during submodule failure. Hence, modular power converters become popular in both industries and the academia for high-voltage, high-power applications.

**Figure 1.1** Classification of high-power converters.

High-power converter topologies are categorized into two groups as shown in Figure 1.1. The first group consists of power converters with an intermediate DC-link (DC energy storage component). This group of converters performs the power conversion in two stages: AC–DC and DC–AC between the AC grid and a machine. This group is further categorized into VSCs and CSCs, depending on the nature of the DC energy storage component [5–9]. VSCs normally employ DC capacitors as DC energy storage component, whereas CSCs employ DC inductors in the DC-bus. VSCs are referred to as voltage source rectifiers (VSR) in the AC–DC conversion stage, and as voltage source inverters (VSI) in the DC–AC conversion stage. Similarly, CSCs

are referred to as current source rectifier (CSR) and current source inverter (CSI), based on their functionality.

The second group consists of power converters without an intermediate DC-link (DC energy storage component). This group of converters performs a direct AC–AC conversion between the AC grid and a machine. CCVs and matrix converters belong to this group. The CCV is a widely used topology in high-power applications, which use an array of thyristors for the direct connection of the AC grid to a machine. CCV allows efficient power flow in both directions. However, CCV has limited dynamic performance, operating voltage, and frequency range, and low power factor at low motor speed [3, 5]. The matrix converter is a new topology capable of the direct AC–AC conversion without DC energy storage element. The main features of matrix converters are sinusoidal input or output waveforms, a controllable input power factor, a wide range of output voltage and frequency control, and light-weight design unlike that of CCV [3, 10]. The power converters shown in Figure 1.1, are briefly discussed in the following sections.

1.3 VOLTAGE SOURCE CONVERTERS

VSCs are a matured technology that uses a DC capacitor as a storage element in the DC-link. Over the past decade, VSCs exhibited higher market penetration and more evident development compared to CSCs and matrix converters. The most prominent developments in VSCs are shown in Figure 1.2. The two-level converter is a standard VSC; that is limited to low-voltage (LV) and low-power applications. For high-power applications, two-level converters require either device in parallel to carry high-current at low-voltage operation or devices in series to reach medium-voltage operation with low current-carrying capacity. The parallel and series connections of devices do not introduce any additional benefits in the improvement of power quality (reduction of voltage and current harmonic distortion) and $\frac{dv}{dt}$ reduction. Power losses and voltage blocking are uneven in series connected devices. Thus, two-level converters are not very popular for high-power applications [7–12].

New converter topologies with low-cost semiconductor technology, also known as multilevel converters, are developed for high-power applications. Multilevel converters have significant advantages compared to high-power, two-level converters. These advantages include low $\frac{dv}{dt}$ and voltage harmonic distortion, near-sinusoidal currents, smaller size of input and output filters (if necessary), high-efficiency, low common-mode voltage, and possible fault-tolerant operation in certain cases. Multilevel converters are composed of an array of low-voltage or medium-voltage semiconductor devices and DC capacitive voltage sources. Multilevel converters generate a stepped voltage waveform with variable magnitude and frequency with a proper arrangement of devices, capacitive voltage sources, and control methods [7–12].

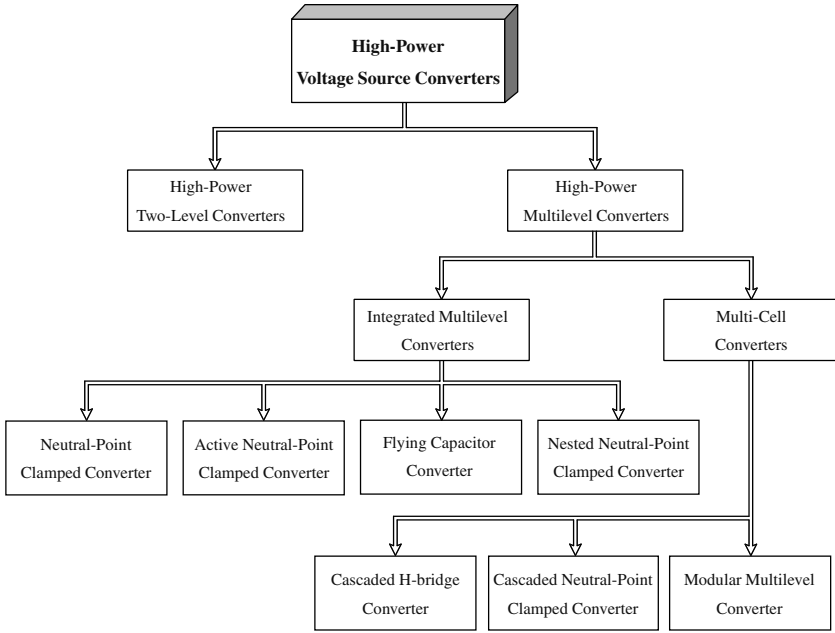


Figure 1.2 Classification of voltage source converters.

Several multilevel converter topologies were established in the past years, and very few succeeded in the industry as shown in Figure 1.2. Neutral-point clamped converter (NPC), active neutral-point clamped (ANPC), flying capacitor (FC), and nested neutral-point clamped (NNPC) converters can handle only a voltage of 2.3–4.16 kV. These converters require significant modifications to increase the operating voltage and a number of voltage levels, which is not cost-effective. These converters must be shut down during faults and other failures, leading to a significant loss of production in industrial processes.

Cascaded converter topologies, also referred to as multi-cell converters, are developed to address the above problems. Among them, the cascaded H-bridge (CHB) and cascaded neutral-point clamped (CNPC) converters are quite popular. These topologies are constructed with a cascade connection of low-power submodules with an isolated DC source in each phase. These topologies have a modular construction, can achieve operating voltages higher than 6 kV up to 13.8 kV, and operate with reduced capacity during faults. The number of submodules in each phase can be increased to achieve higher operating voltage. However, CHB and CNPC requires a phase-shifting transformer with multiple secondary windings to generate isolated DC sources. The transformer increases the overall size and cost of the converter system [7–12]. The details and commercial products based on the above converter topologies are presented in the following subsections.

Recently, the MMC has been developed to address the problems associated with the current cascaded converter topologies. MMC preserves the features of cascaded converters and do not require isolated DC sources. Hence, the phase-shifting transformer can be eliminated, which significantly minimizes the cost and size of the converter system. The unique features of MMC are that, it can reach an operating voltage up to 400 kV without a transformer. This most prominent feature is exploited and successfully applied in various industrial applications. This book mainly focused on the control and applications of MMCs, and are separately discussed in Section 1.6.

1.3.1 Neutral-Point Clamped Converter

Three-level neutral-point clamped (3L-NPC) converters are basically composed of two traditional two-level VSCs stacked one over the other with some minor modifications as shown in Figure 1.3. The negative bar of the upper converter and the positive bar of the lower converter are joined to form a new output phase, whereas the original output terminals are connected via two clamping diodes to form a neutral point “*o*” [9, 11].

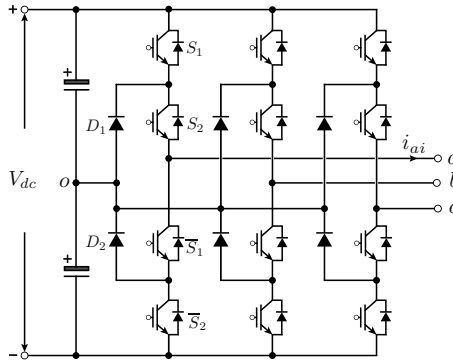


Figure 1.3 Three-level neutral-point clamped converter.

The neutral point divides the total DC-link voltage into two halves. Each power device has to block only half of the total DC-link voltage. With the same semiconductor technology, the operating voltage and power rating of the 3L-NPC converter can be doubled compared to that of a two-level converter. The neutral point of 3L-NPC enables the generation of zero voltage level along with $-\frac{V_{dc}}{2}$ and $+\frac{V_{dc}}{2}$. This process results in low $\frac{dv}{dt}$ and harmonic content in the output voltage and current waveforms.

One of the major problems in 3L-NPC is the neutral-point voltage balancing and low-frequency ripple at higher modulation indices [13, 14]. The neutral-point voltage oscillations increase the voltage stress on devices and generate a sixth-order harmonics in the output voltage. Traditionally, the DC-link capacitance is significantly increased to minimize the voltage oscillations. On the other hand, several modulation

schemes have been presented to address the issue of neutral-point voltage balancing in the literature [15, 16]. Among them, the carrier based PWM schemes are simple and easy to implement. In this approach, the zero sequence voltage included in the reference voltage. The injected zero sequence voltage does not affect the output line voltages, and it is only influence the device switching states and neutral point potential [15, 16].

Alternatively, the nearest three vectors and virtual vector based space vector modulation (SVM) schemes are presented for the 3L-NPC [15, 16]. In these approaches, redundant switching vectors are employed to balance the neutral-point potential. The zero sequence voltage and neutral-point current are important variables used in the selection of redundant switching vectors [15, 16].

The NPC topology with a higher number of voltage levels is required for high-power applications. Hence, the NPC topology requires additional power devices, clamping diodes, and DC capacitors to increase the number of output voltage levels. However, the NPC with a higher number of voltage levels is preferable because of the uneven distribution of power losses between the outer and inner devices. Also, the series connection of clamping diodes is required to block the total DC-link voltage. The series connection of devices introduces additional conduction losses and produces reverse recovery currents during the commutation that affects the switching losses of other devices. Furthermore, the balancing of DC-link capacitor voltages is difficult to achieve over the entire operating range [9, 11].

Table 1.2 Selection of devices in 3L-NPC

System Voltage	Device Rating
2.3 kV	3.3 kV
3.3 kV	4.5 kV
4.16 kV	6.5 kV

Among the high-power converters shown in Figure 1.2, the 3L-NPC is the most widely used in all industrial applications in the range of 2.3–6.6 kV. The rating of semiconductor devices in NPC is selected based on the system voltage as shown in Table 1.2. A 3L-NPC converter requires 3.3 kV devices to handle a voltage of 2.3 kV [17]. With the current semiconductor technology, 3L-NPC allows an output voltage up to 4.16 kV without connecting the devices in series. Today, several manufacturers offer 3L-NPC with different type of devices and system voltages as indicated in Table 1.3. Asea Brown Boveri (ABB) offers 3.3 kV converters with 4.5 kV IGCT, Convertteam offers 3.3 kV converters with 4.5 kV press-pack IGBT technology, and Siemens offers a range of 2.3–6.6 kV converters with 3.3 kV and 6.5 kV IGBT technology.

Table 1.3 Market overview of VSCs for medium-voltage drives

Topology	Manufacturer	Product Model	Power (MVA)	Voltage (kV)	Semiconductor
3L-NPC	ABB	ACS 1000	0.3–5	2.3–4.16	IGCT
		ACS 6000	3.0–27	2.3–3.3	IGCT
	Converteam	VDM 7000	7–9.5	3.3	GTO/MV-IGBT
		MV 7000	0.4–40	1.25–6.6	IGCT/HV-IGBT
	Siemens	Sinamics GM150	0.6–10.1	2.3–6.6	MV-IGBT
		SM 150	5–28	3.3	IGCT
	TMEIC-GE	Dura-Bilt5i MV	0.3–2.4	4.16	IGBT
	Ingedrive	Ingedrive MV100	0.8–15	3.15–4.16	HV-IGBT
		Ingedrive MV500	6–36	3.15–3.3	IGCT
3L-ANPC	ABB	PCS 8000	6–100	6–220	IGCT
4L-FC	Alstom	VDM 6000	0.3–8	2.3–4.2	MV-IGBT
CHB	Siemens	Perfect Harmony	0.3–30	2.3–13.8	LV-IGBT
	Hitachi	Hivectol-HVI-E	0.31–10	2.3–11	IGBT
	LS Ind. Systems	LS MV Drive	0.2–3	3.3–6.6	IGBT
	Schneider	HARSVERT-A	0.25–6.25	3.3–11	LV-IGBT
	Rongxin Power	MVC	0.25–10	10	IGBT
	Rockwell Automation	PF6000	0.2–5.6	3–11	IGBT
5L-HNPC	ABB	ACS 5000	1.7–27	6–6.9	IGCT
	TMEIC-GE	TMdrive-XL85	30–120	7.2	GCT
MMC	Siemens	Sinamics SM120	6–13.7	3.3–7.2	IGBT
	Benshaw	M2L 3000	0.224–7.466	2.3–6.6	IGBT

1.3.2 Active Neutral-Point Clamped Converter

One of the drawbacks of the 3L-NPC is the unequal loss distribution between the inner and outer semiconductor devices in each leg. Thus, the semiconductor devices are cooled with separate heat sinks and cooling systems, resulting in the asymmetrical distribution of junction temperatures between the semiconductor devices. This process affects the cooling system design and limits the output power and switching frequency of the converter. This drawback is overcome by replacing the clamping diodes with active switches as illustrated in Figure 1.4. The corresponding circuit configuration is called active neutral-point clamped converter (ANPC) [18, 19]. The active switches provide a controllable path for the neutral-point current, which al-

lows the symmetrical loss distribution among the devices and helps to balance the neutral-point voltage [3, 8, 10].

The three-level ANPC is commercially available in the form of a back-to-back configuration by ABB as shown in Table 1.3. This configuration covers a power range of 20–200 MVA and can be connected to a 200 kV grid through a transformer. The ANPC concept is extended to a five-level hybrid multilevel converter, which combines a 3L-ANPC leg with a three-level flying capacitor cell. This circuit configuration effectively increases the number of output voltage levels and is referred to as a five-level ANPC [20]. The five-level ANPC is commercially introduced in a back-to-back configuration for an operating voltage of 6–6.9 kV and 0.4–1 MVA power capacity with a maximum output frequency of 75 Hz.

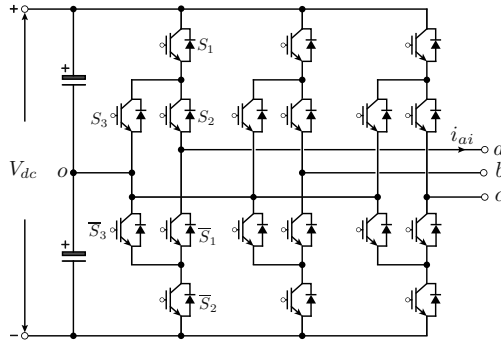


Figure 1.4 Three-level active neutral-point clamped converter.

1.3.3 Flying Capacitor Converter

A flying capacitor (FC) converter is quite similar to the NPC converter, provided that the clamping diodes in NPC are replaced with flying capacitors as shown in Figure 1.5. In FC converter, each pair of semiconductor devices with a flying capacitor forms a power cell. The number of output voltage levels can be increased by adding the power cells to a converter. Thus, it is considered as a modular converter [9].

The circuit configuration of four-level FC (4L-FC) topology is shown in Figure 1.5. The 4L-FC topology has two flying capacitors C_{c1} and C_{c2} with rated voltages of $\frac{V_{dc}}{3}$ and $\frac{2V_{dc}}{3}$, respectively, and six semiconductor devices with a voltage rating of $\frac{V_{dc}}{3}$. The flying capacitors have zero initial voltage and must be regulated at their rated value to generate a four-level voltage waveform at the output. Hence, the FC converter requires an additional pre-charging circuit during the start-up process and balancing control during steady-state operation. The natural voltage balancing of flying capacitors can be obtained by using the phase-shifted carrier modulation (PSC-PWM) scheme with high carrier frequency [21]. Also, the PSC-PWM scheme ensures symmetrical loss distribution among the devices, which makes this topol-

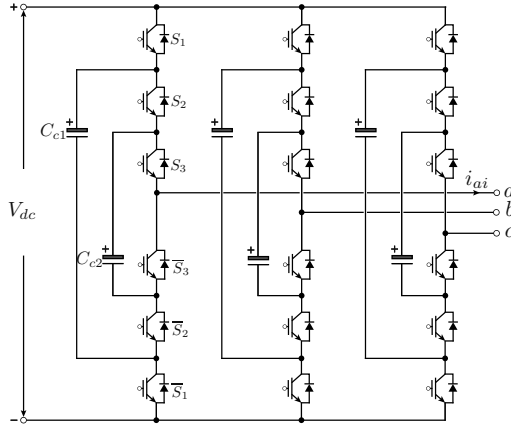


Figure 1.5 Four-level flying capacitor converter.

ogy more attractive for the high-speed drives or applications with low current ripple requirements.

The capacitor voltage ripple is one of the major drawbacks in the flying capacitor converter. The magnitude of the voltage ripple proportionally increases with the magnitude of the load current and is inversely proportional to the switching frequency. To maintain the voltage ripple within the permissible limits, either large-size flying capacitors or a higher switching frequency is required. The larger size of the flying capacitors significantly increases the cost and size of the converter. Also, the converter operation at higher switching frequency increases the switching losses and effects the converter efficiency. These issues limit the application of flying capacitor converters to the medium switching frequency applications only. The 4L-FC topology is commercially available for traction applications and pumps in the water industry. The 4L-FC converter is equipped with a medium voltage IGBT technology and available for an operating voltage of 2.3–4.2 kV and 0.3–8 MVA power capacity as shown in Table 1.3.

1.3.4 Nested Neutral-Point Clamped Converter

Nested neutral-point clamped (NNPC) converter is a recent development in multilevel converters. NNPC combines the structure of an NPC converter and FC converter as shown in Figure 1.6. The flying capacitor in NNPC is divided into two equal parts, and its mid-point is clamped with the diodes. The flying capacitor voltage is maintained at one-third of the total DC-bus voltage such that the NNPC generates a four-level voltage waveform at the output. Also, the switching devices block identical voltages during reverse blocking mode [22]. The nested neutral-point clamped converter requires fewer semiconductor devices and passive components compared to that of other four-level multilevel converter topologies [22, 23].

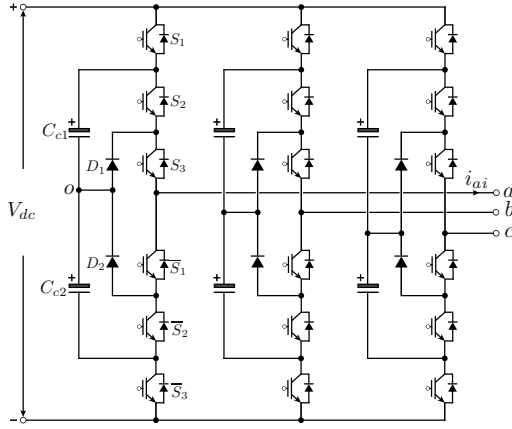


Figure 1.6 Four-level nested neutral-point clamped converter.

In NNPC converter, the load current charges and discharges the flying capacitors, causing voltage ripple. The voltage ripple in the flying capacitors is very high during the low-speed operation, resulting in a poor quality of voltage and current waveforms at the output. Also, the voltage ripple increases the voltage stress on devices and capacitors, which leads to a possible device failure and affects the reliability of the converter. Similar to the FC converter, the NNPC converter requires large-sized capacitors or injection of common-mode voltage with modulation signals to minimize the voltage ripple. The voltage ripple minimization and capacitor voltage balancing at a low-speed operation are the current research focus.

A four-level NNPC converter can operate at a voltage range of 2.4–7.2 kV without devices in series. The other variations of nested neutral-point clamped converter are five-level NNPC and cascaded NNPC converter topologies, which are designed to handle higher operating voltages. Cascaded NNPC converter topology can handle a voltage of 10 kV and requires a phase-shifting transformer to generate the isolated DC sources [24, 25].

1.3.5 Cascaded H-bridge Converter

Multilevel converters such as NPC, ANPC, FC, and NNPC topologies can handle a voltage up to 6.6 kV without devices in series. These topologies are not cost-effective for an operating voltage greater than 6.6 kV. Cascaded converter topologies can handle voltages greater than 6.6 kV (up to 13.8 kV) using low-cost, and low-voltage IGBT technology. The most popular cascaded converter topology is the CHB converter, which consists of several three-level H-bridge power modules in cascade as shown in Figure 1.7. Each H-bridge power module requires an isolated DC source, which is generated using a phase-shifting transformer with multiple secondary windings and a diode bridge rectifier. In regenerative applications, the three-phase, two-

level VSC is used instead of a diode bridge rectifier [8, 12, 26]. The transformer and rectifier configuration forms a multi-pulse rectifier on an AC-grid side, which improves the power quality and eliminates the dominant harmonic components from the AC grid voltage.

The series connection of H-bridge power modules naturally increases the converter voltage, and consequently the power rating. The output voltage waveform with a higher number of voltage levels and lowest harmonic distortion can be obtained. The number of voltage levels in the output voltage is $2N + 1$, where N represents the number of H-bridge power modules per phase. However, the CHB topology requires a large number of isolated DC sources to power each H-bridge, which limits the number of H-bridge power modules in each phase. Also, the CHB topology requires a complicated phase-shifting transformer, which increases the volume, size, and cost of the overall converter system.

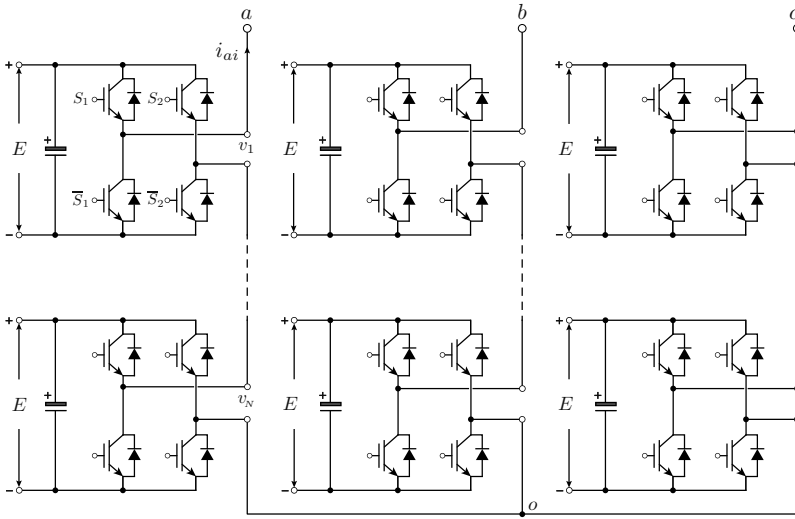


Figure 1.7 Cascaded H-bridge converter.

The CHB topology has a modular construction and allows the fault-tolerant operation with redundant power modules [27]. The CHB topology is commercially available in different numbers of voltage levels with a maximum operating voltage of 13.8 kV as shown in Table 1.3. Siemens developed a CHB topology with 17 voltage levels to handle a system voltage of 13.8 kV. This topology uses low-voltage IGBT technology that is available in the market under the trade name *Perfect Harmony*. In CHB topology, each H-bridge DC source voltage is maintained at an identical value. This topology is referred to as a symmetrical CHB. It is also possible to maintain a certain DC voltage ratio between the H-bridge power modules. Hence, an output voltage waveform with the higher number of voltage levels can be obtained without

increasing the number of H-bridge power modules in each phase. This topology is referred to as an asymmetrical CHB.

The asymmetrical CHB concept is introduced for magnetic resonance imaging applications with the powers of two voltage ratios ($1 : 2 : \dots : 2^{N-1}$). This ratio allows the generation of seven-level voltage waveform with two H-bridge power modules per phase. Another important voltage ratio called powers of three ($1 : 3 : \dots : 3^{N-1}$) was introduced, which eliminates all redundant switching states and maximizes the number of voltage levels at the output. This converter is referred to as a “ternary hybrid multilevel converter.” Aside from the exponential increase in the number of voltage levels, the asymmetrical topology minimizes the switching losses and improves the efficiency [7, 10]. However, it requires devices with different voltage ratings to build the H-bridge modules, and different thermal designs for each power module. Hence, the modularity feature no longer exists in the asymmetrical CHB.

1.3.6 Cascaded Neutral-Point Clamped Converter

Asymmetrical CHB converter generates an output voltage with a higher number of levels using a smaller number of lower H-bridge power modules in each phase. This topology loses the modularity feature and requires the devices with different voltage ratings and thermal designs. These drawbacks can overcome by replacing the three-level H-bridge power modules with other multilevel converters. One of the most popular topologies is the cascaded neutral-point clamped converter (CNPC), which is shown in Figure 1.8. This topology uses two three-level neutral-point clamped converter legs to form an H-bridge structure in each phase, which is referred to as an HNPC.

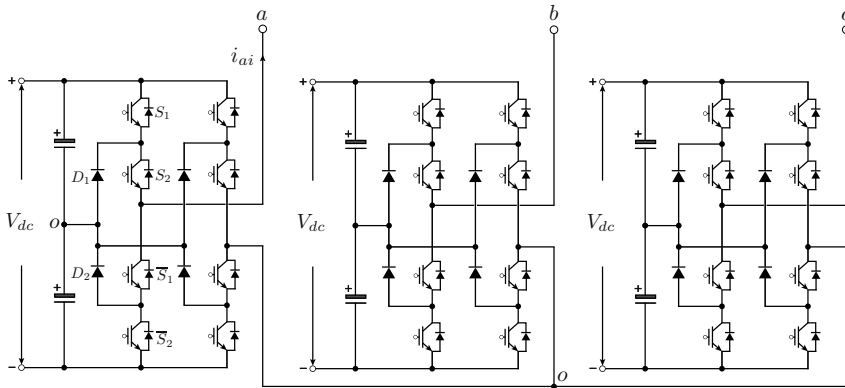


Figure 1.8 Cascaded neutral-point clamped converter.

Each HNPC power module generates a five-level voltage waveform at the output [3, 10, 28]. The HNPC power module uses identical voltage rated devices and capacitors, unlike asymmetrical CHB converter. Due to the control complexity, the number of HNPC modules in the cascaded neutral-point clamped converter is limited to one. Also, the CNPC converter requires a phase-shifting transformer with a rectifier unit to generate the isolated DC source for each HNPC module. Thus, the maximum operating voltage of the cascaded neutral-point clamped converter is limited to 6.6–7.2 kV without devices in series. The five-level CNPC converter is commercially available with a 36-pulse rectifier system featuring IGCT devices for compressors and conveyor applications. Several other topologies were developed with a maximum operating voltage of 7.2 kV, featuring MV-IGBTs, IEGT, and GCT devices as presented in Table 1.3.

1.4 CURRENT SOURCE CONVERTERS

The current source converter (CSC) technology is well suited for high-power applications. The main features of CSC include a simple converter structure, low switch count, low switching $\frac{dv}{dt}$, reliable, and over current and short-circuit protection, unlike VSCs. Despite all of these advantages, it has a limited dynamic performance because of the large DC inductor used in the DC-link [3, 5]. The CSCs are classified into load-commutated current source converter (LC-CSC) and pulse width modulated current source converter (PWM-CSC) as shown in Figure 1.9. These topologies are briefly discussed in the following subsections.

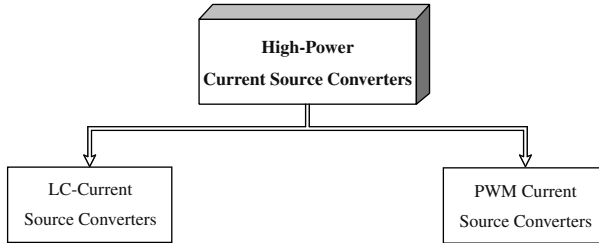


Figure 1.9 Classification of current source converter.

1.4.1 Load-Commutated Current Source Converter

The load-commutated current source converter (LC-CSC) is one of the earliest topologies used in the high-power variable speed drives and HVDC systems. The thyristor devices are employed in the LC-CSC topology as shown in Figure 1.10. The phase-controlled thyristor rectifier is used to adjust the magnitude of DC-bus current i_{dc} . The DC inductor smoothened the DC-link current and fed to the LC-CSC. The thyristor devices in LC-CSC does not have the self-turn-off capability. These devices are

naturally commutated by the load voltage with a leading power factor. Therefore, the ideal load for the LC-CSC is a synchronous motor that operates at a leading power factor. The leading power factor operation can be easily achieved by adjusting the rotor field current of a synchronous motor [5]. On the other hand, the rectifier input current is highly distorted. Hence, the LC-CSC fed drives are equipped with harmonic filters to reduce the line current harmonic distortion. These filters can also serve as a power factor compensator.

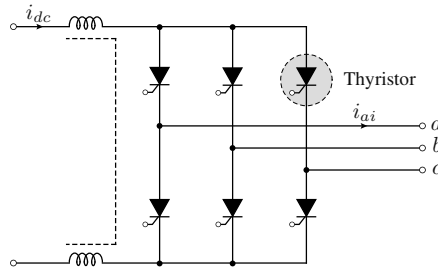


Figure 1.10 Load-commutated current source converter.

The thyristor is a natural-commutated device that has low power losses and high-efficiency. Therefore, LC-CSCs are suitable for very large electric drives with tens of megawatt power capacity. The use of thyristor leads to a lower manufacturing cost and high reliability compared to that of other motor drives based on IGBT and IGCT devices. A typical example of LC-CSC drive is a 100 MW synchronous motor drive installed in NASA's wind tunnel facility [5]. Several commercial products based on the LC-CSCs were developed by the leading industrial manufacturers, such as Siemens, ABB, and Alstom as indicated in Table 1.4. These products have a maximum power rating greater than 70 MW with a maximum operating voltage greater than 10 kV.

Table 1.4 Market overview of CSCs for MV drives

Topology	Manufacturer	Product Model	Power (MVA)	Voltage (kV)	Semiconductor
LC-CSC	Siemens	Sinamics GL150	2.8–75	2.3–12	Thyristor
	ABB	MEGADRIVE-LCI	2.0–72	2.1–10	
	Alstom	ALSPA SD7000	2.0–100	1.0–10	
PWM-CSC	Rockwell Automation	Power Flex 7000	0.15–25.4	2.4–6.6	SGCT

1.4.2 PWM Current Source Converter

Unlike LC-CSC, the pulse width modulated current source converters (PWM-CSC) use force-commutated devices such as GTO and GCT. Therefore, the induction motors and synchronous motors can be employed in PWM-CSC fed drives. The PWM-CSC is also used in the grid integration of offshore wind farms and HVDC systems. PWM-CSC can be controlled by employing a pulse width modulation scheme such as selective harmonic elimination (SHE), trapezoidal-PWM, and current space vector modulation [5, 28–30]. The typical configuration of SGCT based PWM-CSC is shown in Figure 1.11. The PWM-CSC requires a three-phase capacitor (C_f) at its output to assist the commutation of SGCT devices. The capacitor provides a current path for the energy trapped in the leakage inductance of a motor when SGCT is turned off. Otherwise, a high-voltage spike would be induced and damage the switching devices. The capacitor C_f also serves as a harmonic filter, thus improves the motor current and voltage waveform quality [28].

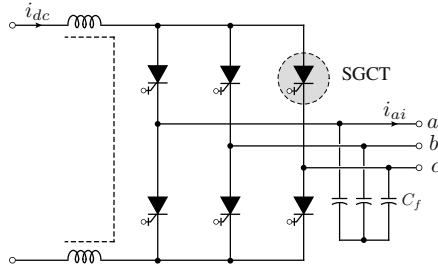


Figure 1.11 Pulse width modulated current source converter.

PWM-CSC generates a common-mode voltage across the motor terminals, causing premature failure of motor winding insulation and motor bearings. PWM-CSC fed drive requires an isolation transformer to block the common-mode voltages [31]. The transformer leakage inductance also serves as a harmonic filter and reduces the line current harmonic distortion. This transformer can be arranged with multiple phase-shifted secondary windings for harmonic cancellation in multi-pulse rectifiers [5].

The modern PWM-CSC fed drives consist of an integrated common-mode DC inductor in place of a conventional DC inductor. The integrated common-mode DC inductor consists of both differential and common-mode inductance, and effectively blocks the common-mode voltage. The integrated inductor eliminates the isolation transformer and significantly reduces the overall drive cost, size, and weight [31]. Modern PWM-CSC fed drive with an integrated common-mode DC inductor is referred to as a transformer-less drive. The transformer-less drives are developed by Rockwell Automation and are commercially available under the trade name Power Flex 7000 as shown in Table 1.4. Power Flex 7000 is available with a targeted voltage range of 2.4–6.6 kV and power capacity of 0.15–25.4 MVA.

1.5 MATRIX CONVERTERS

The matrix converter (MC) is a force-commutated converter that belongs to the direct AC–AC power conversion family. Unlike CCVs, the matrix converter (MC) employs fully controllable IGBT devices, and are controlled with PWM schemes. The conventional matrix converter has three inputs and three outputs only. However, it can be extended to any number of inputs and outputs, depending on the application. The main features of MC are four-quadrant operation and fast dynamic response because of the single-stage power conversion. It provides a sinusoidal input and output waveforms with controllable input power factor. The output frequency can be adjusted to either higher or lower than that of the input frequency [32–34]. Despite all of these advantages, the major issues in matrix converters are commutation problems, switching losses, and leakage currents because of the common-mode voltage [35–37]. The matrix converters are classified into direct matrix converter (DMC), indirect matrix converter (IMC), and multi-modular matrix converter (MMMC) as shown in Figure 1.12. These converters are discussed in the following subsections.

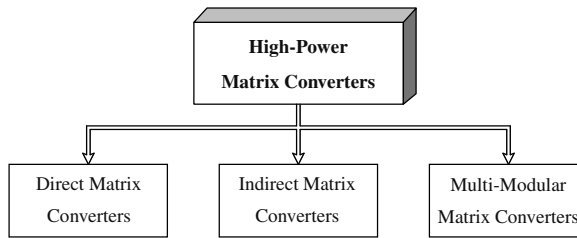


Figure 1.12 Classification of matrix power converters.

1.5.1 Direct Matrix Converter

Figure 1.13 shows the configuration of a three input and three output direct matrix converter (DMC), where input phases (a_g, b_g, c_g) are directly connected to the output phases (a_i, b_i, c_i) through bidirectional switches and an input filter. The bidirectional switches should carry the current and block the voltage in both the directions [38]. These switches are implemented by an anti-series connection of two IGBT devices (with a common collector or emitter) as shown in Figure 1.13. The input filter (C_f) is designed to attenuate the higher-order harmonic components in the input current and to reduce the input voltage harmonic distortion.

Direct matrix converters have several issues such as the maximum voltage transfer ratio from the input to the output; that is limited to 0.5 in the linear modulation region. Also, there is limited control over the input power factor. Several switching methods are presented in the literature to increase the voltage transfer ratio. The switching method based on the three line–line input voltages produce a 0.75, and two line–line input voltages produce a 0.866 transfer ratio with input power factor

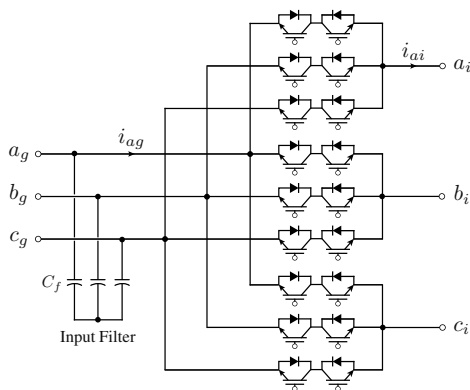


Figure 1.13 Configuration of direct matrix converter.

control in the entire operating range [39]. However, these methods cause a low-frequency distortion in the input currents and the output voltages.

Space vector modulation (SVM) approach is exploited and successfully used in the control of the matrix converters. This approach has full control over the instantaneous value of output voltages and the input power factor and provides a voltage ratio of 0.866. The SVM approach is further improved to achieve a voltage ratio of 1.155 at the cost of high-switching frequency. The other major issue is the simultaneous commutation of bidirectional switches without generating an over current or over voltage spikes during the interruption of inductive load current. This problem is solved with the multi-step commutation techniques, which allows the safe operation of devices [38].

The direct matrix converters are commercially used in the low-voltage motor drive products of FRENIC-MC series by Fuji Electric Systems and, AC7 and U1000 Matrix drive by Yaskawa. These products are available in 30 kW at 230 V input and 45 kW at 480 V input options.

1.5.2 Indirect Matrix Converter

Unlike direct matrix converters, the indirect matrix converters (IMC) consist of a rectifier stage and an inverter stage. The rectifier stage is constructed with either unidirectional or bidirectional switches, and an inverter stage is constructed using a conventional two-level voltage source converter (2L-VSC) as shown in Figure 1.14. Therefore, the conventional modulation schemes such as carrier and space vector modulation schemes can be independently applied to the rectifier and inverter stages. The main features of indirect matrix converter include the elimination of commutation problem presented in the DMC, and less number of devices is required compared to that of the DMC [37, 40]. However, the voltage transfer ratio remains the same as that of the DMC. The Z-source network is employed in the IMC to increase the voltage transfer ratio.

The performance of the IMC can be improved by replacing the 2L-VSC with a multilevel VSC technology, such as NPC and FC converters. These topologies are referred to as multilevel matrix converters. The multilevel VSC generates a stepped voltage waveform at the motor terminals and reduces the voltage harmonic distortion and switching $\frac{dv}{dt}$.

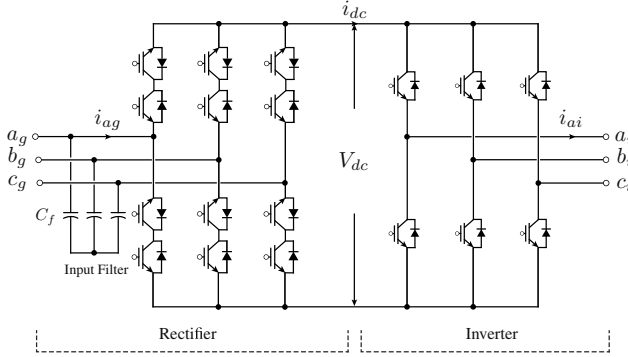


Figure 1.14 Configuration of indirect matrix converter.

1.5.3 Multi-Modular Matrix Converter

The direct and indirect matrix converters are available for low-voltage, and low-power applications only. These topologies are difficult to apply for the medium- and high-voltage, and high-power applications because of the limited voltage rating of semiconductor devices. The modular multilevel converter technology is employed to increase the voltage and power rating of the matrix converters. This new converter technology is referred to as an multi-modular matrix converter (MMMC) or cascaded matrix converter as shown in Figure 1.15.

The multi-modular matrix converter consists of identical power modules in each phase [41, 42]. These power modules are simple three input and two output direct matrix converters (3 x 2 DMC) as shown in Figure 1.16. The three-phase input of each power module is connected to the AC grid through a phase-shifting transformer. This phase-shifting transformer provides an isolation and improves the input and output power quality. However, the transformer increases the weight and volume of the converter. The output of each 3 x 2 DMC module is connected in cascade to increase the number of voltage levels. Several power modules such as regenerative H-bridge and non-regenerative H-bridge modules are studied for MMMC [43]. These power modules are built with low-voltage IGBT technology.

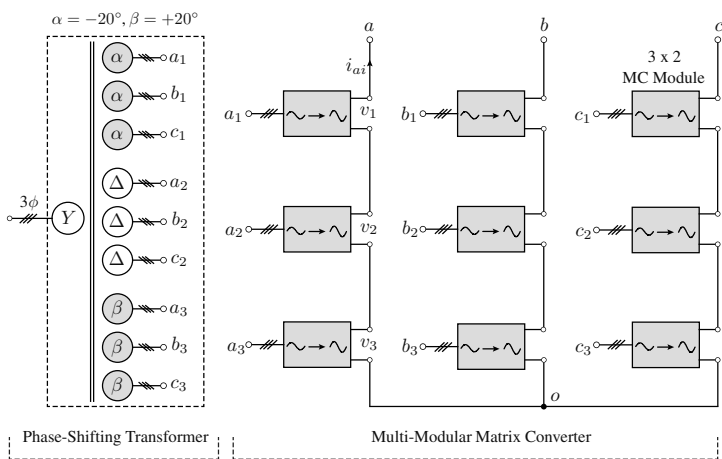


Figure 1.15 Configuration of multi-modular matrix converter.

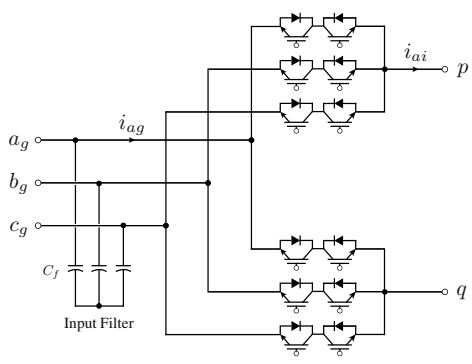


Figure 1.16 Configuration of 3 x 2 matrix converter.

Multi-modular matrix converters are commercially available for the medium-voltage motor drives, and their specifications are shown in Table 1.5. The commercial product FSDrive MX1S is designed by Yaskawa with a targeted voltage of 3 kV with a power rating of 0.2–3 MVA, and 6.6 kV with a power rating of 0.4–6 MVA. This product consists of 3 x 2 DMC modules in each phase (three modules per phase for 3 kV and six modules per phase for 6.6 kV drive).

Table 1.5 Market overview of MCs for MV drives

Topology	Manufacturer	Product Model	Power (MVA)	Voltage (kV)	Semiconductor
MMMC	Yaskawa	FSDrive MX1S	0.2–6	3–6.6	IGBT

1.6 MODULAR MULTILEVEL CONVERTERS

Cascaded converter topologies have a modular construction, voltage and power scalability with a cascade connection of power modules, fault-tolerant operation, and high reliability and use a low-cost, low-voltage semiconductor technology, unlike other multilevel converters. These topologies can achieve higher operating voltages without the series connection of semiconductor devices. However, the cascaded converter topologies require a large number of isolated DC sources and complicated phase-shifting transformer with multiple secondary windings. The phase-shifting transformer improves the power quality on the AC grid side, but increases the overall size and cost of the converter.

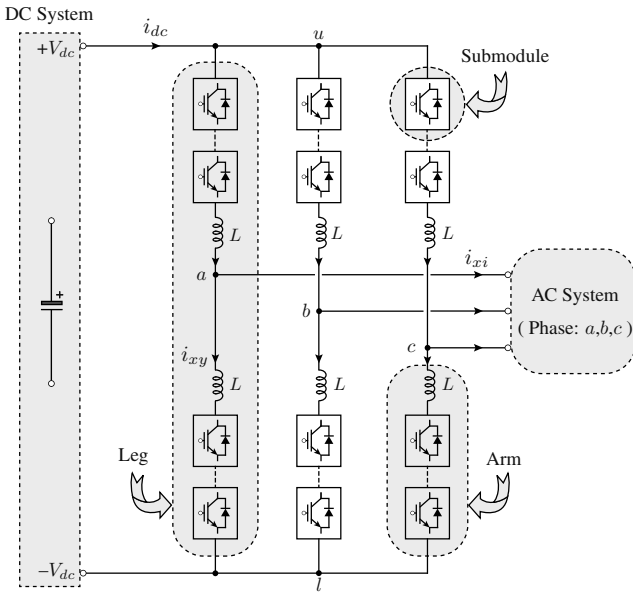


Figure 1.17 Configuration of modular multilevel converter.

The MMC is one of the recent developments in the multi-cell converter family [44, 45]. The MMC preserves the features of cascaded converter topologies and does not require isolated DC sources and complicated phase-shifting transformer. Therefore, MMCs can reach any operating voltage from the medium (2.3–13.8 kV) to high-voltage (33–400 kV) and power rating of 0.226–1000 MW. These features have attracted researchers from both industry and the academia and developed several commercial products for a wide range of high-power applications, such as medium-voltage motor drives, HVDC transmission systems, multi-terminal HVDC systems, offshore wind farms, and static synchronous compensators (STATCOM). The MMC also requires a complex control structure to meet several control objectives [44, 46,

47]. The applications and technical challenges associated with the operation and control of MMC are presented in the following subsections.

1.6.1 Converter Technology

The circuit configuration of the MMC is shown in Figure 1.17. The voltage and power capacity of MMC can be naturally increased by adding the submodules in each arm. Similar to other cascaded converter topologies, any power converter circuit such as full-bridge or H-bridge, flying capacitor, and neutral-point clamped converters can be utilized as a submodule (SM) in MMC [48, 49]. The three-phase MMC can be extended to multi-phase applications because of its modular construction. Several submodule topologies have been developed in the past few years to meet the application requirements. The details of the most widely used submodule configurations are presented in the Chapter 2. These submodules have floating capacitors and are pre-charged through the DC system, unlike other cascaded converter topologies. For the safe and reliable operation of MMC, the submodule capacitor voltage in each arm must be maintained at their nominal value. The implementation of capacitors voltage control methods is discussed in the Chapter 3. Each arm of MMC has an inductor to limit the inrush and circulating currents during the start-up and steady-state operation of MMC [50, 51]. However, the complete elimination of circulating currents is necessary to minimize the converter power losses and to improve the efficiency. The circulating current control methods are presented in the Chapter 3.

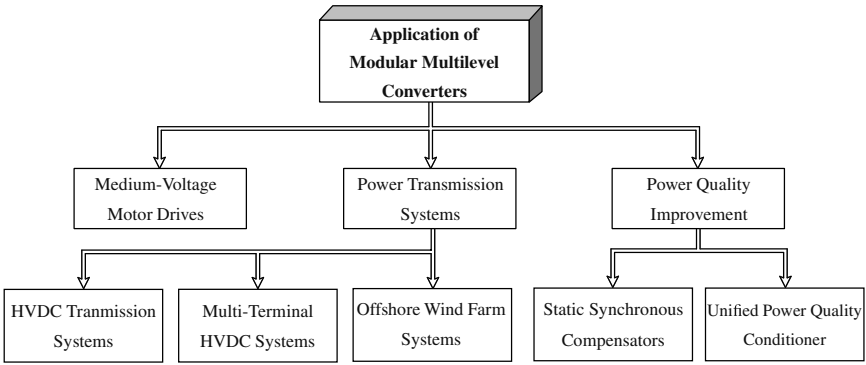


Figure 1.18 Applications of modular multilevel converter.

1.6.2 Applications

Modular multilevel converters are commercialized in the form of various standard and customized products for high-power applications. MMC is used in several industrial applications such as motor drives, power transmission systems, and power quality improvement as shown in Figure 1.18. In this book, the most popular applications

such as medium-voltage motor drives, HVDC transmission systems, multi-terminal HVDC systems, offshore wind farms, static synchronous compensator (STATCOM), and unified power quality conditioner (UPQC) are discussed in detail [50, 51]. The summary of commercially available MMC-based products is presented as well.

(1) Medium-Voltage Motor Drives: One of the applications of MMC is the medium-voltage motor drive system. The MMC offers a simple voltage scalability by connecting the SMs in series, operating with standard motors without output filters, and offers a simple construction with less engineering effort, unlike conventional multi-level converters.

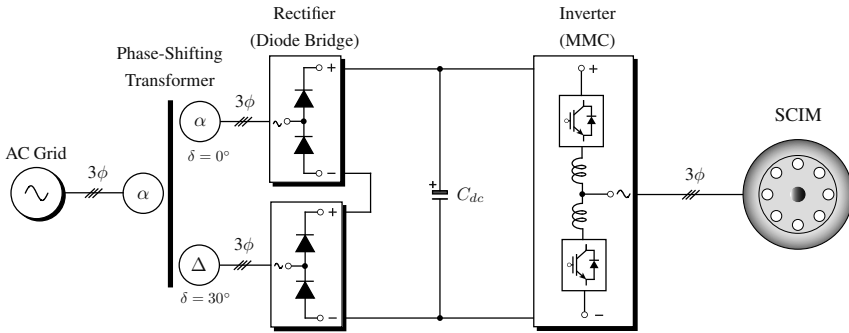


Figure 1.19 MMC-based motor drive with passive rectifier.

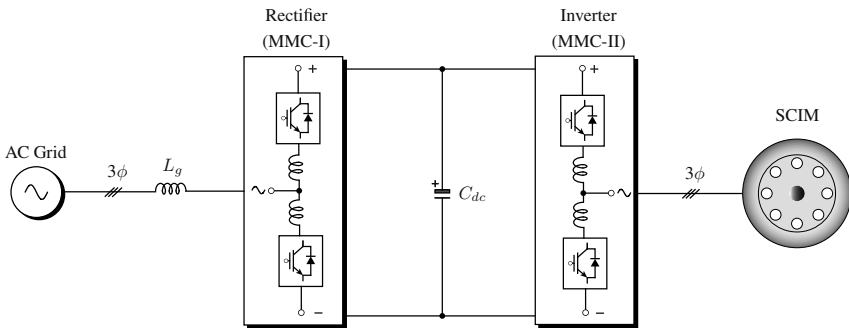


Figure 1.20 MMC-based motor drive with active rectifier.

The typical configuration of MMC-based medium-voltage motor drive developed by the Benshaw is shown in Figure 1.19. The motor drive uses a 12-pulse diode rectifier on the AC grid side and an MMC with a cascade half-bridge submodule on the motor side. The 12-pulse rectifier eliminates the lower-order harmonics in the line current and improves power quality on the AC grid side. Also, the transformer on the AC grid side blocks the common-mode current from entering into the system. On the other hand, the MMC consists of six submodules in each arm and generates a

phase-voltage with 13 levels at the motor terminals. Hence, the output filters are not required.

For regenerative applications, the motor drive systems employ MMCs on both the AC grid and motor side as shown in Figure 1.20. The MMC-I is controlled with a voltage-oriented control (VOC) approach, and generates a sinusoidal current on the AC grid side and improves the grid power factor. The MMC-II is controlled with a field-oriented control (FOC) to meet the motor requirements such as speed and torque. An in-depth analysis and control of MMC-fed motor drive systems are presented in the Chapter 8. Currently, the MMC-based motor drives are commercially available with a maximum voltage of 7.2 kV and power rating of 13.7 MVA by Siemens as indicated in Table 1.6.

Table 1.6 Market overview of MMC-based motor drive systems

Project Name	Power (MVA)	Voltage (kV)	Developed by
Sinamics SM120 MV Drive	6–13.7	3.3–7.2	Siemens
M2L 3000 Series MV Drive	0.224–7.466	2.3–6.6	Benshaw

(2) HVDC Transmission Systems: HVDC systems are employed to interconnect two asynchronous AC systems over a long distance using a back-to-back converter configuration. The HVDC system can be implemented with either CSCs or VSCs. The CSC-based HVDC system works effectively with silicon-controlled rectifier (SCR) devices and can handle higher powers and voltage ratings than that of the IGBT-based VSC-HVDC system. However, the VSC overcomes the important disadvantages of CSCs such as the reduction of harmonic distortion on both the AC and DC side. Thus, the size of output filters can be reduced. Also, the active and reactive powers can be independently controlled, and ability to operate with weak AC grids.

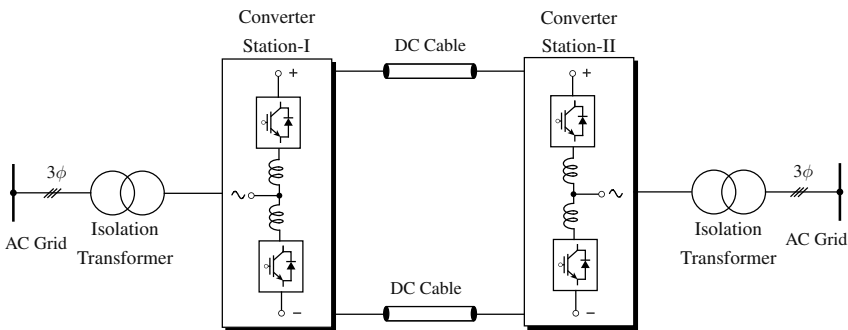


Figure 1.21 MMC-based HVDC system.

Table 1.7 Market overview of MMC-based HVDC systems

Project Name	Power (MW)	Voltage (±kV)	DC Cable (km)	Company	HVDC Tech.
Trans Bay	400	200	85	Siemens	HVDC Plus
INELFE	2 x 1000	320	65	Siemens	HVDC Plus
Sydvestlanken	2 x 720	300	260	Alstom	HVDC MaxSine
Piemonte-Savoia	2 x 600	320	190	Alstom	HVDC MaxSine
Dalian City Feed	1000	320	43	C-EPRI	HVDC Flexible
Xiamen Island HVDC	1000	320	10.7	C-EPRI	HVDC Flexible

A typical MMC-based VSC-HVDC transmission system is shown in Figure 1.21, where the MMC is employed in converter station-I and station-II. The AC system of converter station-I and II is connected to the AC grid through an isolation transformer, and their DC systems are inter-connected through a DC cable several kilometers long. The MMC provides a high-quality output voltage and current waveforms and eliminates the need for harmonic filters in the DC and AC system side.

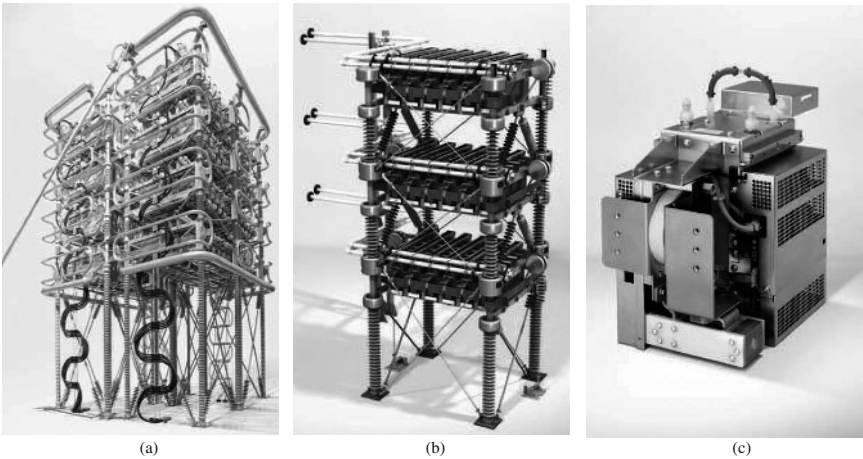


Figure 1.22 MMC-based HVDC plus technology : (a) converter leg, (b) converter arm, and (c) submodule (Courtesy: Siemens).

Currently, four types of MMC-based HVDC technologies were commercialized as follows: HVDC Plus, HVDC Light Gen.4, HVDC Flexible, and HVDC MaxSine, which can reach up to a voltage ± 320 kV [52]. The list of MMC-based HVDC projects is summarized in Table 1.7. These technologies adopt different type of submodules and arm structure to configure the MMC. San Francisco’s Trans Bay project is the first MMC-based HVDC system installed by Siemens

in 2010. This project supplies a power 400 MW at a voltage rating of ± 200 kV through a sub-sea cable 85 km long. In this project, the half-bridge submodules are connected in cascade to form an MMC. In HVDC MaxSine technology, the full-bridge submodules along with IGBT devices are connected in series to form the MMC. These variations of HVDC technologies and possible submodule configurations are discussed in the Chapters 2 and 9.

Commercially available MMC-based Siemens HVDC technology is presented in Figure 1.22. MMC consists of 200 half-bridge submodules in each arm to handle a voltage of ± 200 kV. The structure of half-bridge submodule is shown in Figure 1.22, which includes the protection, cooling, sensor boards, local controller, and communication circuits to the central controller. Currently, the MMC handles a power of 1000 MW at a voltage of ± 320 kV.

(3) Multi-Terminal HVDC Systems: A typical configuration of MMC-based multi-terminal HVDC system is shown in Figure 1.23, which allows the interconnection of different HVDC systems to form an HVDC grid with high controllability, efficiency, and reliability unlike that of the AC grid. The DC system of MMCs are interconnected through the DC cable, and the AC system is connected to the AC-grid through an isolation transformer. The power converters are used to control the active and reactive power flow between the asynchronous AC grids.

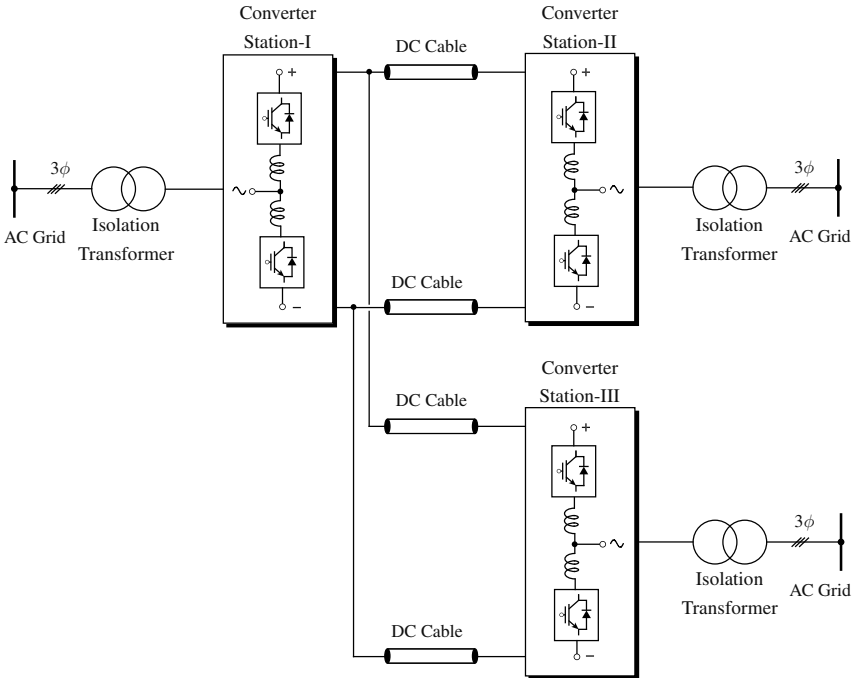


Figure 1.23 Multi-terminal MMC-HVDC system.

Multi-terminal HVDC grids are most vulnerable to DC-side faults and asymmetrical AC faults. The application of MMCs for multi-terminal HVDC system needs further evaluation of fast protection systems and robust power management schemes to withstand the asymmetrical AC faults, which is an on-going research topic. The China Electric Power Research Institute (CEPRI) installed an MMC-based multi-terminal HVDC system in Zhoushan to distribute the power among multiple regions as indicated in Table 1.8. In this project, the HVDC Flexible technology is employed to handle a voltage ± 200 kV.

Table 1.8 Market overview of multi-terminal MMC-based HVDC systems

Project Name	Power (MW)	Voltage (\pm kV)	DC Cable (km)	Company	HVDC Tech.
Zhoushan	400/300/100 /100/100	200	134	CEPRI	HVDC Flexible

(4) Offshore Wind Farm: Typically, offshore wind farms are located in the sea, which is far from the utility grids. These offshore wind farms are connected to the AC grid for the subsequent distribution and consumption of generated power. The MMC-HVDC system is a suitable candidate to transfer the power over a long distance. The connection of an offshore wind farm with the AC grid through a submarine cable and MMC-HVDC network is shown in Figure 1.24. The MMC-HVDC provides a black start operation, requires less space and compact structure, and does not require output filters and reactive power support compared to that of the line-commutated converter (LCC) based HVDC system [53].

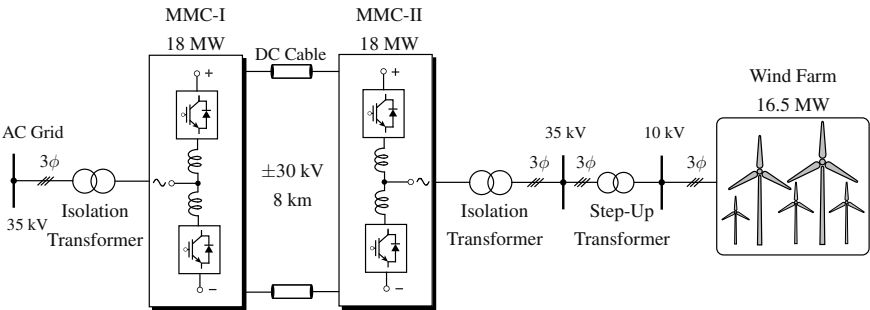


Figure 1.24 MMC-HVDC with submarine cable for offshore wind farm.

The MMC-based HVDC systems are used to interconnect offshore wind farms with the AC grid as shown in Table 1.9. These projects are mainly installed in the European region with a maximum voltage of ± 320 kV and power rating of 900 MW.

Table 1.9 Market overview of MMC-HVDC-based offshore wind farms

Project Name	Power (MW)	Voltage (\pm kV)	DC Cable (km)	Company	HVDC Tech.
Borwin-2	800	300	200	Siemens	HVDC Plus
Sylwin-1	864	320	205	Siemens	HVDC Plus
Dolwin-2	900	320	135	ABB	HVDC Light Gen. 4
Dolwin-3	900	320	160	Alstom	HVDC MaxSine
Nanhui	18	30	8.4	C-EPRI	HVDC Flexible

(5) Static Synchronous Compensator: Another potential application of MMC is to operate as a static synchronous compensator (STATCOM) to compensate both harmonics and reactive power demanded by the distorted and unbalanced loads. MMC-based STATCOM has modularity and voltage scalability features, and allows the direct connection (without transformer) to the medium- or high-voltage power system networks as shown in Figure 1.25.

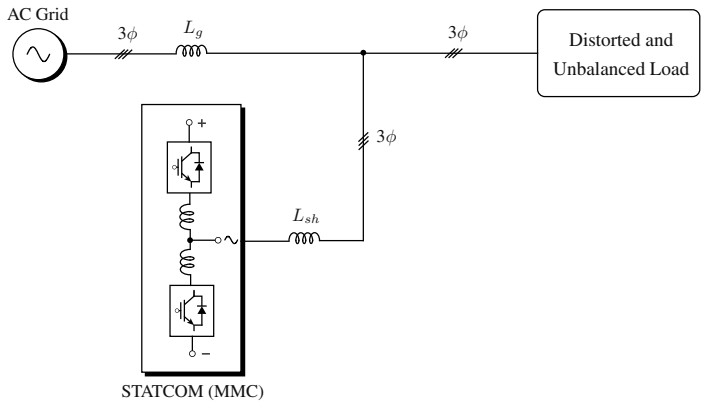


Figure 1.25 MMC-based STATCOM system.

Table 1.10 Market overview of MMC-based STATCOM

Project Name	Power (\pm MVar)	Voltage (kV)	Company	STATCOM Tech.
Kikiwa SVC Plus	2 x 35	220/11	Siemens	SVC Plus M
Mocuba Substation	35	33	Siemens	SVC Plus M
Inter Island Link pole 3	50	220	Siemens	SVC Plus C
Rio Branco SVC Plus	55	230	Siemens	SVC Plus C
Offshore Greater Gabbard	50	13.9	Siemens	SVC Plus L

In this application, the half-bridge and full-bridge submodules are preferred for MMCs. The MMC-based STATCOM technologies were developed by Siemens to handle a voltage of 33 kV without a transformer and 220 kV with a transformer as shown in Table. 1.10. These technologies are installed in offshore wind farms, substations and arc furnace industries to supply the reactive power.

(6) Unified Power Quality Conditioner: The unified power quality conditioner (UPQC) is another important and widely used technology in the power quality improvement. The UPQC system has two stages of compensation with the series and parallel connection of the power converters. The UPQC can be realized using a back-to-back connection of MMC as shown in Figure 1.26.

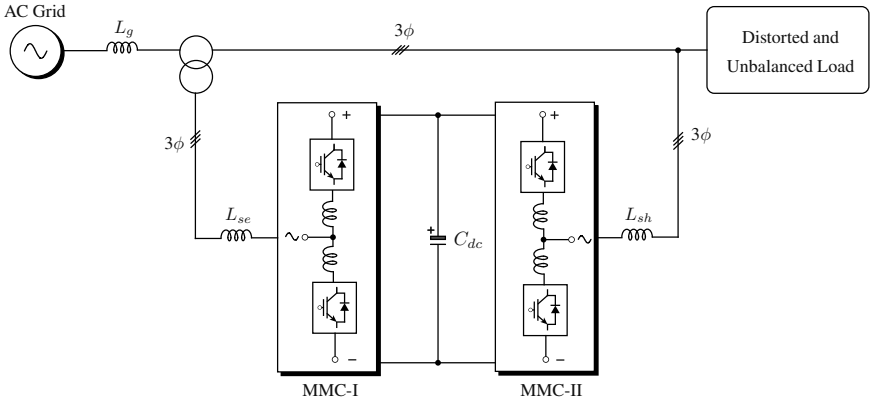


Figure 1.26 MMC-based UPQC system.

The MMC-I is connected to the AC grid through a transformer. It provides the series compensation, where it handles the voltage sag and voltage swell problems of the AC grid. The MMC-II provides a shunt compensation, which is directly connected to the AC grid without any transformer. Eliminating the transformer in shunt compensation is one of the advantages of MMC [54, 55]. The shunt compensator handles the reactive power and harmonic compensation of the distorted load. High-quality output waveforms and the fast current control of MMCs helps to improve the active filtering capability of the UPQC system. The control and power quality improvement using UPQC is discussed in Chapter 9.

1.6.3 Technical Challenges

In this section, the technical challenges associated with the operation and control of MMCs, including the design constraints, submodule capacitor pre-charging process, submodule capacitor voltage control, submodule capacitor voltage ripple, circulating current, and fault-tolerant issues are presented [50, 51]. These technical challenges

and corresponding control methods are presented in the subsequent chapters of this book.

(1) Design Constraints: Arm inductance (L) and submodule capacitor (C) are the only passive components used in MMCs. Arm inductance filters the switching frequency harmonics in the arm current and limits the DC short-circuit current. Therefore, sizing of the arm inductor depends on the arm current ripple and short-circuit current. The suppression of undesirable low-frequency currents needs to be considered during the design of an arm inductor. Arm inductor size can be reduced by using an integrated arm inductor, where the upper and lower arm inductors in each leg are wound on the same core. The submodule capacitor is sized based on the tradeoff between the size or cost and capacitor voltage ripple. It is designed to provide a permissible peak-to-peak ripple at twice the fundamental frequency.

(2) Submodule Capacitor Pre-Charging Process: The submodules in each arm of MMC has floating capacitors with zero initial voltage. These submodule capacitors must be charged to its nominal voltage level before starting the normal operation. However, the charging process of submodule capacitors during startup and after a fault can lead to a large inrush current because of the small equivalent impedance of the converter. The pre-charging of submodule capacitors without inrush current is one of the major challenges in MMC.

(3) Submodule Capacitor Voltage Control: The submodule capacitors voltage must be regulated at the given reference voltage value to produce a multilevel stepped waveform at the output of MMC. The MMC has several submodules in each arm and controlling these submodules is one of the challenging tasks. The capacitor voltage control is usually separated into three stages named as, leg voltage control, voltage balance among the arms, and voltage balance among the submodules within the arm. The first stage can be integrated into the control scheme. In this stage, the distribution of energy among converter legs is controlled by changing the DC-link current reference. The voltage unbalance among the arms causes a circulating current. Therefore, the circulating current control is commonly employed to ensure a voltage balance among the arms. Voltage balance among the submodules within the arm depends on the direction of the arm current and capacitor voltage error. It can be implemented at either the control stage or modulation stage. Implementing the submodule capacitor voltage control requires a significant number of sensors to measure the submodule capacitor voltages and arm currents.

(4) Submodule Capacitor Voltage Ripple: The interaction between the arm currents and voltage causes a voltage ripple in submodule capacitors. The ripple in submodule capacitors is dominated by the fundamental and second-order harmonic components only. The magnitude of voltage ripple is inversely proportional to the fundamental frequency. Therefore, the voltage ripple is severe in variable speed motor drive systems rather than HVDC applications. In motor drive applications, each submodule requires a large capacitance value to suppress the voltage ripple at zero

and low speed of operation. Thus, it increases the converter cost. Hence, the suppression of voltage ripple is a trade-off between the performance/efficiency/reliability and the cost/size of the MMC.

(5) Circulating Currents: Circulating currents originate from the voltage difference between the arms in each converter leg. These currents mainly contain negative sequence components, which flows internally among the converter legs only. The circulating currents do not affect the AC output voltages and currents. However, it increases the peak and RMS value of the arm current, which consequently increases converter power losses and the ripple in submodule capacitor voltage. Therefore, the circulating currents must be suppressed for a reliable and efficient operation of the MMC.

(6) Fault Tolerance: The modular multilevel converter is always designed with the redundant submodules to continue their operation during the faults. Typically, the submodules are designed with a bypass switch connected across the AC output terminals. During the fault condition, the bypass switch is used to disconnect the faulty submodule and insert one of the redundant submodules in the arm. Thus, the effect of faults on the MMC operation can be significantly minimized. However, detecting of faults and inserting redundant submodules without inrush current is a great challenge.

The DC-link short-circuit fault is another major issue in the MMC-based HVDC systems. The DC circuit breaker is commonly employed to protect the system during the DC faults. On the other hand, the submodules with DC fault-blocking capability can be employed in the MMC-HVDC system. During the fault condition, the submodules are controlled to generate the negative voltage level at the AC output terminal, which blocks the fault current flowing through the devices.

1.7 SUMMARY

The rapid industrialization in various industrial sectors such as manufacturing, petrochemical, and mining sectors increases their power demand and rate of production. To address these issues, several high-power converters were developed and commercialized in the form of standard and customized products. In this Chapter, a comprehensive overview of several high-power converters including VSCs, CSCs, and matrix converters, and their limitations for high-voltage, high-power applications are presented. Among them, VSCs achieved a major market share and had noticeable developments in the past decade. The technical challenges, limitations, and voltage and power capacity of the most popular and commercially available VSCs are presented. With the present semiconductor technology, VSCs can handle an operating voltage up to 6.6 kV without devices in series. For the higher operating voltage, some of the topologies are not cost-effective. Another few topologies require isolated DC sources and a complicated phase-shift transformer, which increases the cost and volume of the converter.

The most recent developments in the voltage source converter is a modular multi-level converter. This topology has a modular construction; voltage and power rating of the converter can be increased by adding the submodules in series. Also, the phases-shifting transformer is not required, which significantly minimizes the cost of the converter. These features led to the commercial success of MMC, and a wide range of products are available in the market. The applications and market overview of the modular multilevel converter are presented. These applications are further analyzed in the subsequent chapters of this book. Despite all its advantages, MMC requires a complex control system to meet multiple control objectives. The technical challenges, which are associated with the control of MMC, are also presented. An in-depth analysis of these challenges is discussed in the following Chapters of this book.

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