1

Overview of High-voltage Converters

1.1 Introduction

With the development of large-scale distributed generation (DG) systems access, such as photovoltaic (PV) panels, wind turbines, energy storage devices, and electric vehicles, the structure and features of power grids are bound to change, which will bring about not only a series of impacts on the safe and stable operation of power grids, but also challenges for ensuring power supply reliability and power quality.

In the traditional power grid shown in Figure 1.1a, the power flow is unidirectional in the power generation, transmission, substation, distribution, supply, and other sectors. Since the penetration rate of small-scale PV panels, electric vehicle charging stations, and energy storage stations is increasing in the power distribution side, as a result, the electric power is allowed to flow bidirectionally in the smart grid, as shown in Figure 1.1b.

As a smart grid is essentially different from a traditional power grid, the development of smart grids provides a great opportunity to interconnect different kinds of DG systems with the grid. In order to achieve a bidirectional flow of electricity and ensure the power quality of the grid, the power electronic converter must have good performance as an interface between the DG system and the power grid. Since a multilevel converter can extend the well-known advantages of low- and medium-power pulse-width modulation (PWM) converter technology into high-voltage high-power applications, it becomes the first choice for grid-connected interface converters and plays an important role in the following three aspects of smart grids:

1) *Power generation side*. The DC power generated by the large-scale PV station can be converted to AC power and transferred to the grid by a multilevel converter. The AC power from large wind farms can be converted into stable AC power and then connected to the grid by a two-stage multilevel converter. Large-scale storage plants can supply power to the grid and be charged by the grid via a bidirectional multilevel converter.
2) *Power transmission side*. High-voltage direct current (HVDC) power transmission associated with flexible alternating current transmission (FACT) are considered the most promising transmission technologies in smart grids. Since high-voltage high-power power conversion is often required, both HVDC and FACT systems were based initially on thyristor technology and more recently on fully controlled semiconductors and voltage-source multilevel converter topologies.

Multi-terminal High-voltage Converter, First Edition. Bo Zhang and Dongyuan Qiu.

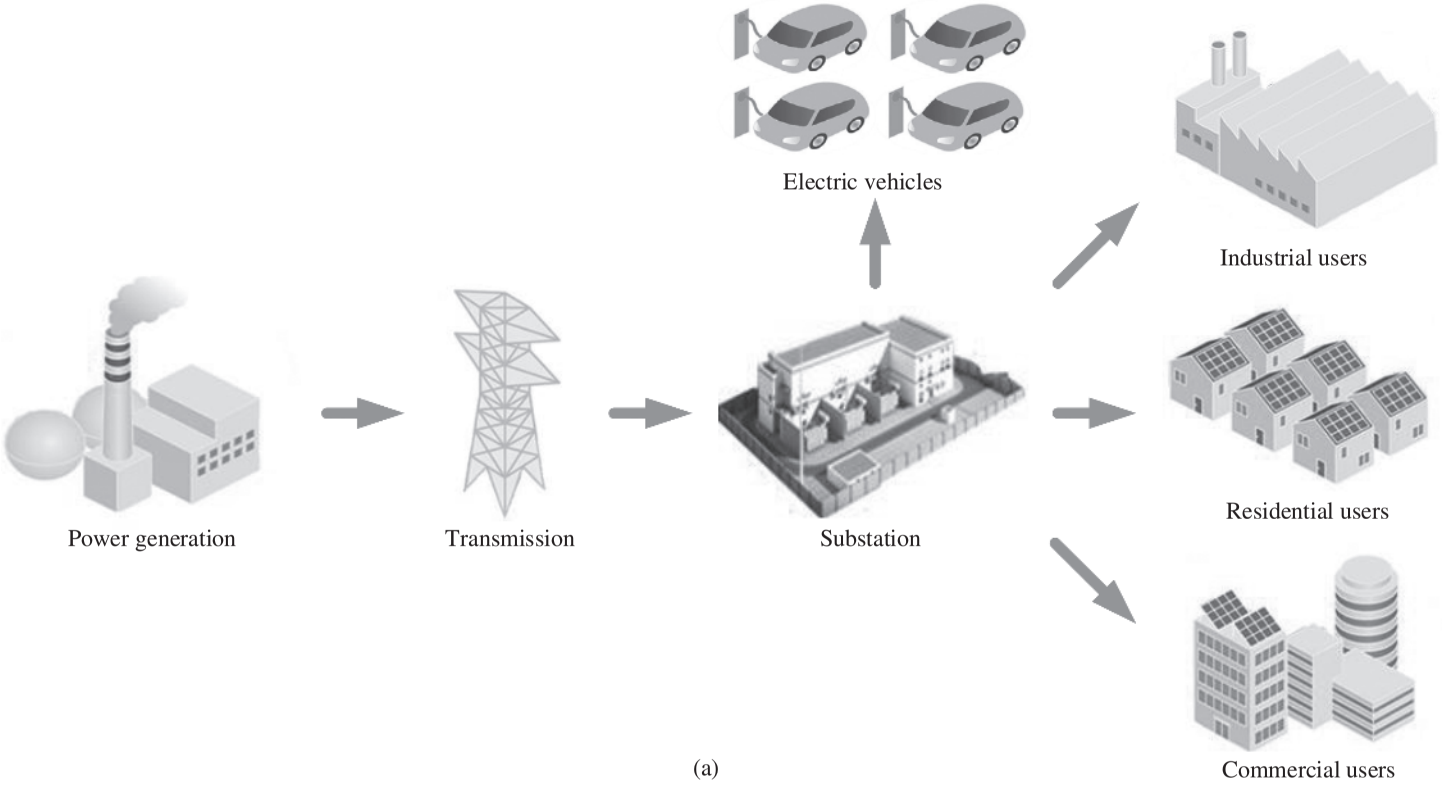
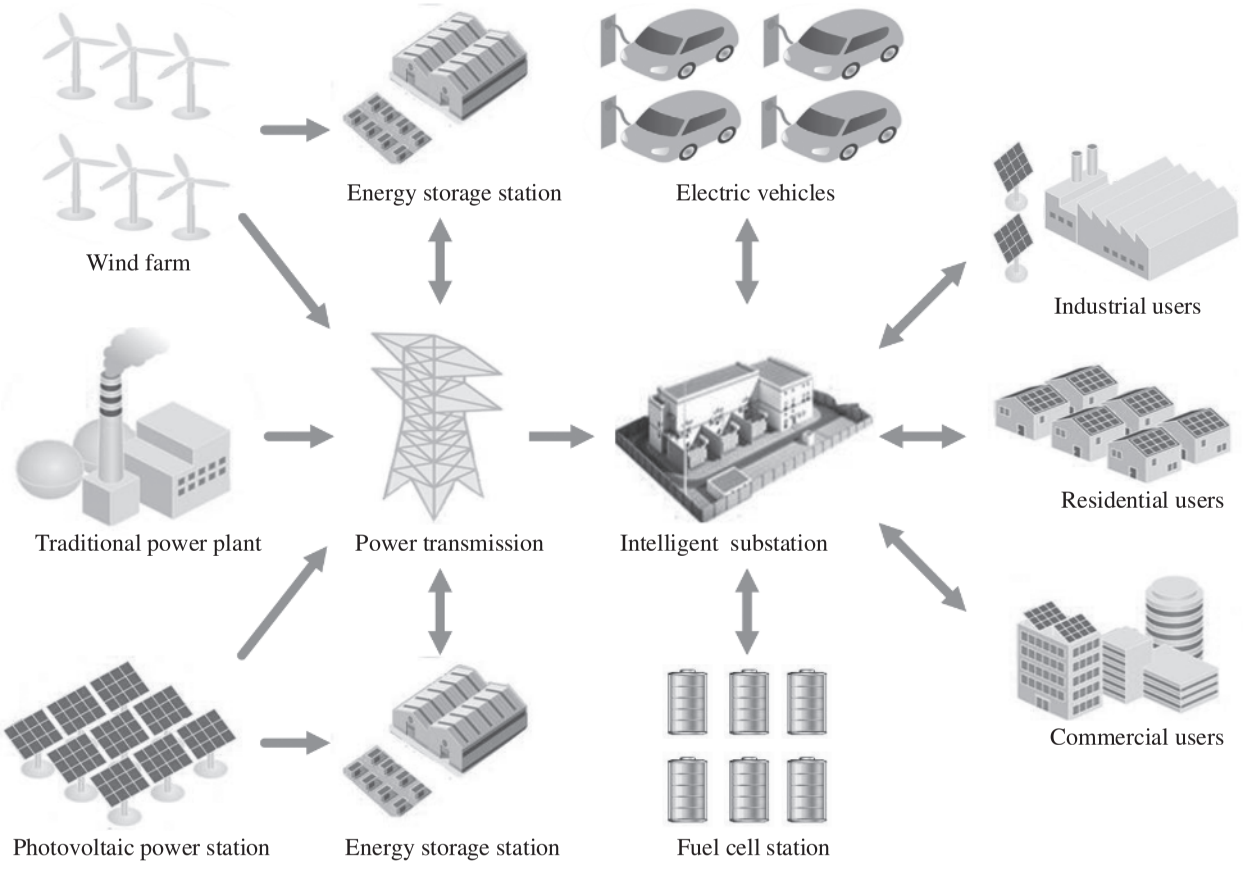


Figure 1.1 Schematic of power grid. (a) Traditional power grid. (b) Smart grid.



(b)

Figure 1.1 (*Continued*)

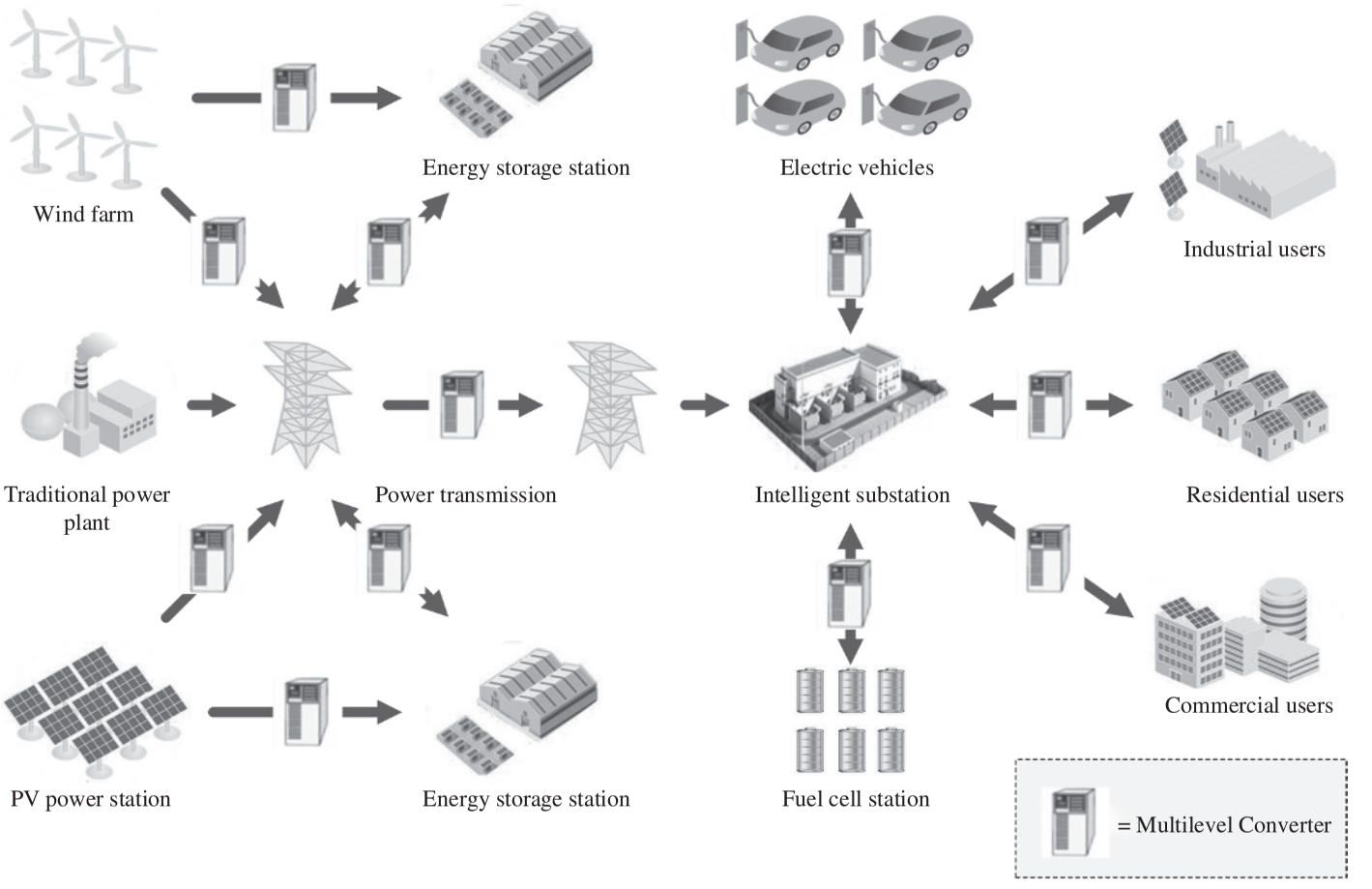


Figure 1.2 Application of multilevel converters in smart grid.

3) *Power distribution side*. The electric power generated by a small-scale wind and solar complementary system can be fed to the grid or supply directly to the user by multilevel converters. Making use of a bidirectional multilevel converter, the charging and discharging functions of the energy storage station or electric vehicle can be achieved.

In summary, a large number of multilevel converters can be found on the generation side, transmission side, and distribution side of a smart grid. As shown in Figure 1.2, future power grids will certainly be presented as an architecture with high-performance multilevel converters and high penetration of DG and energy storage systems.

On the power generation side, the large-scale DG systems, such as PV stations and wind farms, often consist of multiple subsystems or units. Although the multilevel converter effectively solves the high-voltage power conversion problem, the existing multilevel converter topologies are generally in the form of single input and single output; multiple multilevel converters are required to connect the large-scale DG system to the grid. Moreover, when more than one local load needs to be powered, only one multilevel converter can be used for one load, resulting in the need for multiple multilevel converters.

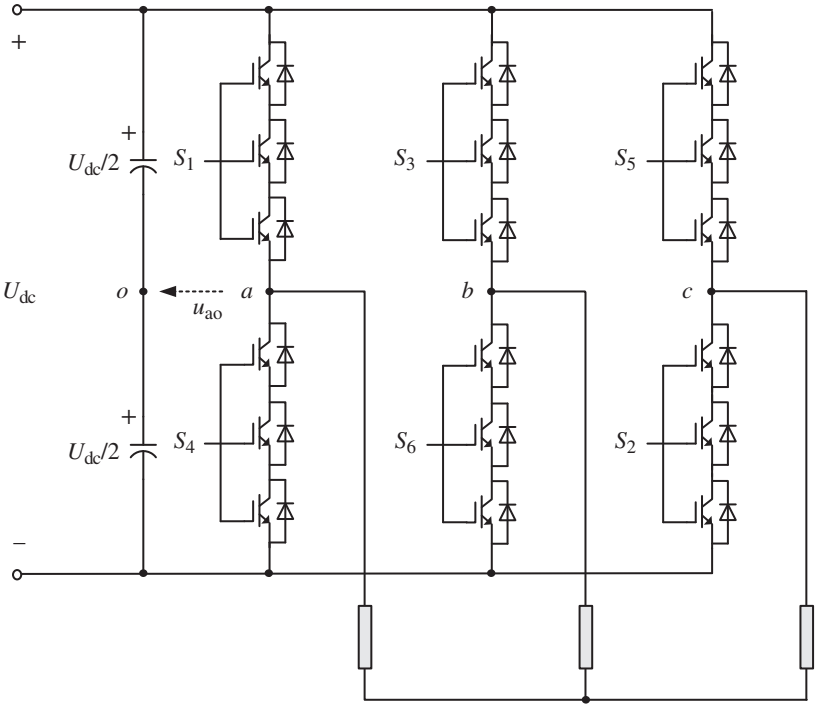
On the power distribution side of a smart grid, the power grid is not the only utility supplier to consumers. Other power suppliers include PV panels, wind turbines, fuel cells, supercapacitors, electric vehicles, and so on. Therefore, the interface converter needs to access multiple power sources and supply multiple loads. Obviously, the single-input single-output converter could not meet the above requirements; the use of multiple multilevel converters inevitably leads to a complex system configuration and high costs. Therefore, it is imperative to develop a high-voltage converter with multiple terminals.

In order to propose the architecture of a multi-terminal high-voltage converter, the development of a high-voltage high-power converter will be reviewed first, then several typical multilevel converters and common control schemes for multilevel converters will be introduced briefly.

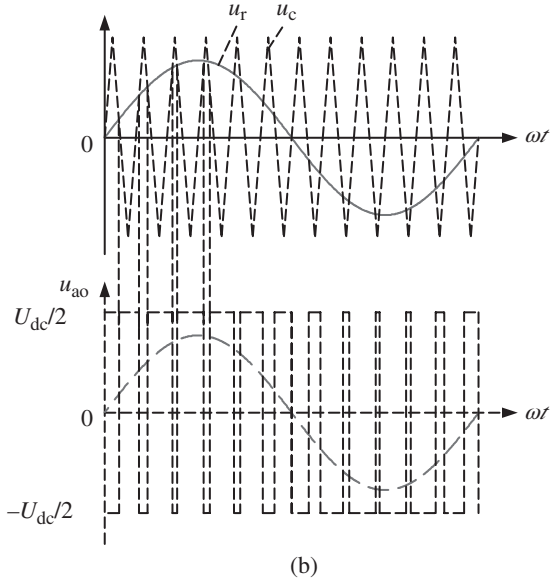
1.2 Classification of High-voltage High-Power Converters

1.2.1 Two-Level Converters

High-voltage high-power converters have experienced high market penetration and noticeable development over the past two decades. The classical two-level converters were limited to low- or medium-power applications due to the blocking voltages of the power semiconductors with active turn-on and turn-off capabilities. The series connection of switching devices enabled the two-level converters to be applied in high-voltage high-power applications, while the number of switches in a series connection depends on the DC link voltage. As shown in Figure 1.3a, each phase of a typical high-power two-level voltage source inverter (2L-VSI) is composed of two groups of active switches, each consisting of three switches in series controlled by the same gating signal and hence working as a single switch [1]. In addition, additional capacitors in series could be necessary to reach the desired DC link voltage.



(a)



(b)

Figure 1.3 High-power two-level voltage source inverter. (a) Topology. (b) Bipolar PWM scheme.

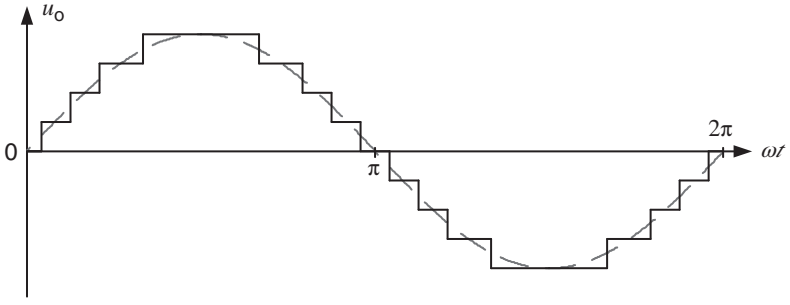


Figure 1.4 Typical stepped waveform of multilevel converter.

The most used modulation schemes for 2L-VSI are the well-known bipolar PWM, including third-harmonic injection, space-vector modulation (SVM), and selective harmonic elimination (SHE), which are usually used to enhance the quality of the output voltage. However, the challenge of the control strategy for high-power 2L-VSI is to require multiple switches per leg to operate at the same time. Moreover, only one DC level U_{dc} is utilized to create an average equal to the reference voltage in each switching cycle, as shown in Figure 1.3b; the switching loss and the total harmonic distortion (THD) of two-level converters are relatively high.

In order to synthesize the output voltage as close to a sinusoid as possible, a few additional components, like diodes or capacitors, can be added to the high-power 2L-VSI to generate a stepped waveform with less harmonic distortion, as shown in Figure 1.4, which originated the multilevel converter technology.

1.2.2 Multilevel Converters

Compared with the two-level waveform, the staircase waveform generated by the multilevel converter results in smaller dv/dt stress and lower THD, which can mitigate the problems associated with electromagnetic interference (EMI) and reduce the filter size. Moreover, the lower switching frequency and the lower voltage stress level for the switching devices lead to a significant reduction in switching losses. In general, the comparably lower switching losses and considerably higher power quality are the great advantages of multilevel converters compared with conventional two-level converters. Therefore, multilevel converters are the preferred choice for electric power conversion in high-voltage high-power applications using mature medium-voltage power semiconductor switches.

The classification of high-power converters is summarized in Figure 1.5. It is noted that only the voltage source converter topologies have been included, because the topic of this book is high-voltage converters. The most common voltage-source multilevel topologies are the neutral-point clamped (NPC) converter, flying capacitor (FC) converter, cascaded H-bridge (CHB) converter, and modular multilevel converter (MMC) [2]. Among these, the three-level neutral-point clamped converter (3L-NPC) presented by Nabae, Takahashi, and Akagi in 1980 is considered the first real multilevel power converter in medium-voltage applications [3]. Years later, the early concepts of the series-connected H-bridge (or CHB) and the FC circuit introduced in the 1960s developed into the multilevel converter topologies we know today [4, 5]. The topology

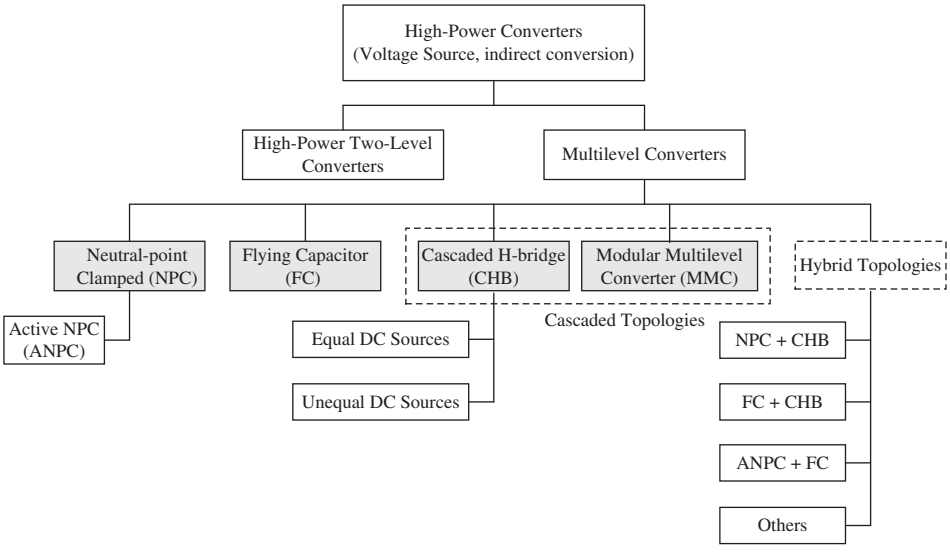


Figure 1.5 High-voltage converters classification.

of a modular multilevel converter (MMC or M2C) was developed in the early 2000s and has received increased attention since then [6].

It is obvious that these multilevel converters present different characteristics, such as the number of components, modularity, control complexity, efficiency, and fault tolerance. Depending on the application, the multilevel converter topology can be chosen by taking these factors into account. For completeness and better understanding of multilevel converter technology, several classic multilevel converter topologies will be reviewed in the next section.

1.3 Topologies of Multilevel Converters

1.3.1 Neutral-Point Clamped Converter

The first three-level NPC converter, also named the diode-clamped converter, was based on a modification of the classic two-level inverter by adding two additional power diodes per phase [3]. As shown in Figure 1.6a, the clamping diode is used to connect the neutral point N to the midpoint of two switches, then an additional voltage level "0" can be produced between the phase output point a and the neutral point N, when S_2 and $S_{1'}$ are switched ON. The phase output voltage u_{aN} will vary between 0 and $-U_{DC}/2$ or $U_{DC}/2$, which yields the name "three-level inverter."

A modified five-level neutral-diode clamped (5L-NPC) converter is shown in Figure 1.6b, in which both the main switches and the clamping diodes can be clamped [7]. In this five-level case, a total of 8 switches and 12 clamping diodes of equal voltage rating are used, and the DC bus consists of four storage capacitors. For a DC bus voltage U_{DC}, the voltage across each capacitor is $U_{DC}/4$, and each device's voltage stress is limited to one capacitor voltage level, or $U_{DC}/4$, through the clamping diodes.

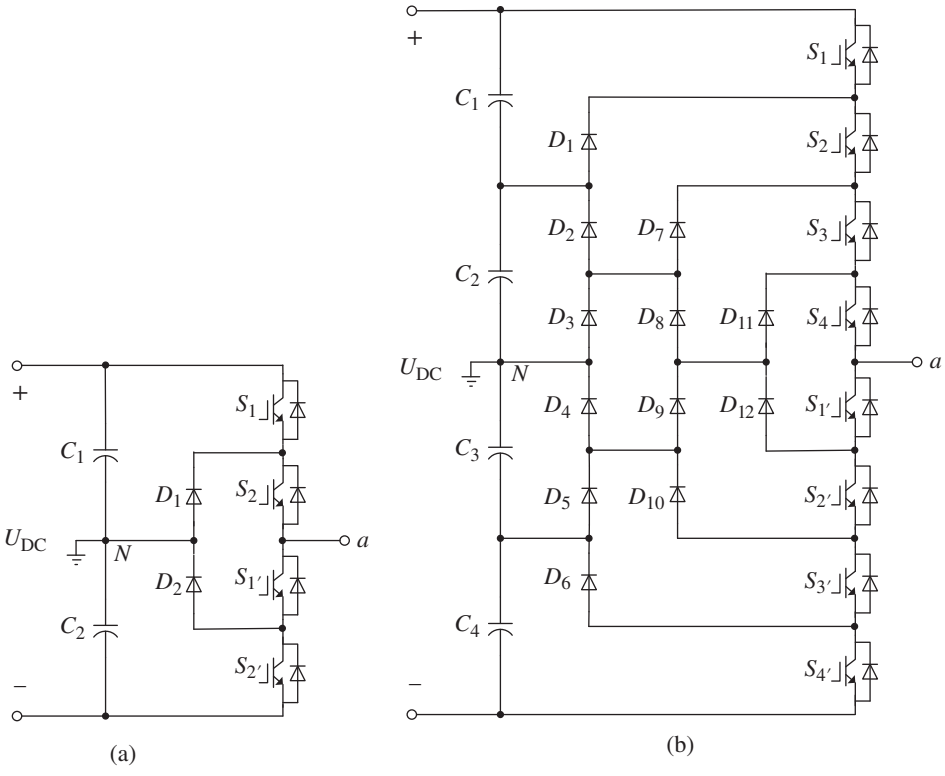


Figure 1.6 Phase structure of the NPC converter. (a) Three level. (b) Five level.

Table 1.1 Phase voltage of the 5L-NPC converter and its corresponding switch combinations.

Phase voltage u_{aN}	Switch states combination							
	S_1	S_2	S_3	S_4	$S_{1'}$	$S_{2'}$	$S_{3'}$	$S_{4'}$
$U_{DC}/2$	ON	ON	ON	ON	OFF	OFF	OFF	OFF
$U_{DC}/4$	OFF	ON	ON	ON	ON	OFF	OFF	OFF
0	OFF	OFF	ON	ON	ON	ON	OFF	OFF
$-U_{DC}/4$	OFF	OFF	OFF	ON	ON	ON	ON	OFF
$-U_{DC}/2$	OFF	OFF	OFF	OFF	ON	ON	ON	ON

The 5L-NPC converter is taken as an example to explain how the staircase voltage is synthesized; five different values for the phase voltage u_{aN} can be obtained using the switch combinations listed in Table 1.1. As a result, there will be nine levels for the phase-to-phase output: $\{-U_{DC}, -3U_{DC}/4, -U_{DC}/2, -U_{DC}/4, 0, U_{DC}/4, U_{DC}/2, 3U_{DC}/4, U_{DC}\}$.

By applying the above diode-clamped method to obtain a higher level, the synthesized output waveform adds more steps as the number of levels increases, producing a staircase wave which approaches the sinusoidal wave with minimum harmonic distortion.

Although the NPC structure can be extended to higher numbers of levels, it is less attractive because the number of devices will increase; for an m-level phase output, $m-1$ storage capacitors, $2(m-1)$ switches, and $(m-1)(m-2)$ clamping diodes are required. In particular, the clamping diodes, which have to be connected in series to block the higher voltages, will introduce more conduction losses and produce reverse recovery currents during commutation, affecting the switching losses of the other devices even more. Furthermore, the DC link capacitor voltage balance will become unfeasible at higher-level topologies.

1.3.2 Flying Capacitor Converter

The FC topology was first proposed by Meynard and Foch in 1992. As shown in Figure 1.7a, the switches in the three-level FC converter are arranged in two pairs (S_1, $S_{1'}$) and (S_2, $S_{2'}$), and the switches within each pair must always be in complementary states. The phase output voltage u_{aN} is equal to $U_{DC}/2$ when S_1 and S_2 are ON, $-U_{DC}/2$ when $S_{1'}$ and $S_{2'}$ are ON, 0 when S_1 and $S_{2'}$ or $S_{1'}$ and S_2 are ON. Obviously, there are redundant switch states in the FC converter that allow the switching stresses to be equally distributed between the switches [5].

For an m-level FC converter, its phase voltage has m levels while the line voltage has $2m-1$ levels, $(m-1)(m-2)/2$ FCs per phase, and $m-1$ capacitors for the DC bus are needed in total, and each capacitor as well as the switching device has the same voltage rating, that is $U_{DC}/(m-1)$. The phase structure of a five-level (5L) FC converter ($m=5$)

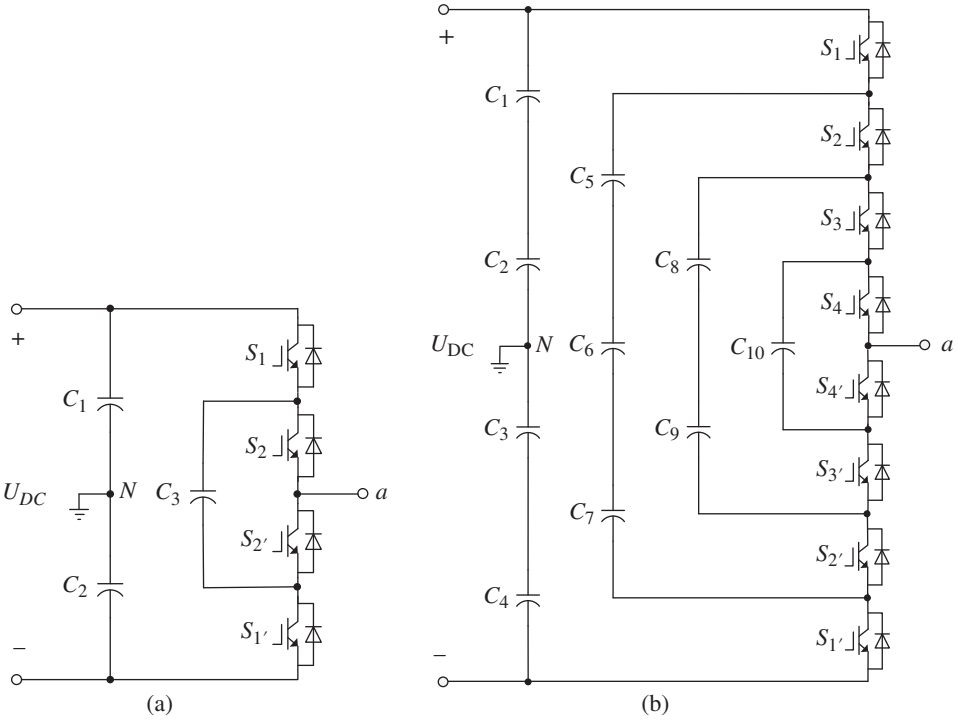


Figure 1.7 Phase structure of the FC converter. (a) Three level. (b) Five level.

Table 1.2 Phase voltage of the 5L-FC converter and its corresponding switch combinations.

Phase voltage u_{aN}	Switch states combination							
	S_1	S_2	S_3	S_4	$S_{1'}$	$S_{2'}$	$S_{3'}$	$S_{4'}$
$U_{DC}/2$	ON	ON	ON	ON	OFF	OFF	OFF	OFF
$U_{DC}/4$	ON	ON	ON	OFF	OFF	OFF	OFF	ON
	OFF	ON	ON	ON	ON	OFF	OFF	OFF
	ON	OFF	ON	ON	OFF	ON	OFF	OFF
	ON	ON	OFF	ON	OFF	OFF	ON	OFF
0	ON	ON	OFF	OFF	OFF	OFF	ON	ON
	OFF	OFF	ON	ON	ON	ON	OFF	OFF
	ON	OFF	ON	OFF	OFF	ON	OFF	ON
	ON	OFF	OFF	ON	OFF	ON	ON	OFF
	OFF	ON	OFF	ON	ON	OFF	ON	OFF
	OFF	ON	ON	OFF	ON	OFF	OFF	ON
$-U_{DC}/4$	ON	OFF	OFF	OFF	ON	ON	ON	ON
	OFF	OFF	OFF	ON	ON	ON	ON	OFF
	OFF	OFF	ON	OFF	ON	ON	OFF	ON
	OFF	ON	OFF	OFF	ON	OFF	ON	ON
$-U_{DC}/2$	OFF	OFF	OFF	OFF	ON	ON	ON	ON

is illustrated in Figure 1.7b, whose phase voltage can be synthesized by the switch combinations listed in Table 1.2 [8]. It is noticeable that the voltage synthesis in an FC converter has more flexibility than a diode-clamped converter.

Higher switching frequencies are necessary to keep the capacitors properly balanced, no matter what kind of capacitor balancing modulation is used, but these switching frequencies are not feasible for high-power applications, where they are usually limited to a range under 1 kHz. Besides the difficulty of balancing the voltage of capacitors connected in series, the major problem in the FC converter is the requirement for a large number of storage capacitors when the number of converter levels is high. Packaging the required number of bulky capacitors will become more difficult for high-level systems, as well as the initialization of the FC voltages.

1.3.3 Cascaded H-bridge Converter

The CHB converter consists of a series of H-bridge (or single-phase full-bridge) inverter units with separate DC sources, which are typically provided from a transformer/rectifier arrangement, or supplied from batteries, capacitors, or PV arrays. Figure 1.8 shows the single-phase configuration of a CHB converter with multiple H-bridge units, in which the AC terminal voltages of H-bridge units are connected in series. Thus, the phase output voltage is synthesized by the sum of inverter outputs, that is $u_{aN} = \sum_{i=1}^{N} u_{Hi}$.

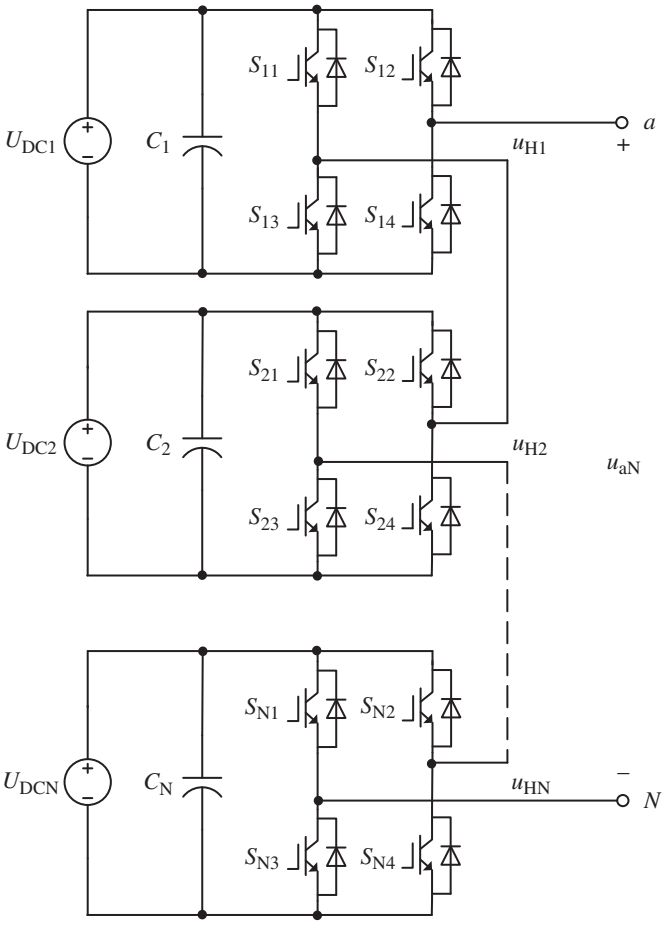


Figure 1.8 Phase structure of the cascaded H-bridge converter.

Assuming that the DC voltage source for the *i*th H-bridge unit is U_{DCi}, the output voltage of the H-bridge, which is denoted by u_{Hi}, has three levels, $-U_{DCi}$, 0, or U_{DCi}, according to the switch combinations listed in Table 1.3. If the DC voltage of each unit is set to the same value ($U_{DCi} = E$), then the level of the output phase voltage is defined by $m = 2N+1$ when N is the number of H-bridge units. If different DC voltages of the H-bridge unit are utilized, then a greater voltage level can be obtained for the phase output, which means that the power quality of the CHB converter may be greatly improved. For example, a CHB converter with two H-bridge units has five-level output with equal DC sources ($U_{DC1} = U_{DC2} = E$), but seven-level output with unequal DC sources ($U_{DC2} = 2U_{DC1} = 2E$), according to the voltage combinations in Table 1.4. Moreover, the 3L H-bridge unit in Figure 1.8 can be replaced by other kinds of bridge inverter, such as the 5L-NPC converter, which will maximize the number of voltage levels obtainable, resulting in high power quality [9].

Therefore, the primary advantage of the CHB converter is its modular structure that enables higher-voltage operation with classic low-voltage semiconductors; fewer or

Table 1.3 Output voltage of the H-bridge unit and its corresponding switch combinations.

Unit output voltage u_{Hi}	Switch states combination			
	S_{i1}	S_{i2}	S_{i3}	S_{i4}
U_{DCi}	OFF	ON	ON	OFF
0	ON	ON	OFF	OFF
	OFF	OFF	ON	ON
	OFF	OFF	OFF	OFF
$-U_{DCi}$	ON	OFF	OFF	ON

Table 1.4 Output voltage of the cascaded H-bridge converter when N = 2.

DC voltage source	Variables	Output voltage						
$U_{DC1} = U_{DC2} = E$	u_{H1}	E	E	0	0	−E	0	−E
	u_{H2}	E	0	E	0	0	−E	−E
	u_{aN}	2E	E		0	−E		−2E
$U_{DC1} = 2E$ $U_{DC2} = E$	u_{H1}	2E	2E	0	0	0	−2E	−2E
	u_{H2}	E	0	E	0	−E	0	−E
	u_{aN}	3E	2E	E	0	−E	−2E	−3E

more H-bridge units can be cascaded in order to decrease or increase the voltage and power level, respectively. However, the main disadvantage of this topology is that each H-bridge unit requires an isolated DC source. The whole system will be more expensive and bulky if the isolated DC sources are fed from phase-shifting isolation transformers.

1.3.4 Modular Multilevel Converter

The MMC, which is composed of multiple modules that are individually added up to synthesize the desired voltage, has become the most attractive multilevel converter topology for VSC-HVDC systems since its publication in 2003 [6].

The phase structure of MMC, consisting of 2N sub-modules (SMs), is shown in Figure 1.9, in which each arm comprises N series-connected SMs and a series inductor L. The upper (lower) arm of each phase-leg is represented by subscript "p" ("n"), the link between two inductors constituting the corresponding phase AC output. Normally, the cascaded SMs are identical and can be considered as a controlled voltage source whose maximum value is U_{SM}.

Since the high voltage at the DC side can be considered as two ideal DC voltage sources with amplitude $U_{DC}/2$, the limitation of the DC voltage and the phase output is related to the number of SMs per arm, that is $U_{DC}/2 + |u_{aN}| \leq N \cdot U_{SM}$. When $U_{SM} = U_{DC}/N$ is chosen, the phase output voltage u_{aN} is restricted to $-U_{DC} \leq u_{aN} \leq U_{DC}$ [10].

There are two kinds of common SM, one is the half-bridge sub-module (HBSM) shown in Figure 1.10a and the other is the full-bridge sub-module (FBSM) shown in Figure 1.10b [11]. The HBSM is composed of a DC capacitor and two switching devices, which are generally a unidirectional insulated-gate bipolar transistor (IGBT) and an

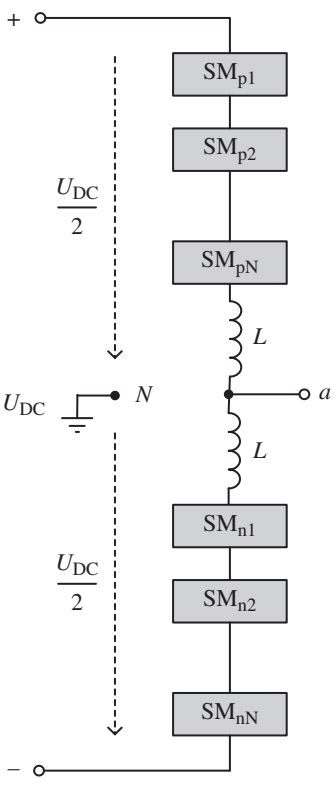


Figure 1.9 Phase structure of MMC.

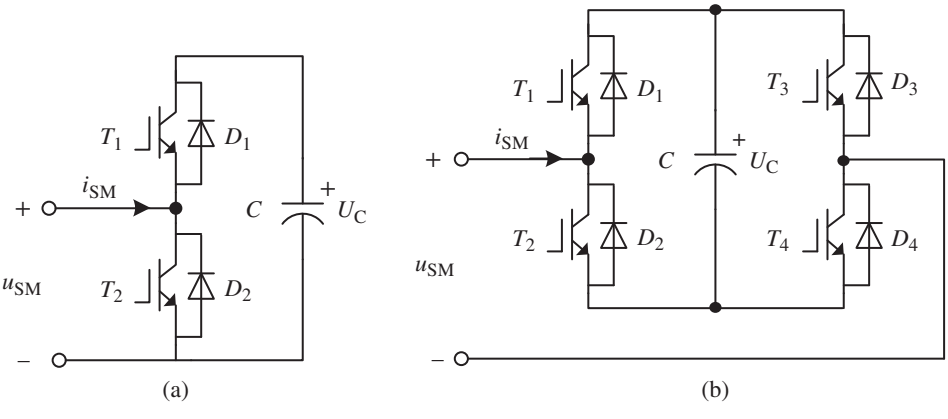
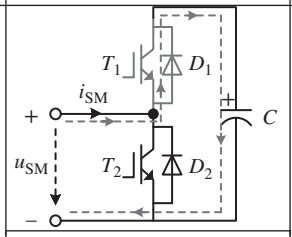
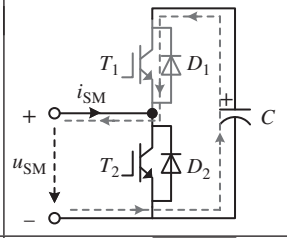
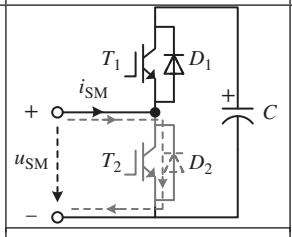
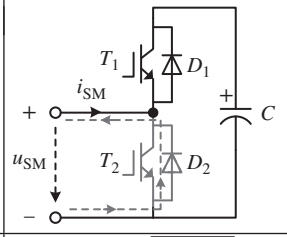
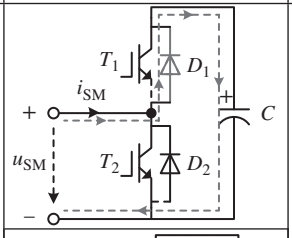
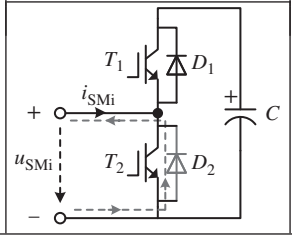


Figure 1.10 Circuit configurations of sub-module. (a) HBSM. (b) FBSM.

antiparallel diode. Two switching devices are driven by complementary signals, and the corresponding module output u_{SM} is either equal to its capacitor voltage U_C or zero.

The various states of the HBSM are listed in Table 1.5. These six states can be divided into three categories: capacitor ON, capacitor OFF, and energization states. The capacitor ON or inserted state appears when a high signal is applied to T_1, IGBT T_1, or the antiparallel diode D_1 conducts depending on the current direction of i_{SM}, and the entire

Table 1.5 Operating states of the HBSM.

No.	Switch ON	Switch OFF	State	Equivalent current path	u_{SM}	i_{SM}	Capacitor status
1	T_1	T_2	Capacitor ON/ Inserted		U_C	Positive	Charging
2						Negative	Discharging
3	T_2	T_1	Capacitor OFF/ Bypassed		0	Positive	Bypass
4						Negative	Bypass
5	—	T_1, T_2	Energization		U_C	Positive	Charging
6					0	Negative	Bypass

capacitor voltage U_C comes across the module terminals. The capacitor OFF or bypass state exists when the SM capacitor needs to be bypassed and have zero voltage across the terminals. To get this state, a high gate signal is applied to T_2. The energization state occurs when no signal is applied to either of the switches, and D_1 or D_2 conducts depending on the current direction of i_{SM}. This state never exists under normal operation of the converter, and only appears during converter failure. Obviously, by controlling the number of SMs in the capacitor ON (or OFF) state, the output voltage synthesized by the MMC is controlled. In addition, all capacitors in the MMC should be pre-charged to a nominal voltage of U_C [10].

The FBSM is composed of a DC capacitor and four switching devices; the output voltage u_{SM} depends on the switching states of T_1 to T_4. All operating states of the FBSM have been summarized in Table 1.6, states 1 to 4 belonging to "capacitor ON," states 5 to 8 belonging to "capacitor OFF," and states 9 and 10 being "energization."

Compared with the states of the HBSM in Table 1.5, there is one more capacitor ON state for the FBSM, in which the output voltage u_{SM} is equal to $-U_C$ when both T_2 and T_3 are switched ON. Another difference between the HBSM and the FBSM is the energization state; the capacitor C is inserted into the module terminals of the FBSM regardless of the current direction, which will be helpful in clearing DC faults. However, the power losses, as well as the cost of an MMC based on the FBSMs, are significantly higher than when using HBSMs, since the number of switching devices of an FBSM is twice that of an HBSM.

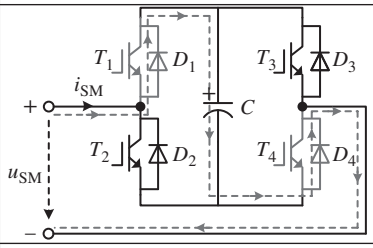
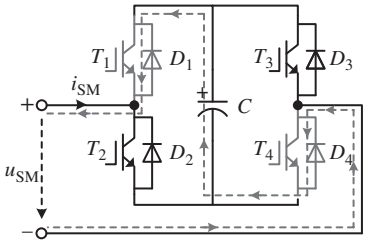
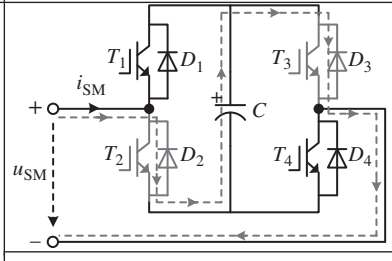
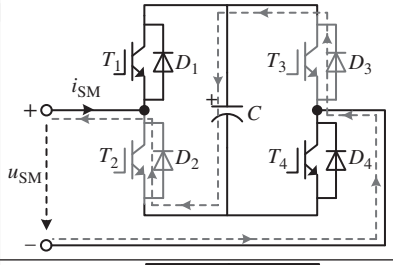
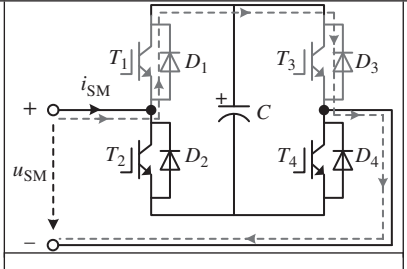
Based on the above analysis, the most distinctive advantages of MMC include: (i) its modularity and scalability to meet any voltage and power-level requirements; (ii) its low THD, which can reduce the size of passive filters; and (iii) its distributed location of capacitive energy storage, resulting in the absence of high-voltage DC link capacitors [11]. However, the disadvantage of the converter is the higher number of switching devices and gate units, and the total stored energy of the distributed capacitors is distinctly higher than that of other multilevel converters [12].

1.3.5 Active Neutral-Point Clamped Converter

The active neutral-point clamped (ANPC) converter is a derivative of the NPC converter presented in Section 1.3.1, which was proposed to overcome the extremely uneven distribution of conduction and switching losses [13]. As depicted in Figure 1.11, the three-level (3L) ANPC converter features additional active switches antiparallel to the clamp diode, which will bring new switch states and new commutations compared with the 3L-NPC shown in Figure 1.6a.

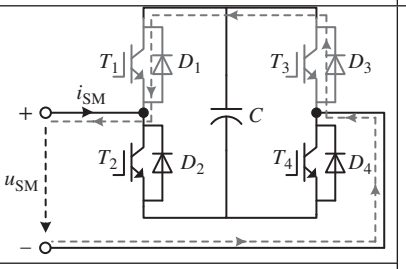
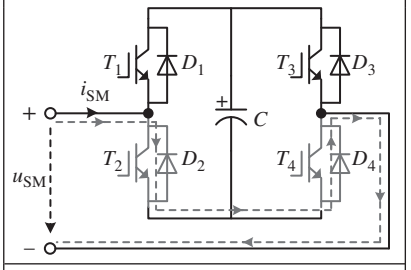
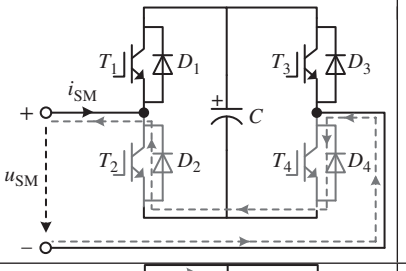
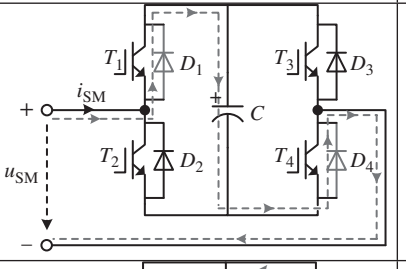
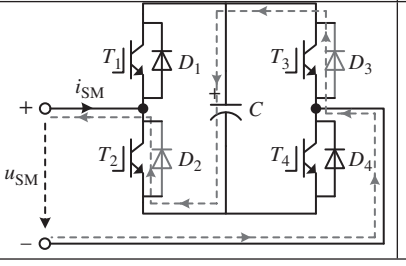
All switch states of the 3L-ANPC converter are given in Table 1.7. It can be found that the phase current can be conducted through the upper path of the neutral tap in both directions by turning on S_2 and S_3, while through the lower path of the neutral tap in both directions by turning on $S_{2'}$ and $S_{3'}$. As a result, there are four switch states for $u_{aN} = 0$, which could control the distribution of the switching losses during the commutations. Furthermore, $S_{3'}$ is turned on to guarantee an equal voltage sharing between $S_{1'}$ and $S_{2'}$ when $u_{aN} = U_{DC}/2$. Analogously, S_3 should be turned on when $u_{aN} = -U_{DC}/2$. Thus, the voltage-balancing resistors across the inner switches can be saved.

Table 1.6 Operating states of the FBSM.

No.	Switch ON	Switch OFF	Equivalent current path	u_{SM}	i_{SM}	Capacitor Status
1					Positive	Charging
2	T_1, T_4	T_2, T_3		U_C	Negative	Discharging
3					Positive	Discharging
4	T_2, T_3	T_1, T_4		$-U_C$	Negative	Charging
5					Positive	
	T_1, T_3	T_2, T_4				

(*continued*)

Table 1.6 (Continued)

No.	Switch ON	Switch OFF	Equivalent current path	u_{SM}	i_{SM}	Capacitor Status
6					Negative	
7	T_2, T_4	T_1, T_3		0	Positive	Bypass
8					Negative	
9	—	$T_1 \sim T_4$		U_C	Positive	Charging
10	—	$T_1 \sim T_4$		$-U_C$	Negative	Charging

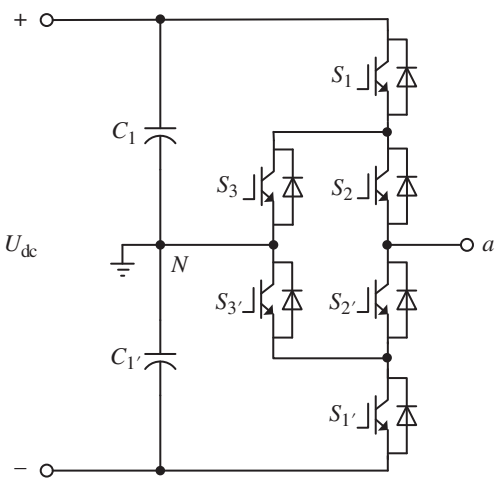


Figure 1.11 Phase structure of the 3L-ANPC converter.

Table 1.7 Phase voltage of the 3L-ANPC converter and its corresponding switch combinations.

Phase voltage u_{aN}	Switch states combination					
	S_1	S_2	$S_{2'}$	$S_{1'}$	S_3	$S_{3'}$
$U_{DC}/2$	ON	ON	OFF	OFF	OFF	ON
0	OFF	ON	OFF	OFF	ON	OFF
	OFF	ON	OFF	ON	ON	OFF
	ON	OFF	ON	OFF	OFF	ON
	OFF	OFF	ON	OFF	OFF	ON
$-U_{DC}/2$	OFF	OFF	ON	ON	ON	OFF

It should be noted that ANPC with higher levels ($m > 3$) belongs to the hybrid multilevel converter, which will be introduced in the next section, because it cannot be obtained by the similar method used to construct the 3L-ANPC converter.

1.3.6 Hybrid Multilevel Converters

Since the introduction of the first multilevel topologies almost four decades ago, many multilevel converters have been published. However, most of them are variations on the three classic multilevel topologies, which are NPC, FC, and CHB, as discussed in the previous sections, or hybrids between them. Among the hybrid multilevel converter topologies, NPC+CHB [14], FC+CHB [15], and ANPC+FC [16] have received sustained attention because of their distinguished performances.

A. NPC+CHB

By cascading NPC and CHB phase legs, more different output voltage levels will inherently be produced. One kind of NPC+CHB topology is shown in Figure 1.12, which consists of a 3L-NPC with integrated-gate commutated thyristors (IGCTs) (main inverter) with an H-bridge (sub-inverter) with IGBTs in series [14], and the total level of phase output voltage will be $m = 9$. Normally, IGCTs with a high-voltage blocking capability

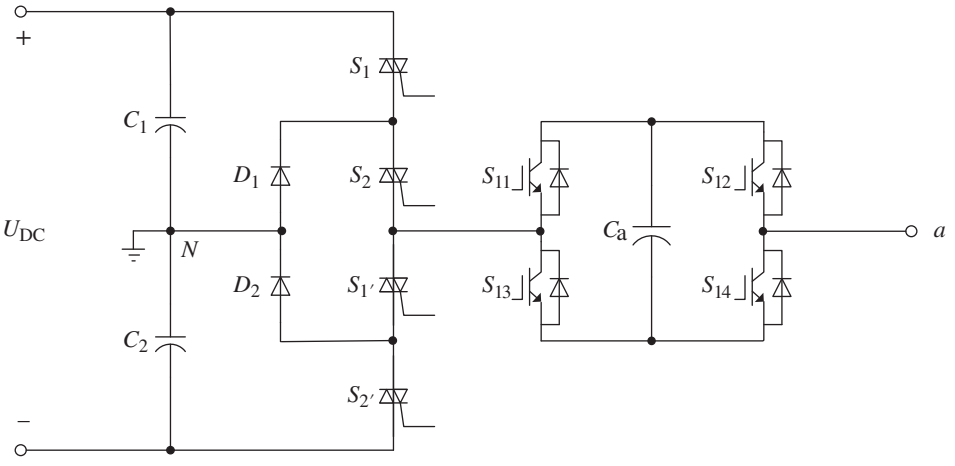


Figure 1.12 Phase structure of an NPC+CHB converter.

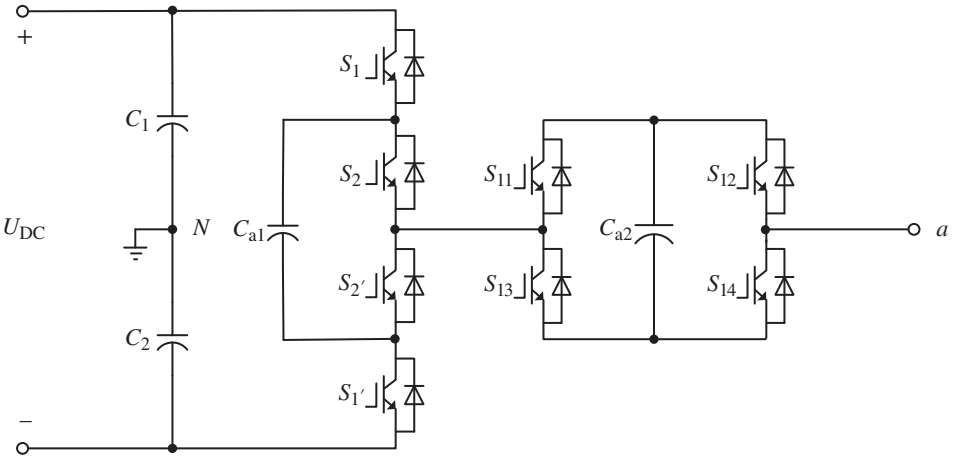


Figure 1.13 Phase structure of an FC+CHB converter.

are used to provide the main power with high reliability and low losses, while IGBTs with a higher switching-frequency capability are used to reduce the output harmonic content. To keep the system simple and the efficiency high, the sub-inverters are fed from the capacitors and supply reactive power only. Thus, the pre-charging of the capacitors in CHB becomes an issue to consider.

B. FC+CHB

FC+CHB is a cascaded topology consisting of a three-level FC converter and a capacitor-fed H-bridge in each phase, as shown in Figure 1.13 [15]. Compared with conventional topologies with the same voltage level, the key advantages of FC+CHB include a reduced number of components and the ability to balance the capacitor voltage by making use of the redundant switching states. Another important feature of this topology is its high reliability, because it can operate as a three-level inverter at full power rating even if one of the H-bridges fails and is bypassed.

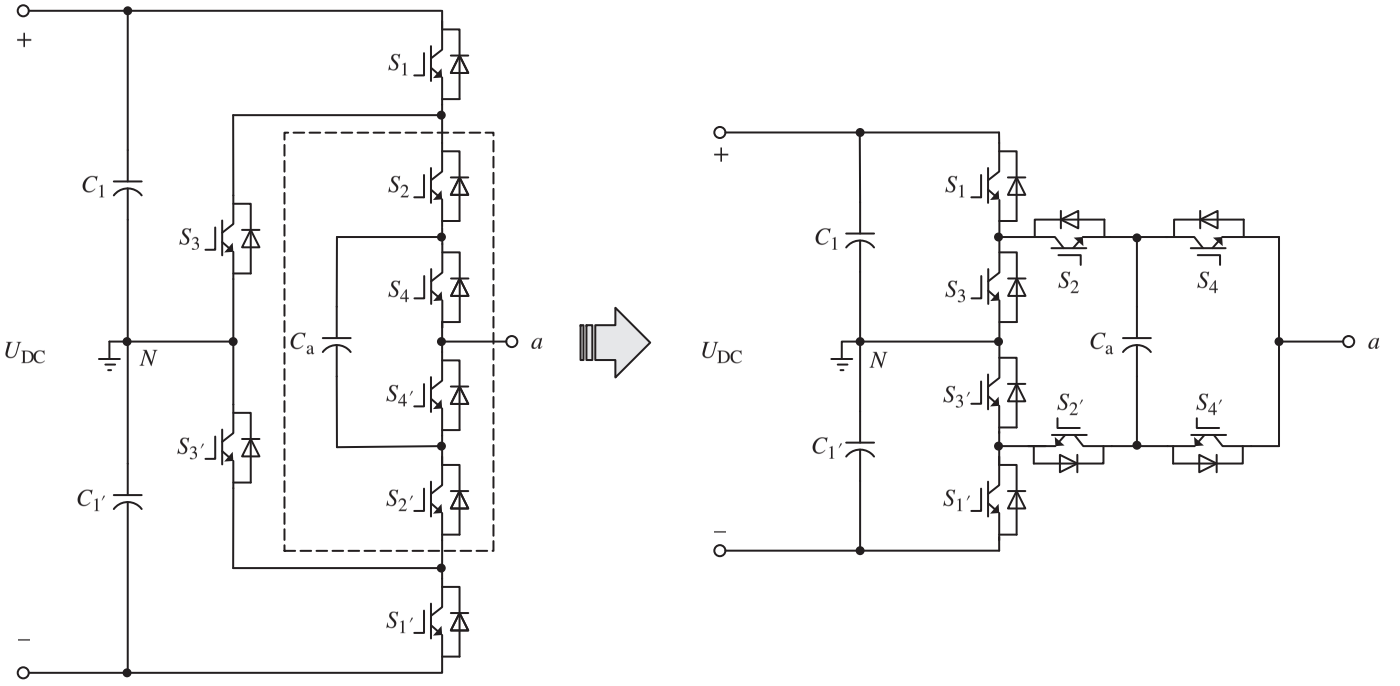


Figure 1.14 Phase structure of an ANPC+FC converter.

Table 1.8 Phase voltage of the 5L ANPC+FC converter and its corresponding switch combinations.

Phase voltage u_{aN}	Switch states combination							
	S_1	S_3	$S_{3'}$	$S_{1'}$	S_2	S_4	$S_{2'}$	$S_{4'}$
$U_{DC}/2$	ON	OFF	ON	OFF	ON	ON	OFF	OFF
$U_{DC}/4$	ON	OFF	ON	OFF	ON	OFF	OFF	ON
	ON	OFF	ON	OFF	OFF	ON	ON	OFF
0	ON	OFF	ON	OFF	OFF	OFF	ON	ON
	OFF	ON	OFF	ON	ON	ON	OFF	OFF
$-U_{DC}/4$	OFF	ON	OFF	ON	ON	OFF	OFF	ON
	OFF	ON	OFF	ON	OFF	ON	ON	OFF
$-U_{DC}/2$	OFF	ON	OFF	ON	OFF	OFF	ON	ON

If the DC bus voltage of the three-level FC converter in Figure 1.13 is U_{DC}, then the voltage across the H-bridge capacitor has to be maintained at $U_{DC}/4$. Obviously, this combination can produce voltage levels of $\{-3U_{DC}/4, -U_{DC}/2, -U_{DC}/4, 0, U_{DC}/4, U_{DC}/2, 3U_{DC}/4\}$ for the phase output voltage u_{aN}.

C. ANPC+FC

The common five-level ANPC converter is a hybrid of FC topology and NPC configuration [16], because its construction is different from that of 3L-ANPC in Section 1.3.5. As shown in Figure 1.14, the phase structure of a five-level ANPC+FC is derived from the 3L-ANPC by replacing the internal switching device pair (S_2, $S_{2'}$) by a 3L-FC cell. By choosing the voltage of the phase capacitor C_a as $U_{DC}/4$, five different voltage levels can be produced for the phase output: $\{-U_{DC}/2, -U_{DC}/4, 0, U_{DC}/4, U_{DC}/2\}$ [17]. All the allowed switching combinations of the 5L ANPC+FC are listed in Table 1.8, where the redundancies can effectively be utilized to control the neutral point and phase capacitor voltages.

The number of voltage levels can be increased by adding more series output switches and inserting phase capacitors in the FC cell [16]. For the same output levels, the total number of components used in APNC+FC is much less than that in NPC or FC.

1.4 Modulation Methods of Multilevel Converter

Multilevel converters present great advantages compared with conventional two-level converters; the improved quality and reduced THD of the output waveforms make multilevel converters very attractive to the industry. Correspondingly, multilevel converter modulation, and control methods, have attracted much attention, focusing on the challenge to extend traditional modulation methods to the multilevel case, the inherent complexity to control more power electronic devices, and the possibility of taking advantage of the extra switching states. As a consequence, a large number of different modulation and control methods have been developed.

As shown in Figure 1.15, the modulation methods for multilevel converters can be divided into two main groups, one based on space-vector generation and the other on

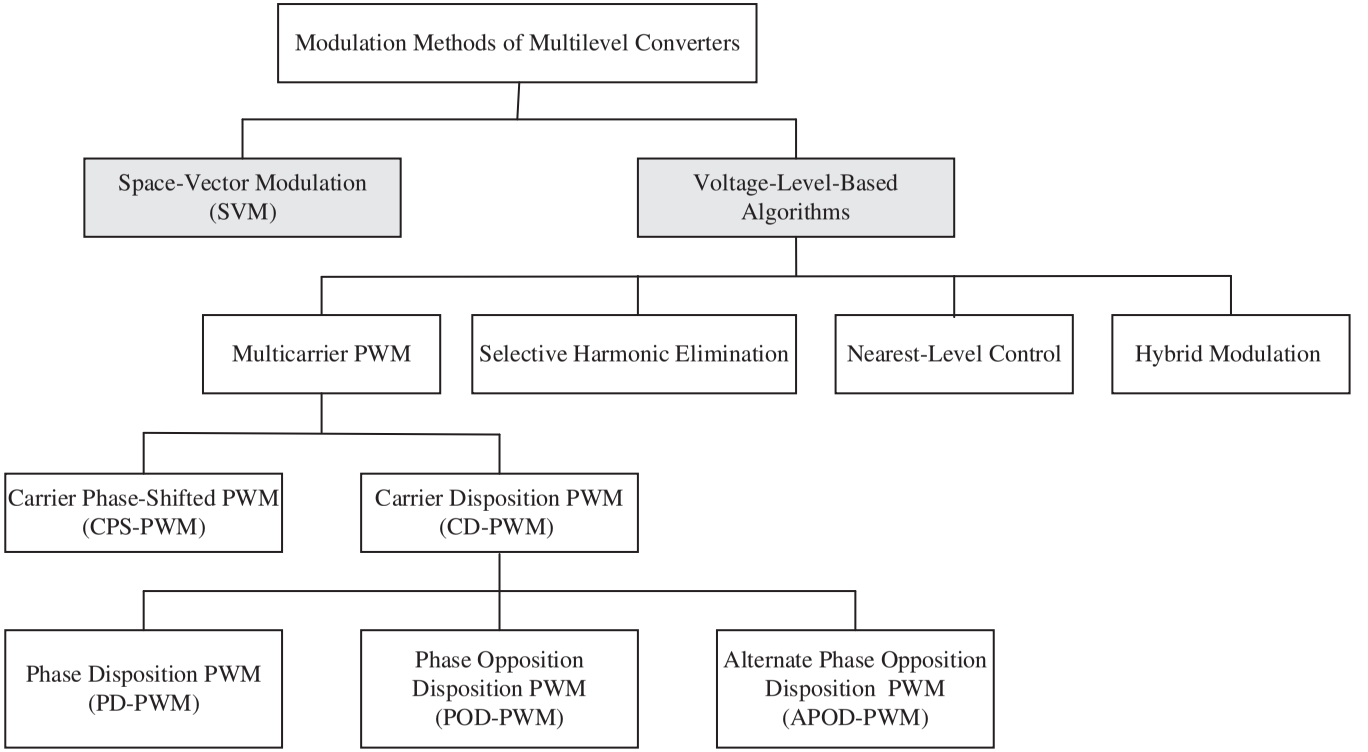


Figure 1.15 Classification of multilevel converter modulation methods.

voltage-level generation [18]. In this section, some typical modulation algorithms will be introduced briefly.

1.4.1 Space-Vector Modulation

SVM is a technique in which the reference voltage is represented as a reference vector. All the discrete possible switching states of the converter lead to discrete output voltages, but the reference vector can be combined by forming the switching sequence and calculating the on-state durations of the respective switching states.

In recent years, several space-vector algorithms have been applied to multilevel converters. Normally, most of them are designed particularly for a specific number of levels of the converter. In high-voltage applications, the more levels to be modulated by SVM, the more complex the vector calculation and selection to be done. The computational cost and algorithmic complexity will increase with the number of levels, thus SVM is not suitable for a multilevel converter with a high number of levels.

1.4.2 Multicarrier Pulse-Width Modulation

Traditional PWM techniques have been successfully extended for multilevel converters using multiple carriers, which is known as multicarrier PWM. Carrier phase-shifted pulse-width modulation (CPS-PWM) and carrier disposition pulse-width modulation (CD-PWM) are two widely used multicarrier strategies to control the MMC. Since each carrier is associated with a particular unit or cell in the multilevel converter and modulated independently, an even power distribution among the units can be provided.

For an m-level converter, the multicarrier PWM operation consists of $m-1$ different carriers, which have the same frequency and the same peak-to-peak amplitude. As shown in Figure 1.16, the symmetrical triangular carriers in CPS-PWM are phase shifted in a certain degree, for example, π/m for the CHB or $2\pi/m$ for the FC. CPS-PWM is normally employed with CHB and FC, because it can mitigate the input current harmonics in the CHB and balance the capacitor voltages in the FC.

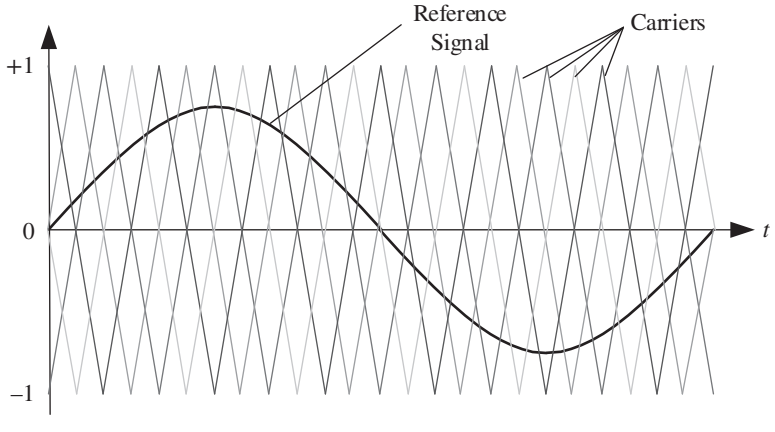


Figure 1.16 Modulation principle of CPS-PWM.

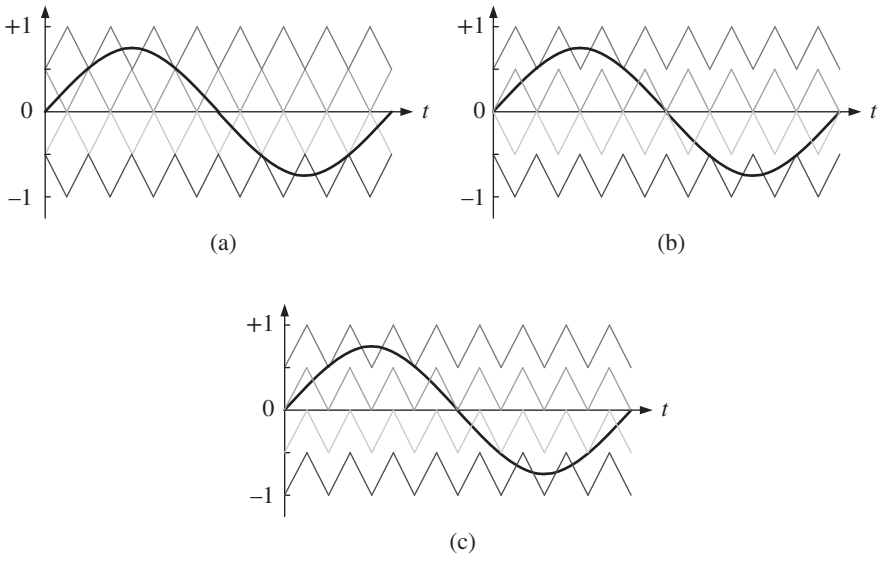


Figure 1.17 Modulation principle of different CD-PWMs. (a) PD-PWM. (b) POD-PWM. (c) APOD-PWM.

Different from CPS-PWM, the carriers in CD-PWM are arranged with shifts in amplitude. Depending on the disposition of the carriers, CD-PWM can be divided into phase disposition pulse-width modulation (PD-PWM), phase opposition disposition pulse-width modulation (POD-PWM), and alternate phase opposition disposition pulse-width modulation (APOD-PWM), as shown in Figure 1.17. The phase of each carrier is the same in PD-PWM, but all carriers are alternatively in phase opposition in APOD-PWM. In POD-PWM, all the carriers above the zero reference are in phase among them but in opposition with those below. The main difference among PD, POD, and APOD is in the harmonic content of the output PWM waveform. For POD and APOD, no harmonic exists at the carrier frequency due to the odd symmetry of their PWM waveforms. For the PD case, the waveform is asymmetric and the first set of undesired harmonics, or those aggregated near the carrier frequency, is relatively high. Thus, POD and APOD are more convenient for single-phase multilevel converters [19].

CD-PWM methods can be implemented for any multilevel topology, and are especially suitable for the NPC, since each carrier signal can easily be related to each power-switching device. However, in the case of low modulated ratio, the conduction time of the switching devices is inconsistent, which limits the further application of CD-PWM.

1.4.3 Selective Harmonic Elimination Modulation

In general, low-switching-frequency methods are preferred for high-power applications due to the reduction of switching losses, while high-switching-frequency algorithms are more suitable for better output quality and high-dynamic-range applications. Thus, selective harmonic elimination pulse-width modulation (SHE-PWM) is highly beneficial for high-power converters operating with low switching frequencies, owing

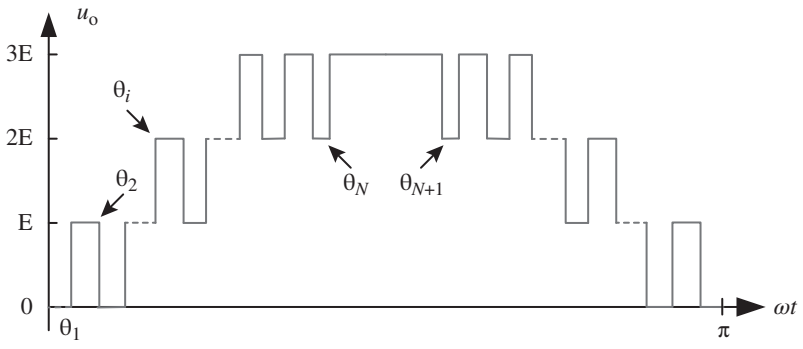


Figure 1.18 Multilevel waveform under SHE-PWM.

to its direct control of the output harmonic spectrum and the strong reduction in switching losses.

The concept of SHE-PWM techniques is based on the Fourier series decomposition of the periodic PWM waveform and calculation of the switching angles to eliminate selected low-order harmonics. Finding the analytical solution of the switching angles is the main challenge of SHE-PWM. Selection of a suitable solving algorithm or method relies heavily on the form of the PWM waveform, because waveform properties such as symmetry, the number and amplitude of voltage levels are important factors in determining the form and complexity of the solution [20]. A typical multilevel SHE-PWM waveform with quarter-wave symmetry is shown in Figure 1.18. Except for calculating the switching angles ($\theta_1 \sim \theta_N$), the distribution of these angles at different units or cells in a multilevel converter is an important aspect of the SHE-PWM method.

SHE-PWM becomes very complex to design and implement for converters with a high number of levels (above five), due to the increase in switching angles and hence nonlinear equations that need to be solved. In addition, online implementation relies on the need for very advanced computational tools and memory capabilities to accommodate the large lookup tables; SHE-PWM appears to be impractical for simultaneous compensation of multiple harmonics.

1.4.4 Nearest-Level Control Method

As presented in Section 1.4.1, multilevel SVM takes advantage of the voltage vectors generated by the converter to approximate the reference vector. The nearest-level control (NLC) method, in essence, has the same principle but considers the closest voltage level that can be generated by the converter instead of the closest vector. As shown in Figure 1.19, the NLC method generates a staircase output voltage by comparing the reference sine waveform with the settled voltage level.

Due to the simple concept and implementation of the NLC method, NLC is widely used in converters with a high number of levels. However, the THD of the output voltage will be high when the modulation index is low, because the operating principle of NLC is based on an approximation and not a modulation with a time average of the reference.

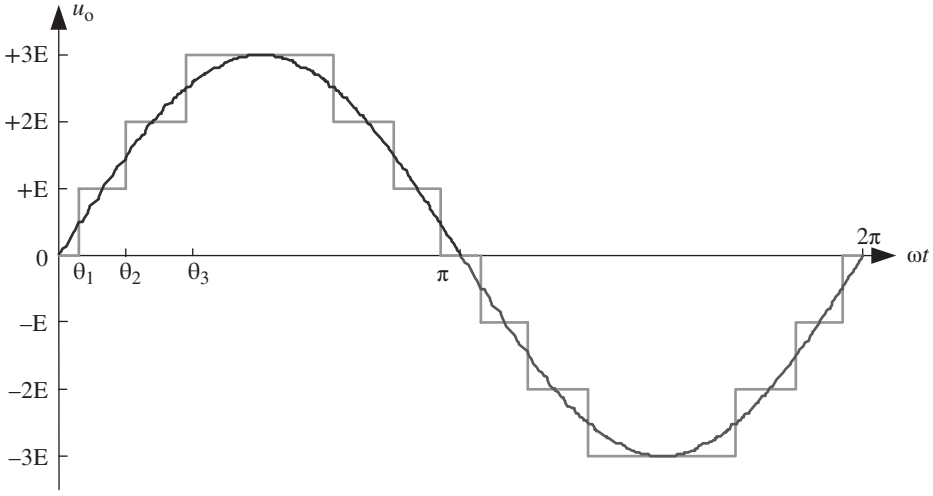


Figure 1.19 Multilevel waveform under NLC.

1.4.5 Hybrid Modulation

Hybrid modulation is in part a PWM-based method that is designed especially for a CHB with unequal DC voltage sources. Normally, the high-voltage units are controlled at the fundamental switching frequency, in which each switch is turned on and off only once per cycle, while the low-voltage unit is controlled by high-frequency PWM.

A CHB with two H-bridge units is taken as an example to illustrate the principle of hybrid modulation, and its typical outputs are shown in Figure 1.20.

As shown in Figure 1.20, the output of the unit with $U_{DC1} = 2E$ or u_{H1} is equal to 2E when the reference sine wave u_r is larger than E, −2E when $u_r < -E$, and otherwise $u_{H1} = 0$. The unipolar PWM scheme is applied to the unit with $U_{DC2} = E$, where the difference between u_{H1} and u_r is used as the reference. Obviously, the output voltage of the CHB is the seven-level waveform with low THD. Compared with the multicarrier PWM strategies, the switching losses of the high-voltage units are reduced by using hybrid modulation and the converter efficiency can be improved consequently.

1.5 Architecture of Multi-terminal High-voltage Converter

Nowadays, renewable energy systems (including wind and solar energies) are experiencing a sharp increase in use in the world; a multi-terminal direct current (MTDC) grid interconnecting multiple AC systems and offshore energy sources (e.g. wind farms) across nations and continents would allow effective sharing of intermittent renewable energy resources and open-market operation for secure and cost-effective supply of electricity. As a result, the need for multi-terminal high-voltage converters will grow rapidly.

In the majority of cases, multiple individual converters are required when multiple distributed AC power supplies need to be connected to the DC grid, which increases the

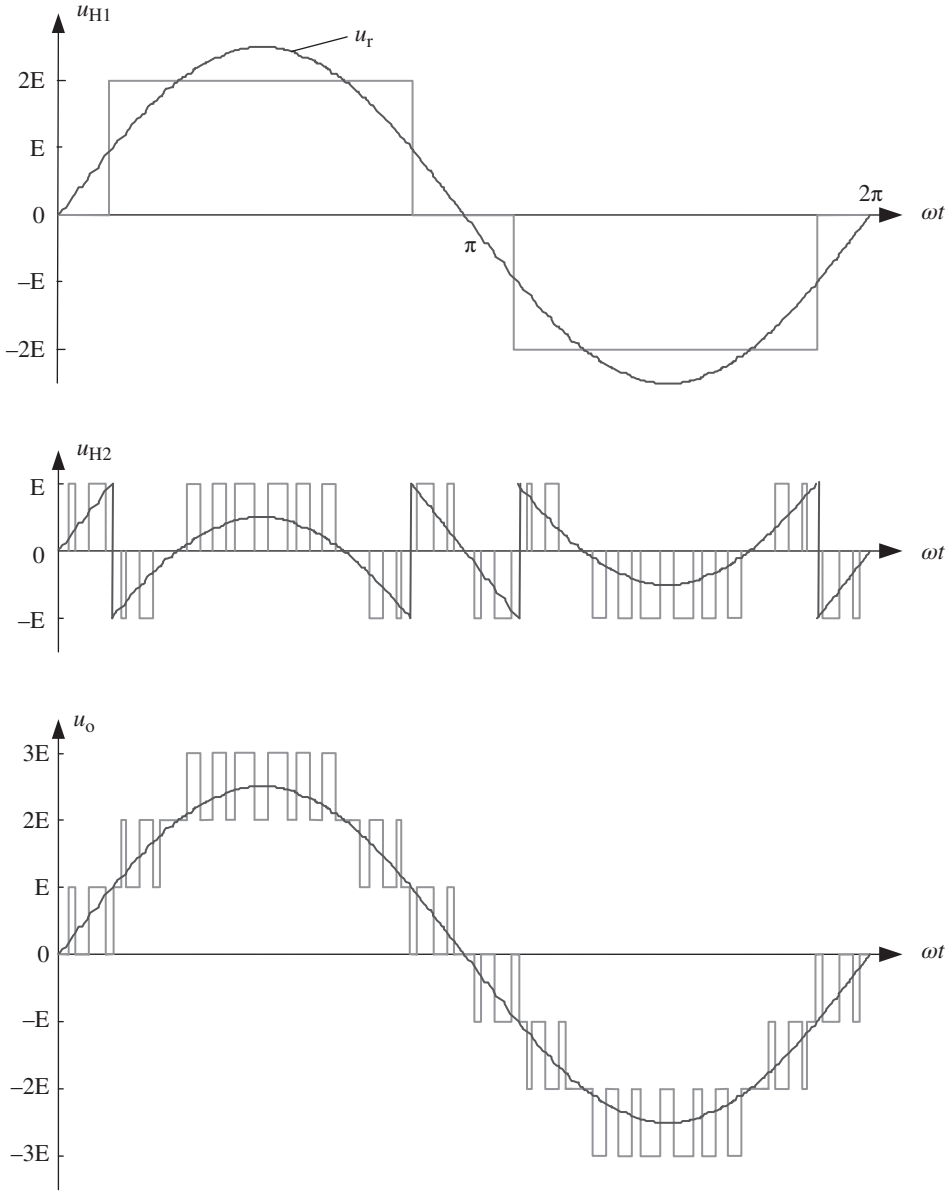


Figure 1.20 Outputs of a seven-level CHB under hybrid modulation.

overall complexity and hence cost of the system. In order to simplify the system structure with multiple AC terminals, it is necessary to design a novel independent high-voltage converter that can connect multiple AC sources simultaneously, as shown in Figure 1.21.

In practice, multi-terminal converters for independent control of large numbers of variable-speed electric drives are often required in industrial applications. Different topologies of multi-terminal converter with reduced number of semiconductor devices

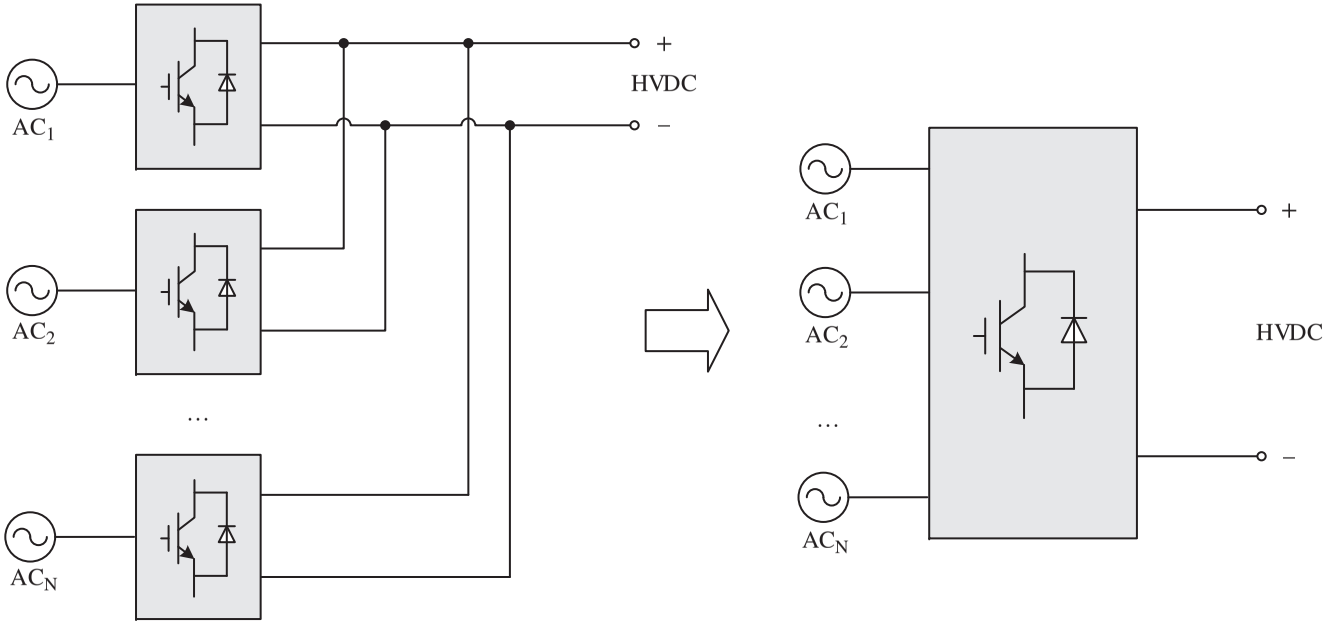


Figure 1.21 Architecture of a multi-terminal high-voltage converter.

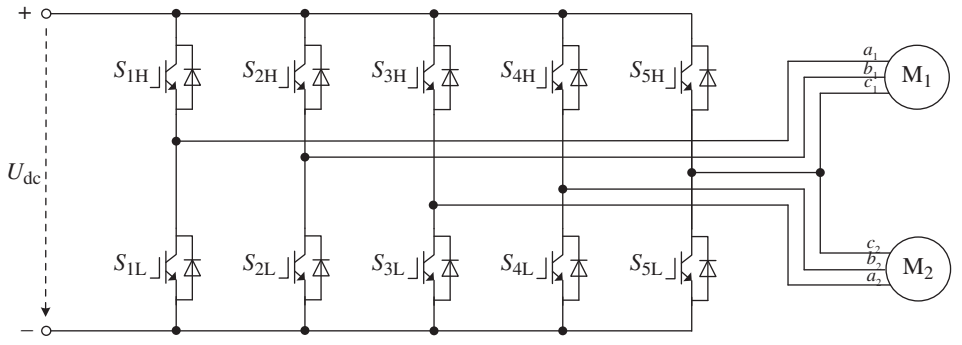


Figure 1.22 Five-leg inverter.

have been developed for the multi-motor drive systems in the past two decades, in order to realize further reductions in complexity and capital cost. For example, the standard dual three-phase voltage source inverter (VSI) configuration is usually used to supply two three-phase induction machines; typical single inverters that can drive two AC motors independently include the five-leg inverter [21], nine-switch inverter [22], and dual two-phase inverter [23].

The five-leg inverter, which has 10 switches, is shown in Figure 1.22; one inverter leg is common to both machines, while the other four inverter legs are connected to the phases of one machine only. The structure of the nine-switch inverter is shown in Figure 1.23, which combines two three-phase inverters with three common switches. The upper inverter for motor M_1 consists of switches S_{UH}, S_{VH}, S_{WH}, S_{UM}, S_{VM}, and

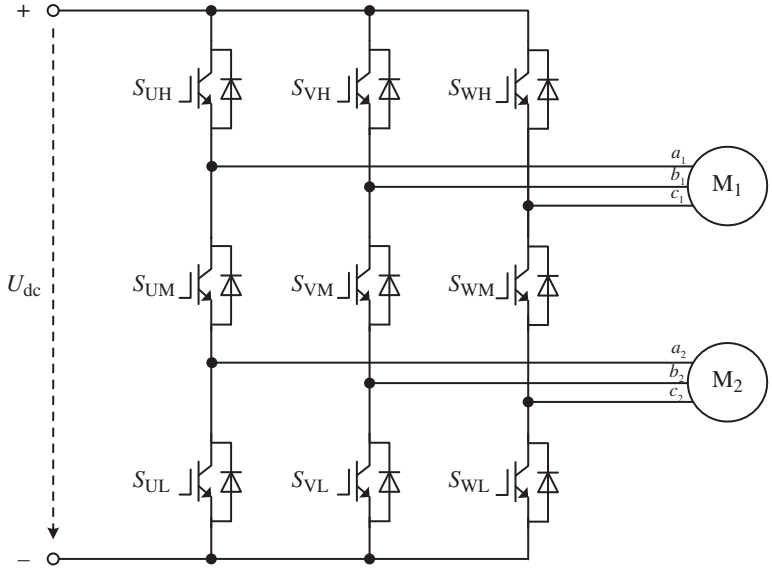


Figure 1.23 Nine-switch inverter.

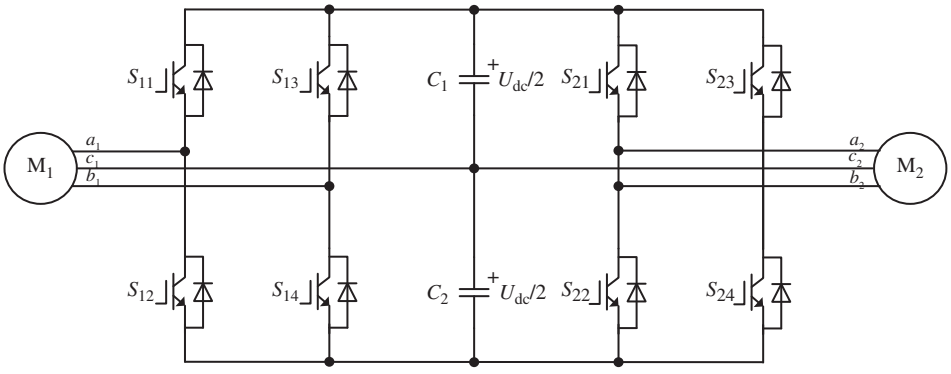


Figure 1.24 Dual two-phase inverter.

S_{WM}. The lower inverter for motor M_2 consists of switches S_{UM}, S_{VM}, S_{WM}, S_{UL}, S_{VL}, and S_{WL}. As shown in Figure 1.24, two two-phase inverters are connected back-to-back with a common DC bus, thus requiring only 8 switches instead of the conventional 12. Similar to the five-leg inverter, two of the machine's phases are connected to two legs of the inverter, but the third phase is connected to the center point of the DC link capacitors.

Therefore, based on the idea of minimizing components in the above converters, it is possible to construct an independent multi-terminal high-voltage converter by extending the terminal number from two to multiple. Taking the needs of high-voltage high-power into account, a multi-terminal DC–AC high-voltage inverter topology is put forward for the first time in this book by combining the nine-switch inverter with the MMC converter. A similar method has been applied to construct a multi-terminal AC–DC high-voltage converter, a multi-terminal AC–AC high-voltage converter, a multi-terminal DC–DC high-voltage converter, and so on [24].

1.6 Arrangement of this Book

The target of this book is to offer an overview of the existing technology and future trends in high-voltage converters, with discussion and analysis of multi-terminal high-voltage converters. Thus, the book starts with an introductory chapter about various kinds of existing high-voltage converter. As the development trend of modern power electronic systems is to pursue low cost, fewer components, high efficiency, and high reliability, a new kind of high-voltage converter with bridge module is proposed in Chapter 2, which is followed by a series of novel multi-terminal high-voltage converters in Chapters 3–7. The proposed multi-terminal high-voltage converters can realize different kinds of conversion, including single DC input/multiple AC outputs, multiple AC inputs/single DC output, multiple AC inputs/multiple AC outputs, multiple DC inputs/multiple DC outputs, and hybrid conversion. The following two chapters, Chapters 8 and 9, focus on some common issues and potential industrial applications of the proposed multi-terminal high-voltage converters, such as short-circuit protection and capacitor voltage balancing schemes.

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