Part Five

High-Power ac Drives

Chapter 12

Voltage Source Inverter-Fed Drives

12.1 INTRODUCTION

The voltage source inverter-fed medium-voltage (MV) drives have found wide application in industry. These drives come with a number of different configurations, each of which has some unique features. This chapter focuses on a few major voltage-source-based MV drives marketed by the world leading drive manufacturers. The advantages and limitations of these drives are analyzed.

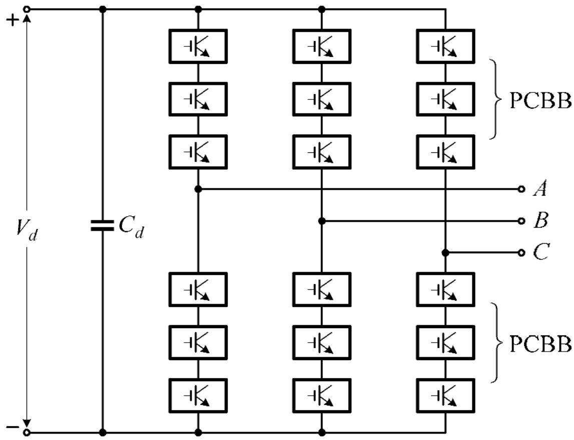
12.2 TWO-LEVEL VSI-BASED MV DRIVES

It is well known that the two-level voltage source inverter is a dominant converter topology for low-voltage ($\leq$600 V) drives. This technology has now been extended to the MV drives, which are commercially available for the power rating up to a few megawatts [1].

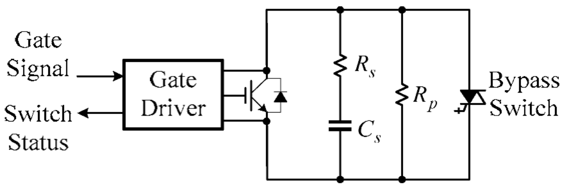
12.2.1 Power Converter Building Block

Figure 12.2-1a shows a typical two-level inverter topology for the MV drive. There are three switch modules in series per inverter branch. Each switch module is composed of an IGBT device, gate driver, snubber circuit, parallel resistor R_p, and bypass switch as shown in Fig. 12.2-1b. This type of switch module is also known as **power converter building block** (PCBB) [2].

The gate driver receives a gate signal from the digital controller of the drive and generates conditioned gating pulses for the IGBT. It also detects the operating status of the IGBT and sends it back to the controller for fault diagnosis. The gate driver normally communicates with the drive controller through fiber-optic cables for electrical isolation and high noise immunity. A number of protection functions can be implemented in the gate driver as well, such as IGBT overvoltage and short-cir-



(a) Two-level inverter



(b) Power converter building block (PCBB)

Figure 12.2-1 Two-level medium voltage inverter with PCBBs.

cuit protections. The active overvoltage clamping scheme presented in Chapter 2 for series-connected IGBTs can also be integrated into the gate driver.

Each IGBT switch is protected by an RC snubber network (C_s and R_s) from overvoltages at turn-off. The snubber also facilitates dynamic voltage equalization for the series connected devices during switching transients. Alternatively, the active overvoltage clamping scheme can be implemented instead of the snubber circuit. However, the use of active overvoltage clamping causes additional switching losses for the IGBTs as discussed in Chapter 2.

The snubber circuit provides an effective means of transferring the switching losses from the IGBT to the snubber resistor, leading to a lower junction temperature rise and better thermal management for the IGBTs. The snubber circuit also helps to reduce the *dv/dt* during the IGBT turn-off transients. The parallel resistor R_p shown in Fig. 12.2-1b is for static voltage sharing, and the function of the bypass switch will be discussed later.

12.2.2 Two-Level VSI Drive with Passive Front End

Figure 12.2-2 illustrates a typical configuration for the two-level VSI drive. A 12-pulse diode rectifier is employed as a front end for the reduction of line current har-

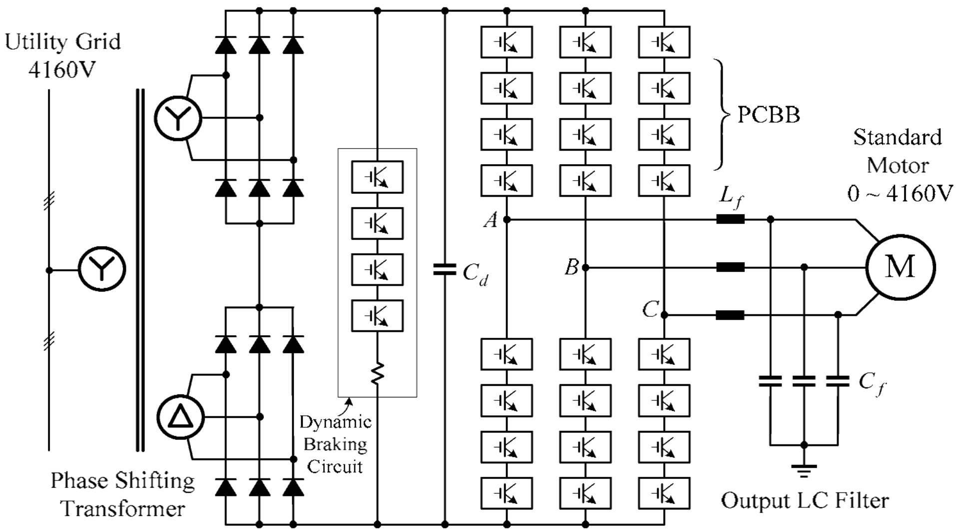


Figure 12.2-2 Typical two-level VSI drive with a passive front end.

monic distortion. For applications with more stringent harmonic requirements, the 12-pulse rectifier can be replaced by an 18- or 24-pulse diode rectifier. The detailed analysis on the multipulse diode rectifiers is given in Chapter 3.

The inverter is composed of 24 switch modules with four modules per inverter branch. Using 3300-V IGBTs, the two-level inverter is suitable for 4160-V (line-to-line) ac motors. The dynamic braking circuit in the dc link is optional. The dc capacitors are normally of oil-filled type instead of electrolytic type commonly used in the low-voltage VSI drives since the latter has limited voltage ratings (a few hundred volts each). The two-level inverter usually requires an LC filter at its output. The inverter can be controlled by either carrier-based modulation or space vector modulation scheme presented in Chapter 6.

The two-level voltage source inverter has the following features:

- **Modular structure using power converter building blocks (PCBBs).** The IGBT device, gate driver, bypass switch, and snubber circuits are integrated into a single switch module for easy assembly and mass production, leading to a reduction in manufacturing cost. The modular design also facilitates fast replacement of failed modules when the drive operates in the field.
- **Simple PWM scheme.** The conventional carrier-based sinusoidal modulation or space vector modulation scheme can be implemented for the inverter. Only six gate signals are required for the six groups of synchronous switches. The number of the gate signals does not vary with the number of the switches in series.
- **Active overvoltage clamping for series connected IGBTs.** The maximum dynamic voltage on the IGBT device at turn-off can be effectively clamped

by the gate driver. The IGBT can be safely protected from overvoltages caused by switching transients.

- **$N + 1$ provision for high reliability.** In applications where high system reliability is required, a redundant switching device ($N + 1$) can be added to each of the six inverter branches. When a switch module malfunctions during operation, the defective module can be shorted out by the bypass switch, and the drive is able to operate continuously at full load with a failed module.
- **Ease of dc capacitor precharging.** The dc capacitor in the two-level inverter needs only one pre-charging circuit. This is in contrast to the multilevel inverters where a multiple sets of precharging circuits are normally required.
- **Provision for four-quadrant operation and regenerative braking.** The multipulse diode rectifier can be replaced by an active front end with the same configuration as the inverter for four-quadrant operation or regenerative braking.

However, there are some drawbacks associated with the two-level voltage source inverter, including the following:

- **High *dv/dt* in the inverter output voltage.** Fast switching speed of IGBTs results in high *dv/dt* at the rising and falling edges of the inverter output voltage waveform. The *dv/dt* is particularly high for the two-level inverter employing series connected IGBTs switching in a synchronous manner. Depending on the magnitude of the dc bus voltage and switching speed of the IGBT, the *dv/dt* can well exceed 10,000 V/μs [3], which causes a number of problems such as premature failure of motor winding insulation, early bearing failure and wave reflections. More detailed explanation is given in Chapter 1.
- **Motor harmonic losses.** The two-level inverter usually operates at low switching frequencies, typically around 500 Hz, resulting in high harmonic distortion in the stator voltage and current. The harmonics produce additional power losses in the motor.
- **Common-mode voltages.** As discussed in Chapter 1, the rectification and inversion process in any converters generates **common-mode voltages** [4]. If not mitigated, these voltages would appear on the motor, causing premature failure of its winding insulation.

The first two problems can be effectively solved by adding a properly designed LC filter between the inverter output and the motor as shown in Fig. 12.2-2. With the use of the filter, the high *dv/dt* in the inverter output voltage is now applied to the filter inductor L_f instead of the motor. The insulation of the inductor should be properly designed for the high *dv/dt*. The LC filter is normally installed inside the drive cabinet and connected to the inverter with short cables to avoid wave reflections. The motor voltage and current can be made nearly sinusoidal by the filter, leading to low harmonic losses in the motor.

However, the use of the LC filter causes some practical consequences, including an increase in manufacturing cost, fundamental voltage drops, and circulating current between the filter and dc circuit. It may also cause LC resonances that can be excited by the harmonics in the inverter PWM voltages. The problem can be mitigated at the design stage by placing the LC resonance frequency below the lowest harmonic frequency [3]. The principle of the active damping control presented in the previous chapter can also be used for the suppression of the LC resonances.

The third problem can be effectively mitigated by the phase shifting transformer in Fig. 12.2-2, through which the common-mode voltages can be blocked. To ensure that the motor is not subject to any common-mode voltages, the neutral of the filter capacitor C_f is grounded directly or through an RC grounding network. In a three-phase balanced system, the neutral points of the capacitor and stator winding should have the same potential. Grounding one makes the other equivalently grounded.

It is worth mentioning that the use of the phase shifting transformer does not lead to the elimination of the common-mode voltage. Grounding the capacitor neutral essentially makes the common-mode voltage be transferred from the motor to the transformer [4]. The insulation system of the transformer should, therefore, be properly designed. The MV drive system is suitable for retrofit applications, where standard ac motors (which are not designed to withstand the common-mode voltages) are usually used.

12.3 NEUTRAL-POINT CLAMPED (NPC) INVERTER-FED DRIVES

The MV drive using three-level NPC inverter technology is marketed by a number of leading drive manufacturers [5–8]. Some manufacturers use GCTs in their drives while the others prefer IGBTs.

12.3.1 GCT-Based NPC Inverter Drives

Figure 12.3-1a shows a typical configuration of a three-level NPC inverter fed drive. A 12-pulse diode rectifier is adopted as a front end. The inverter consists of 12 reverse-conducting GCT devices and six clamping diodes. The mechanical assembly for one of the three inverter legs is illustrated in Fig. 12.3-1b, where four GCTs, two diodes, and a number of heatsinks can be assembled with just two bolts, leading to high power density and low package costs.

There are two *di*/*dt* clamp circuits, each composed of L_s, D_s, R_s, and C_s. One clamp circuit is in the positive dc bus for the switches in the upper half-bridge, and the other is in the negative dc bus for those in the lower half-bridge. With a few micro Henries for the *di*/*dt* limiting choke L_s, the rate of current rise during GCT turn-on transients can be limited to a certain value, typically below 1000 A/μs.

The neutral point *Z* of the NPC inverter can be connected to the midpoint *X* of the diode rectifier. Such a connection makes the total dc voltage equally divided between the two dc capacitors. The inverter neutral point voltage control in this case is no longer an issue.

Similar to the two-level VSI drive, an LC filter is usually installed at the inverter

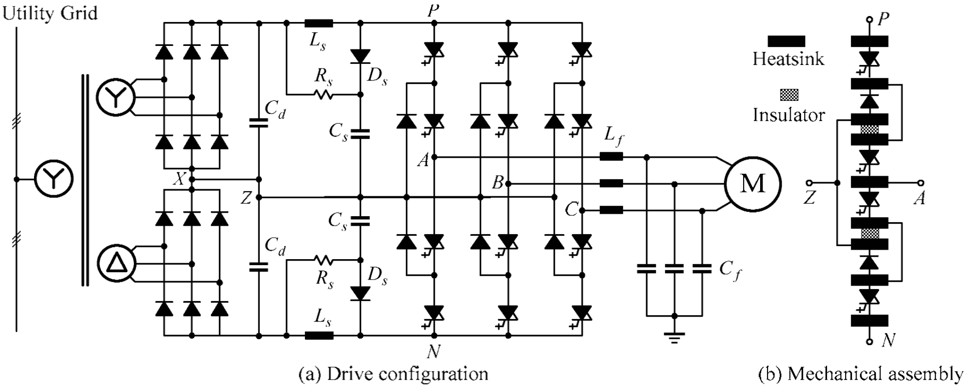


Figure 12.3-1 Typical configuration for a three-level NPC inverter-fed drive.

output terminals for sinusoidal outputs. The filter can also solve the *dv/dt* problems caused by fast switching of the GCT devices.

Figure 12.3-2 illustrates a three-level NPC drive with two more protection schemes added to the drive system of Fig. 12.3-1 [5, 6]. The drive is equipped with protection GCT switches S_d in the dc circuit for fuseless short-circuit protection. The *di/dt* limiting choke L_s limits the rate of rise of the dc current and facilitates a safe shutdown of the drive during a short-circuit fault.

As mentioned earlier, the common-mode voltages produced by the rectifier and inverter are transferred from the motor to the transformer for motor protection by grounding the neutral point of the filter capacitor C_f. To minimize the effect of the common-mode voltages on the transformer and its cables, a special common-mode choke L_{cm} is added to the dc link for the reduction of peak currents that cause charging and discharging of the capacitance of the cables that connect the transformer

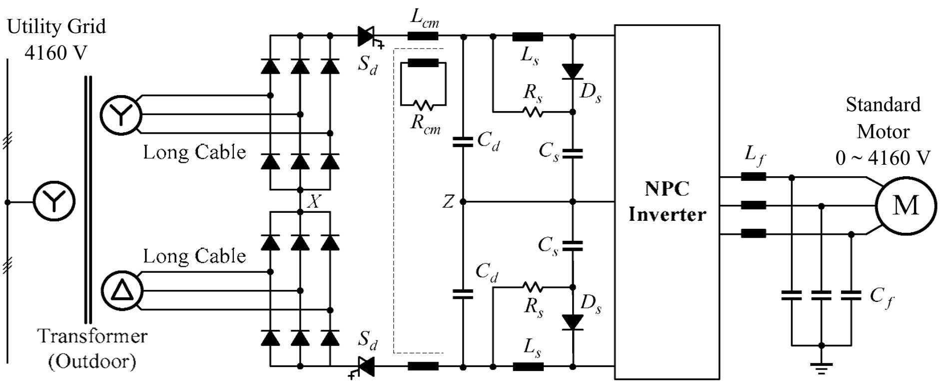


Figure 12.3-2 Three-level NPC drive with a common-mode choke for long transformer cables.

secondary windings to the rectifier. The choke has an auxiliary coil, to which a resistor R_{cm} is connected to suppress transient oscillations. With a properly designed L_{cm} and R_{cm}, the cable length can reach 300 m [6]. The transformer can then be placed outside the control room, which reduces the floor space and room cooling requirements as well.

It should be mentioned that the neutral point Z of the NPC inverter and midpoint X of the 12-pulse rectifier should be left unconnected due to the use of S_d and L_{cm}. As a result, the inverter neutral-point voltage should be tightly controlled as discussed in Chapter 8.

Table 12.3-1 gives the main specifications for the three-level NPC inverter fed

Table 12.3-1 Main Specifications for the Three-Level GCT-Based Drives

Drive System Specifications	Nominal input voltage	2300 V, 3300 V, 4160 V
	Output power rating	400–6700 HP (0.3–5 MW)
	Output voltage rating	0–2300 V, 0–3300 V, 0–4160 V
	Output frequency	0–66 Hz (up to 200 Hz optional)
	Drive system efficiency	Typically > 98.0% (including output filter losses but excluding transformer losses)
	Input power factor	> 0.95 (displacement power factor > 0.97)
	Output waveform	Sinusoidal (with output filter)
	Motor type	Induction or synchronous
	Overload capability	Standard: 10% for one minute every 10 minutes Optional: 150% for one minute every 10 minutes
	Cooling	Forced air or liquid
	Mean time between failure (MTBF)	> 6 years
	Regenerative braking capability	No
Control Specifications	Control scheme	Direct torque control (DTC)
	Dynamic speed error	< 0.4% without encoder < 0.1% with encoder
	Steady-state speed error	< 0.5% without encoder < 0.01% with encoder
	Torque response time	< 10 ms
Power Converter Specifications	Rectifier type	Standard: 12-pulse diode rectifier Optional: 24-pulse diode rectifier
	Inverter type	PWM, three-level NPC inverter
	GCT switching frequency	500 Hz
	Number of GCTs per phase	4
	Number of clamping diodes per phase	2
	Modulation technique	Hysteresis modulation generated by DTC scheme
	Inverter/rectifier switch failure mode	Non-rupture, non-arc

MV drive [5]. Without any GCTs connected in series, the drive is capable of powering ac motors with a rated voltage of 2300 V, 3300 V, or 4160 V. For the 4160-V drives, the GCTs rated at 5500 V can be selected. The rated power of the drive is typically in the range of 0.3 MW to 5 MW. It can be extended to 10-MW for 6600-V applications, where each switch position in the NPC inverter is replaced by two series-connected GCTs [7].

The switching frequency of the GCTs is typically around 500 Hz. However, the motor sees an equivalent switching frequency of 1000 Hz due to asynchronous switchings of the GCT devices, leading to a reduction in harmonic distortion and output filter size. This is one of the main features of the three-level NPC inverter-fed drive. In addition, the drive can operate at the medium voltages up to 4160 V without GCTs connected in series, which reduces the cost and increases the reliability of the drive due to the low component count.

12.3.2 IGBT-Based NPC Inverter Drives

The configuration of an IGBT-based three-level NPC drive is shown Fig. 12.3-3. The drive topology is essentially the same as that given in Fig. 12.3-2 except that neither the *di/dt* clamp circuits nor the protection switches are required. This is due to the fact that the rate of rise of IGBT anode current can be effectively controlled and the short-circuit protection can be fully implemented by the IGBT gate driver.

The main specifications of the three-level IGBT drive are given in Table 12.3-2. Depending on applications and customer requirements, the front end can be either the 12- or 24-pulse diode rectifier. A three-level IGBT-based NPC rectifier can also be used for the drives requiring four-quadrant operation or regenerative braking.

The MV drive can operate at the nominal utility/motor voltages of 2300 V, 3300

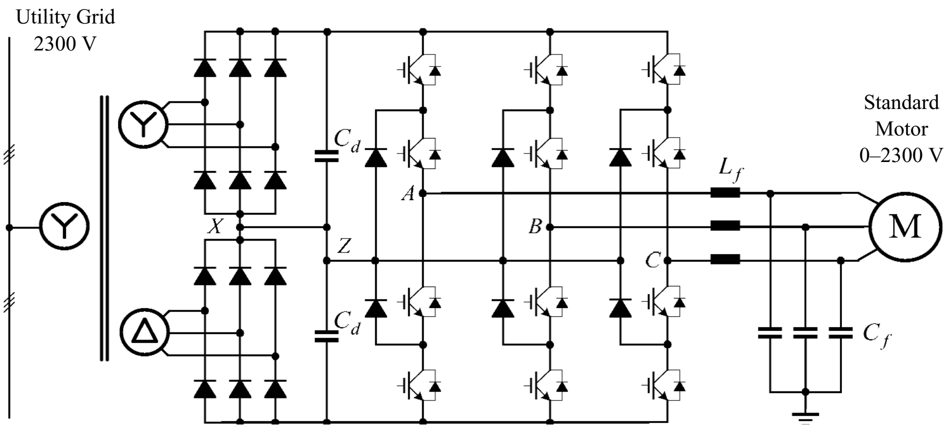


Figure 12.3-3 Three-level IGBT inverter-fed drive.

Table 12.3-2 Main Specifications for the Three-Level IGBT-Based Drives

Rectifier:	Standard: 12-pulse diode rectifier Optional: 24-pulse diode rectifier or active front end (PWM IGBT rectifier)
Displacement power factor ($\cos\varphi$):	> 0.96 (12-pulse diode rectifier)
Nominal utility/motor voltage:	2300 V, 3300 V, 4160 V, 6600 V
Output power rating:	0.8–2.4 MW @2300 V 1.0–3.1 MW @3300 V 1.3–4.0 MW @4160 V 4.7–7.2 MW @4160 V (parallel converter configuration) 0.6–2.0 MW @6600 V
Output voltage range:	0–2300 V, 0–3300 V, 0–4160 V, 0–6600 V
Output frequency:	0–100 Hz (standard)
Motor speed range:	1:1000 (with encoder)
Drive system efficiency:	Typically > 98.5% (at rated operating point, excluding transformer losses)

V, 4160 V and 6600 V. For the 2300-V applications, the NPC inverter is composed of 12 pieces of 3300-V IGBTs without devices in series. For the drives operating at higher voltages, two series-connected IGBTs can be used in each switch position in the inverter.

As listed in the table, the maximum power ratings of the drive are 2.4 MW at 2300 V, 3.1 MW at 3300 V and 4 MW at 4160 V. The power rating can be further increased to 7.2 MW at 4160 V with the two inverters operating in parallel. The operating voltage of the drive can be extended to 6600 V by adding a step-up autotransformer to the output of the 2300-V drive [9]. The leakage inductance of the autotransformer can also serve as the filter inductance, a viable solution for cost reduction.

12.4 MULTILEVEL CASCADED H-BRIDGE (CHB) INVERTER-FED DRIVES

The multilevel cascaded H-bridge (CHB) inverter is one of the popular inverter topologies for the MV drive [10, 11]. Unlike other multilevel inverters where high-voltage IGBTs or GCTs are used, the CHB inverter normally employs low-voltage IGBTs as a switching device in H-bridge power cells. The power cells are then connected in cascade to achieve medium voltage operation.

12.4.1 CHB Inverter-Fed Drives for 2300-V/4160-V Motors

The CHB inverters can be configured with different voltage levels. A seven-level cascaded H-bridge inverter fed MV drive is illustrated in Fig. 12.4-1. The phase-shifting transformer is an indispensable device for the CHB inverter. It provides

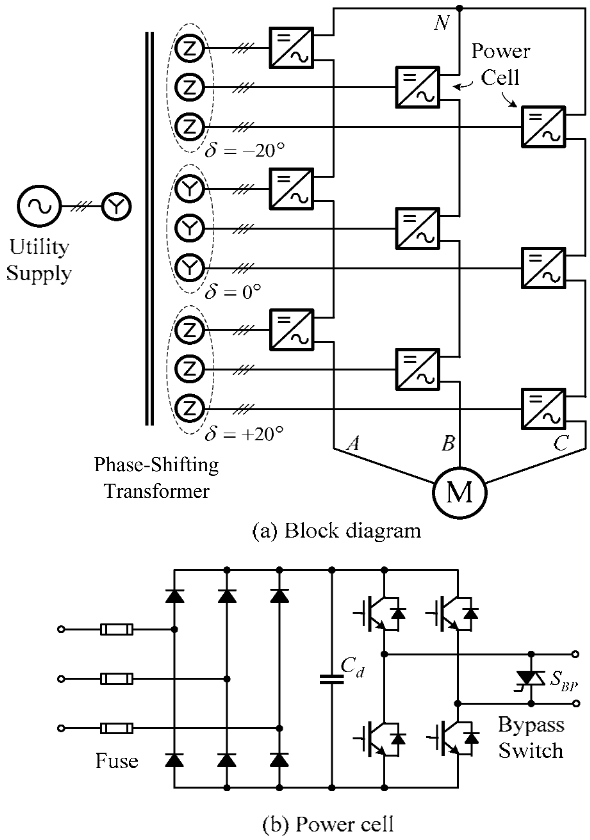


Figure 12.4-1 Seven-level CHB drive with an 18-pulse diode rectifier.

three main functions: (a) isolated power supplies for the power cells, (b) line current THD reduction, and (c) isolation between the utility and the converter for common-mode voltage mitigation.

The phase-shifting transformer has three groups of secondary windings. Each group has three identical windings. The phase shift between any two adjacent winding groups is 20° for the seven-level CHB drive. Since each of the secondary windings is connected to a three-phase diode rectifier, this configuration is essentially an 18-pulse separate type diode rectifier discussed in Chapter 3.

The power cell is composed of a three-phase diode rectifier, a dc capacitor and a single-phase H-bridge inverter as shown in Fig. 12.4-1b. Each power cell is protected by fuses at the input and a bidirectional bypass switch S_{BP} at the output. The nominal output voltage of each power cell is typically 480 V (rms fundamental voltage). This design leads to the use of low-voltage components such as 1400-V IGBTs that are mass produced with a cost advantage over high-voltage (>1700 V) IGBTs. It is worth noting that the power cells should be insulated from each other and from ground at medium-voltage levels even though they use low-voltage components.

Three power cells are cascaded at their ac output to form one line-to-neutral voltage of the three-phase system output. The inverter can produce seven distinct line-to-neutral voltage levels. The phase-shifted multicarrier sinusoidal modulation scheme presented in Chapter 7 is normally used in the CHB inverter. To boost the output voltage of each H-bridge, the 3rd harmonic injection method introduced in Chapter 6 can be adopted.

Table 12.4-1 summarizes the configuration of the multilevel CHB inverter-fed drives for medium-voltage applications. The topologies of the rectifier and inverter usually vary with the drive system operating voltages. For instance, with the utility/motor voltage of 3300 V, a 24-pulse diode rectifier and a nine-level CHB inverter can be selected. To reduce switching losses, the IGBT switching frequency $f_{sw,dev}$ is typically around 600 Hz. However, the equivalent inverter switching frequency $f_{sw,inv}$ is much higher due to the multilevel structure. The power rating of the drive is in the range of 0.3 MW to 10 MW.

The multilevel CHB inverter drive has a number of unique features:

- **Modular construction for cost reduction and easy repair.** The low-voltage power cells can be mass-produced for the multilevel CHB inverters operating at various medium voltages. Defective power cells can be easily replaced, which minimizes the downtime of the production-line.
- **Nearly sinusoidal output waveforms.** The CHB inverter is able to produce ac voltage waveforms with small voltage steps. The inverter normally does not require any filters at its output. The motor is protected from high *dv*/*dt* stresses and has minimal harmonic power losses.
- **Bypass function for improved system availability.** The faulty power cells can be bypassed and the drive can resume operation at reduced capacity with remaining cells. Although the bypass of defective cells may cause three-phase unbalanced operation for the motor, it allows the process to continue.

Table 12.4-1 Configurations of CHB Inverter-Fed MV Drives Using Low-Voltage IGBTs

Nominal Utility/ Motor Voltage (Volts)	Mulltipulse Diode Rectifier			Multilevel CHB Inverter					
	Rectifier Pulses	Secondary Windings	Transformer Secondary Cables	Power Cells	IGBTs	Voltage Levels (v_{AN})	Cell Output (Volts)	$f_{sw,dev}$ (Hertz)	$f_{sw,inv}$ (Hertz)
2300	18	9	27	9	36	7	480V	600	3600
3300	24	12	36	12	48	9	480V	600	4800
4160	30	15	45	15	60	11	480V	600	6000

- **Provision for N + 1 redundancy.** The drive system reliability can be improved by adding a redundant power cell to each of the inverter phase legs. When a power cell fails, it can be bypassed without causing reduction in the inverter output capacity.
- **Nearly sinusoidal line current.** This is mainly due to the use the multipulse diode rectifier.

There are a number of drawbacks for the multilevel CHB drive, including

- **High cost of phase-shifting transformer.** The multi-winding transformer is the most expensive device in the CHB drive. Its secondary windings should be specially designed such that the symmetry of leakage inductances is preserved for harmonic current cancellation.
- **Large number of cables.** The multilevel CHB inverter drive normally requires 27–45 cables connecting the power cells to the transformer. It is, therefore, expensive to place the transformer away from the drive. With the transformer installed inside the drive cabinet, the footprint of the drive increases, and so does the room cooling requirements.
- **Large component count.** The CHB inverter drive uses many low-voltage components, which potentially reduces reliability of the system.

12.4.2 CHB Inverter Drives for 6.6-kV/11.8-kV Motors

The operating voltage of the multilevel CHB inverter can be extended to 6600 V. A practical design for such a drive system is shown in Fig. 12.4-2, where two identical units of the seven-level CHB inverters are connected in cascade. The IGBTs used in the H-bridge power cells are typically rated at 1700 V, and each power cell produces a nominal voltage of 640 V. The power rating of the drive is in the range of 0.6 MW to 6 MW without IGBTs in series or parallel [12].

To drive the motors rated at 11.8 kV, the output voltage of each power cell can be increased to 1370 V. With five cells in cascade for the 11-level CHB inverter, its line-to-line voltages can reach 11.8 kV. High-voltage IGBTs should be used in this drive.

12.5 NPC/H-BRIDGE INVERTER-FED DRIVES

Figure 12.5-1 shows the drive configuration using 5-level NPC/H-bridge inverter [13]. The phase shifting transformer has three identical groups of secondary windings. Each group of secondary windings feeds a 24-pulse diode rectifier. The phase shift between any two adjacent secondary windings in each group is 15°. The neutral point of the NPC/H-bridges is tied to the midpoint of the rectifiers to avoid inverter neutral voltage deviation. The inverter phase voltage v_{AN} is composed of five

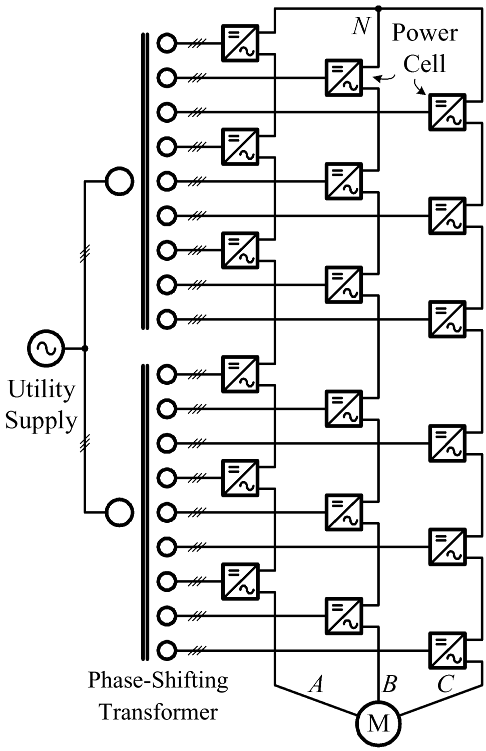


Figure 12.4-2 Topology of a 6600-V drive with two identical 7-level CHB inverters in cascade.

voltage levels while its line-to-line voltage v_{AB} has nine levels as discussed in Chapter 9.

The drive features very low ac line harmonic distortion, no switching devices in series, and low motor current THD. However, it requires a complex phase shifting transformer with 12 secondary windings. The drive also requires a *dv/dt* filter at the inverter output. The power rating of the drive using high-voltage IGBTs is in the range of 0.5 MW to 4.8 MW.

12.6 SUMMARY

This chapter presents various practical configurations of VSI-based MV drives, including two-level IGBT-fed drive, three-level NPC inverter drive, multilevel CHB inverter drive, and NPC/H-bridge inverter drive. The advantages and drawbacks of these drives are analyzed. Some practical problems are addressed, including high *dv/dt* stresses, wave reflections, common-mode voltages, and line/motor current distortion. Commonly used mitigation methods are also introduced.

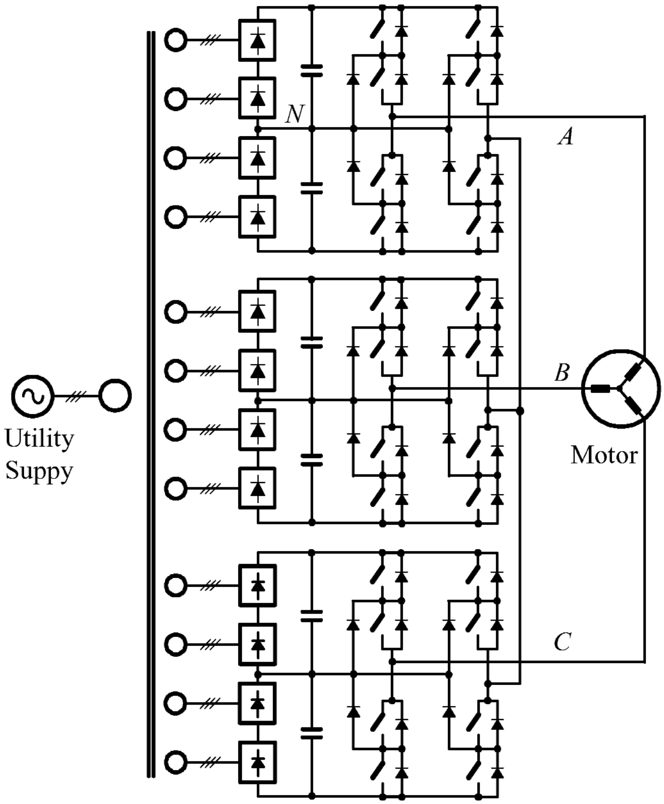


Figure 12.5-1 Five-level NPC/H-bridge inverter-fed MV drive.

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