VARIABLE SPEED DRIVES

Industrial processes often require speed control of electric motors that drive industrial equipment. Motor speed is best and most conveniently controlled by adjusting motor supply voltage or current and/or frequency. Variable speed drives (VSDs) are electric power conversion equipment that convert standard utility power into controllable sources for motors. VSDs are also called adjustable speed drives (ASDs).

VSD COMPOSITION

Modern VSDs are almost exclusively based on static solid-state semiconductor power electronic devices. The power electronic devices function as controllable power switches between the utility source and the motor. Through proper on-off switching, the desired motor voltage or current characteristics can be synthesized from a constant dc or ac source. We all have daily experience with some types of electronic power converters, for example, ac-to-dc adapters, dimmer switches, and power supplies in PCs and other home electronics. They all involve converting 50 Hz or 60 Hz household power into some other form of power by electronic switching. In principle, VSDs based on power electronic devices function much the same way, except that they are power converters designed specially for variable speed motor applications. The power electronic devices in VSDs generally have much higher power ratings than home electronics.

Before the advent of power semiconductors, electromechanically based VSDs dominated for many years. An example is the classical Ward-Leonard dc motor drive that uses a constant speed induction motor driving a dc generator to create a variable dc voltage by controlling the generator's magnetic field. The electromechanically based VSDs have been supplanted because equipment based on power semiconductor electronic devices generally has lower cost, higher efficiency, smaller size, higher reliability, better maintainability, higher dynamic performance, and no moving parts.

Power electronic switching devices are essential to a variable speed drive. In addition, other hardware components are often necessary as integrated parts of a drive, depending on the converter topology. The hardware for VSD can be classified into four major categories:

1. Power conversion circuit components, including
   - power electronic devices
   - auxiliary switching and protection circuits, such as snubbers, commutation circuits, fuses, and grounding networks
   - reactors and capacitors as energy storage components
2. Mechanical components, including
   - heat sinks for power electronic devices, consisting of extruded aluminum heat sinks and sometimes heat pipes for air-cooled drives, and liquid pipes, reservoirs, and heat exchangers for liquid-cooled drives
   - blowers or fans for forced air cooled drives
   - bus bars, connectors, and harnesses
3. Control hardware, including
   - gate drive circuits that generate on-off gate signals for thyristors and power transistors
   - sensors for voltage, current, and speed measurements, which are often required for closed-loop controls
   - control processors for processing feedback, executing control algorithm, generating control commands, and handling external communication. They are the control centers and the brains of the drive. A power device switching is usually first initiated by a processor.
   - interface between control processors and sensors, gate drives, and other control hardware. Modern VSDs all use digital control technology, and the interface performs D/A and A/D transformation, signal receiving, processing, and transmitting.
   - communication I/O circuits interfacing with external equipment and systems, for example, high-level process controllers, computers, and other VSDs.
   - power supplies for control hardware circuits that usually are in the form of printed wire circuit boards.
4. Interface components, including motor contactors, switchgears, surge suppressors, transformers, and input and output filters for harmonics and waveform conditioning

Software is also an essential part of digitally controlled VSDs. A drive today is almost entirely operated by executing software programs usually stored in read-only memory in processors as firmware. Software covers all facets of drive operation: control, communication, data processing, diagnostics, and protection. It is becoming an increasingly bigger part of a VSD as digital technology advances and more sophisticated operating algorithms are being developed and implemented.

The technology drivers behind VSD development are power semiconductor technology and digital control and computer technology. Because these technologies are progressing rapidly, VSD technology has been changing fast, new and better drives are being developed continually, and new applications are being pursued. A major factor in the development of VSD technology is customer demand for additional VSD performance to compensate for deficiencies in motor, power factor, and electrical noise issues.

POWER ELECTRONIC DEVICES IN VSDs

All commercially available power electronic devices are used in motor drives. The three basic types of power electronic devices are power diodes, thyristors, and power transistors (1–3). Like semiconductor electronic devices used in microelectronics, all power electronic devices are based on *p–n* junctions, conduct only unidirectional current under normal operation, and thus are “switches.” Thyristors and transistors have three terminals: anode (positive), cathode (negative), and a gate. The function of the gate is to control the turn-on and turn-off of the device. Current flows from anode to cathode with forward voltage bias and a proper gate signal. Power diodes have only anodes and cathodes, and their conduction or blocking is determined solely by the voltage bias across the two terminals. Therefore, power diodes are noncontrollable switches, whereas thyristors and power transistors are controllable switches. Some types of controllable switches are essential for a VSD power converter. A thyristor differs from a transistor in that the thyristor is a latching device that requires only a pulse gate signal to turn on or off. The transistor is a nonlatching device that requires a continuous on or off gate signal for conduction or blocking. Each category of power electronic devices has a number of variants. The commonly used power transistors in VSDs include bipolar junction transistors (BJTs), metal oxide semiconductor field effect transistors (MOSFETs), and insulated gate bipolar transistors (IGBTs). The commonly used thyristors include phase-controlled thyristors (SCRs), gate-turn-off thyristors (GTOs), and MOS-controlled thyristors (MCTs)

- Power diodes, similar to their counterparts in microelectronics, conduct when they are forward biased. Commutation, the process of turning-off and transfer of current from one diode to another, occurs when diodes are reverse biased and their current decreases to zero. Diodes are usually used in rectifiers, commutative circuits, and protection circuits. Their ratings are up to several kilovolts in voltage and several kiloamperes in current.
- SCRs are current triggered switches and can be turned on by gate current pulse signals when they are in the forward-blocking state. SCRs can only be turned off like diodes by reverse bias. Their switching speed is relatively low. They have large voltage and current handling capabilities with voltage ratings up to 5 kV to 7 kV and current ratings up to 4 kA. SCRs are usually used in naturally commutated, high-power applications.
- GTOs are current triggered devices like SCRs but are also turned off by gate pulses. They also have high power capabilities and handle voltages up to several kilovolts and current up to several kiloamperes. Their switching time is in the range of microseconds to tens of microseconds. GTOs are used in high power drives.
- BJTs are current-controlled devices, and their base current must be continuously supplied to keep them in the on-state. Typical switching time for BJTs ranges from hundreds of nanoseconds to microseconds. Their voltage ratings are up to 1000 V and current ratings to several hundred amperes. BJTs are used in low-voltage, low-power drives.
- MOSFETs are voltage-controlled devices that require continuous positive gate voltage to keep them conducting and negative gate voltage to turn them off. MOSFETs switch very fast and their switching time is in the range of tens to hundreds of nanoseconds. Their voltage ratings are below 1000 V, and current ratings are below 100 A. MOSFETs are used in low-voltage, low-power drives.
- IGBTs combine some characteristics of BJTs and MOSFETs. They have relatively low losses and relatively fast switching time. Their gate control is similar to MOSFETs and their switching time ranges from hundreds of nanoseconds to microseconds. Their voltage ratings can go up to 4.5 kV, and current ratings are above 1 kA. They are used in medium-power drives.
- MCTs are voltage-controlled devices. They have many of the properties of GTOs, but have simpler gate drive circuitry and faster switching speed. Their voltage ratings are comparable to GTOs but their current ratings are much lower. MCTs are suitable for medium power drives.

VSD APPLICATIONS

VSDs are frequently found in every industry sector and most commonly in the

- pulp and paper industry for paper machines, dryer fans, boiler fans and pumps, chippers, refiners, and conveyors
- metal industry for rolling mill stands, reels, and winders
- material handling industry for cranes and conveyors
- mining industry for excavators, conveyors, and grinding mills
- cement industry for kiln drives and fans and conveyors
- petroleum and chemical industry for pipeline compressors and pumps, oil well drilling equipment (draw works, top drives, mud pumps, and cement pumps), water and wastewater pumps, and rubber and plastics equipment (extruders, inlet pumps, pelletizers, and mixers)
- transportation industry for locomotive traction, ship propulsion, aircraft generators, and off-highway vehicles
- automotive industry for electric vehicles, dynamometers, and wind tunnels
- appliance industry for washing machines, air conditioners, and HVAC
- electric utility industry for turbine starters, boiler and cooling tower fans and pumps, wind turbines, and microturbines

- textile and man-made fiber industry for extruders, pumps, fans, HVAC, and conveyors.

The drive size ranges from a fraction of a horsepower in an appliance to tens of megawatts in rolling mills. The type of loads in VSD applications are often variable torque loads, such as fans and pumps whose torque is a function of speed or constant torque loads whose torque is independent of speed.

CLASSIFICATION OF VSDs

Based on the types of motors they drive, there are two general categories of VSDs, dc drives and ac drives. Ac drives include induction motor drives and synchronous motor drives. Switching reluctance motor (SRM) drives and permanent magnet (PM) synchronous motor drives (known as dc brushless motors) are two important variants of ac synchronous motor drives.

VSDs can be further classified in many other ways:

- Based on input power source, a VSD can be either dc fed or ac fed.
- Based on voltage ratings, a VSD is low voltage if lower than 600 V or medium voltage if above 600 V.
- Based on converter topology, there are phase-controlled rectifiers, choppers, and pulse-width-modulated (PWM) choppers for dc drives, and for ac drives, load-commutated inverters (LCI), cycloconverters, current source inverters (CSI), voltage source inverters (VSI), and PWM-VSIs.
- Based on power electronic devices, a VSD can be a GTO, IGBT, MCT, or MOSFET drive.
- Based on commutation techniques, a VSD can be line-commutated, load-commutated, or force-commutated.
- Based on cooling technology, a VSD can be naturally cooled, forced air-cooled, or liquid-cooled.
- Based on control technologies, a VSD can be analog or digital, open-loop controlled or close-loop regulated, with sensors or sensorless, and in the case of ac drives, scaler-controlled or vector-controlled.
- Based on braking capability, a VSD can be regenerative (with braking power) or nonregenerative.
- Based on applications, a VSD can be a stand-alone drive or a system drive where multiple drives are used in a coordinated system, such as paper machines or rolling mill stands. System drives usually require highly precise control.

VSD PERFORMANCE INDEXES

There are three basic categories of performance indexes for VSD, those related to speed control, those related to power converters, and those related to interface with utility power source and motor. Some of the most important are listed here (3–5):

- Speed range: the ratio between maximum speed and minimum speed. A related parameter is field-weakening speed range defined as the ratio of top speed to rated speed.
- Speed accuracy: the error in speed as a percentage of rated speed. For digitally controlled and tachometer-based VSDs, the steady-state error is as low as 0.01%.
- Speed regulation response: characterized through response time to a step change in speed command. A typical industrial application requires a 15 rad/s or less speed regulator.
- Overload capability
- Starting torque
- Efficiency
- Input power factor
- Voltage and current harmonics generated in motors and input power sources
- Regenerative capability
- Ride-through capability, that is, tolerance to input power disturbance.

DC DRIVES

Dc Motor Speed Control

Because VSDs are power converters for controlling motor speed, it is essential to understand motor speed control to understand the topology and operation of a VSD. Figure 1 is a schematic representation of a dc motor. The armature and field windings can be connected in different ways to form series-connected dc motors, shunt-connected dc motors, separately excited dc motors, and compound-connected dc motors (6). Separately excited dc motors, including permanent magnet motors, dominate in dc VSD applications. Following are the basic equations for a separately excited dc motor

$$\Phi = k_f I_f \qquad (1)$$

$$T = k_a \Phi I_a = k_a k_f I_f I_a \qquad (2)$$

$$E = k_e \omega_m \Phi = k_e k_f \omega_m I_f = V_a - I_a R_a \qquad (3)$$

where k_a, k_e, and k_f are constants, I_f is the field current, V_a is the armature voltage, R_a is the resistance of the armature winding, T is the torque, Φ is the flux, E is the emf, and ω_m is the mechanical angular speed of the motor.

Its steady-state torque-speed characteristic is given by

$$\omega_m = \frac{V_a}{k_e k_f I_f} - \frac{R_a}{k_e k_a k_f^2 I_f^2} T \qquad (4)$$

Equation 4 indicates that three basic means for dc motor speed control are by armature voltage, flux or field current, or armature resistance. The most common approach in dc VSD applications is combining voltage and field control. Below

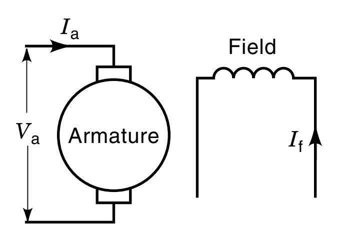

Figure 1. Schematic representation of dc motors.

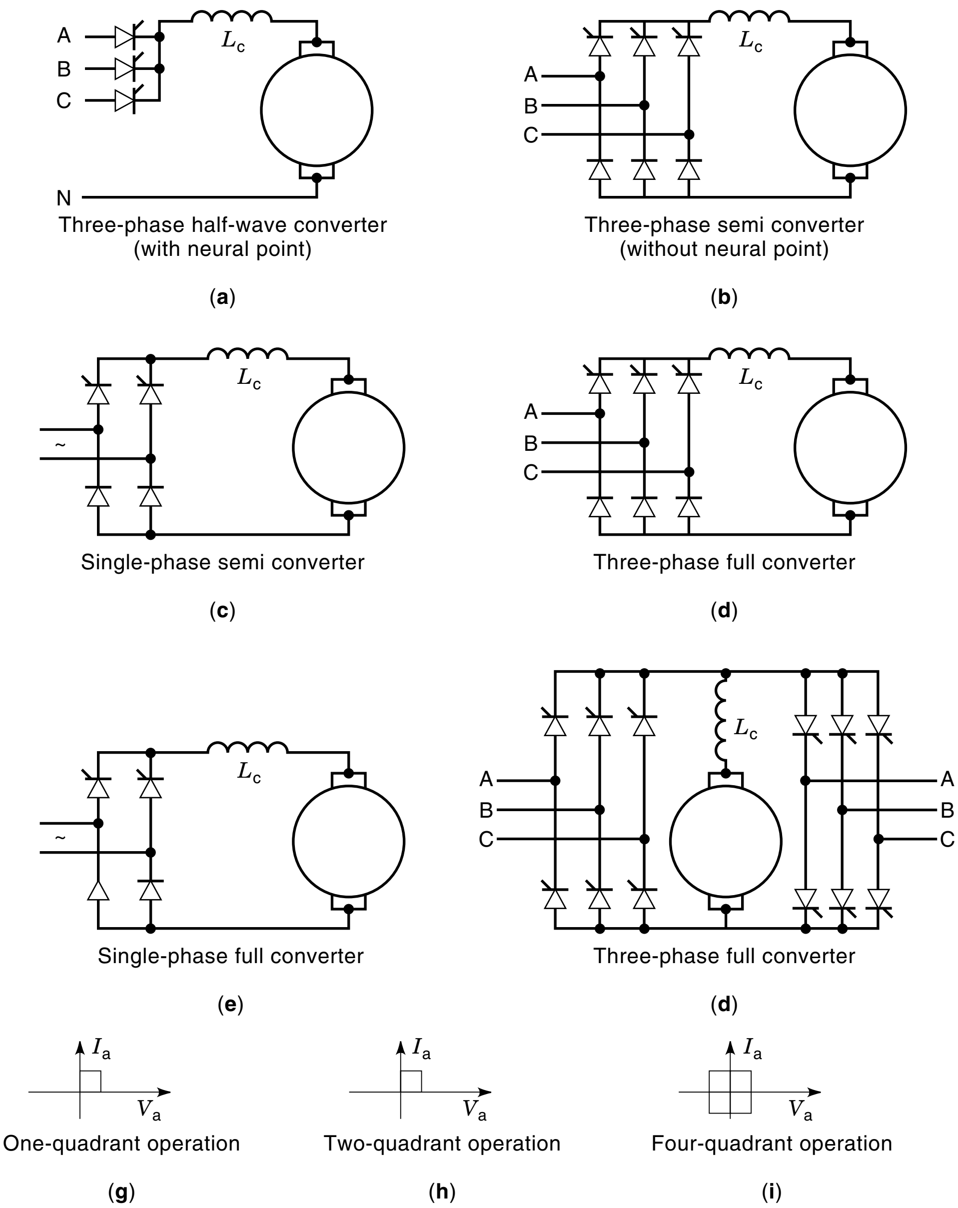

Figure 2. Topology of phase-controlled dc drive converters.

rated speed, ω_m is adjusted by armature voltage, and field current I_f and therefore motor flux Φ are kept constant at their rated values. Above rated speed, ω_m is adjusted by I_f such that V_a remains constant at its rated value. The technique of decreasing the field current to extend speed range beyond rated motor speed is termed field-weakening control. The field-weakening region is often called the constant power region because the power holds constant for a constant motor current when the voltage is constant. Below rated speed is the constant torque region where the torque holds constant for a constant motor current when the flux is constant. Power angle control can be applied to PM dc motors to extend the speed range beyond the rated speed (6).

Based on the principles of dc motor speed control, a dc VSD in general should be an adjustable dc voltage source plus a controllable field exciter.

Phase-Controlled Rectifiers (3,7)

Phase-controlled rectifiers convert line-frequency ac voltage to controlled dc voltage. Figure 2 shows several possible topologies for such converters where SCRs are the main switching devices. If these SCRs are substituted by diodes, these converters would be the familiar diode rectifier bridges that convert line-frequency ac to constant dc. In the case of diode rectifiers, a diode conducts as soon as it enters the forward bias state. An SCR conducts under forward bias only when a gate pulse is also fired. By controlling the firing angle α, defined as the delay angle from its initial forward bias point, the equivalent dc voltage of the rectifier can be controlled. Figure 3 shows a dc equivalent circuit for converters in Fig. 2. Circuit parameters for different converter topologies are listed in Ta-

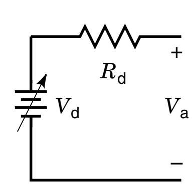

Figure 3. Dc equivalent circuit of line-frequency converters.

Table 1. Dc Equivalent Circuit Parameters[a]

Converter Type	R_d	V_d	V_{d0}
Fig. 2(c)	$\frac{2}{\pi}\omega L_c$	$\frac{V_{d0}}{2}(1+\cos\alpha)$	$\frac{\sqrt{2}V_{rms}}{\pi}$
Fig. 2(e)	$\frac{2}{\pi}\omega L_c$	$V_{d0}\cos\alpha$	$\frac{\sqrt{2}V_{rms}}{\pi}$
Fig. 2(b)	$\frac{3}{\pi}\omega L_c$	$\frac{V_{d0}}{2}(1+\cos\alpha)$	$\frac{3\sqrt{6}V_{ln-rms}}{\pi}$
Fig. 2(d)	$\frac{3}{\pi}\omega L_c$	$V_{d0}\cos\alpha$	$\frac{3\sqrt{6}V_{ln-rms}}{\pi}$

[a] Ref. 7.

ble 1. Clearly, the terminal voltage can be controlled by SCR firing angles. The range for α is from 0° to nearly 180°.

Table 1 indicates that semicontrolled converters in Fig. 2(b) and (c) have only positive dc ouput voltages whereas voltages for fully-controlled converters in Fig. 2(d) and (e) can alternate polarity. All four topologies allow only unidirectional dc current into the motor armature. Therefore, with semicontrolled converters, a dc motor can operate in only one quadrant, the motoring operation quadrant, as shown in Fig. 2(g). With fully-controlled converters, the motor can work in two quadrants: motoring and regenerating, as shown in Fig. 2(h). However, to have braking capability, the motor field current must alternate polarity in two-quadrant converters.

Figure 2(f) shows a dual fully-controlled converter topology with both forward and reverse current capability that can operate in all four quadrants, as shown in Fig. 2(i). It is a popular configuration and provides full regenerating capability because it does not require a polarity change for field current and has superior dynamic performance. When a phase-controlled rectifier is regenerating, it is said to be working in an inverter mode.

The output current of a phase-controlled rectifier normally contains ac ripples that are multiples of ac line frequency, and a series smoothing reactor is often required to filter out these current ripples.

Phase-controlled dc drives always have lagging power factors. They generate harmonics in input ac line currents because of discrete switching. Because the switching and commutation are based on ac line frequency, these harmonics are characteristic harmonics or multiples of line frequencies.

Dc Choppers (1)

Dc-fed dc converters are called choppers. A PWM scheme is usually used to control voltages applied to dc motors. The dc sources in VSD applications are usually phase-controlled or PWM ac-to-dc fully regenerative sources and can be common sources shared by multiple dc-fed drives.

A four-quadrant operation chopper is shown in Fig. 4(a). The chopper has four switches and four antiparallel diodes. The two switches on the same leg, S1+ and S1−, or S2+ and S2−, do not turn on or off simultaneously. When S1+ is on and S1− is off, $V_{AN} = V_d$. When S1+ is off and S1− is on, $V_a = V_{AV} - V_B$. Therefore V_{AN} is independent of the direction of I_a, and

$$V_{AN} = V_d \cdot (\text{duty ratio of S1+}) \tag{5}$$

A similar relationship exists for V_{BN}:

$$V_{BN} = V_d \cdot (\text{duty ratio of S2+}) \tag{6}$$

Because $V_a = V_{AN} - V_{BN}$, the terminal voltage of a dc motor is either positive or negative. The armature current I_a can also be dual directional. The possible operating quadrants are shown in Fig. 4(a). Because the source current I_d changes direction instantaneously, it is important that the source has a low internal impedance. In practice this is usually done by installing a large filtering capacitor in parallel with the dc source.

Figure 4(b) shows a two-quadrant chopper, where one of the two switches is on at any time to keep the output voltage independent of the direction of I_a. The motor terminal voltage V_a can be controlled in magnitude but always remains unipolar. When the motor is in the braking mode, I_a reverses and flows into the source, as shown in Fig. 4(b).

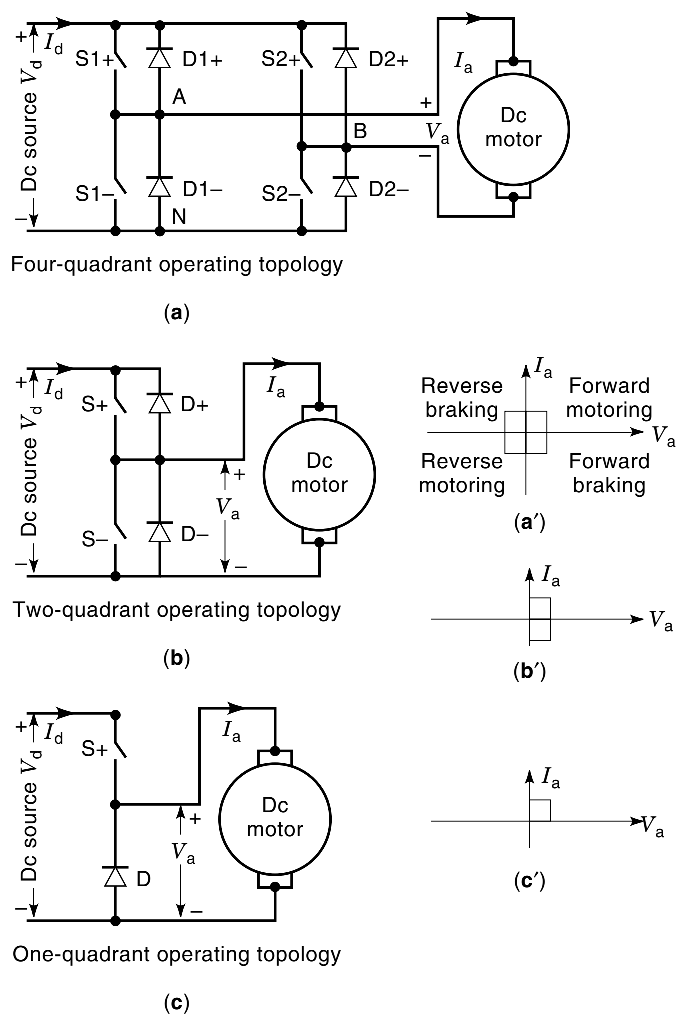

Figure 4. Chopper topology for dc drives.

When the motor speed is unidirectional and no motor braking is needed, the topology of Fig. 4(c) can be used. Operation is limited to the first quadrant as in Fig. 4(c).

Choppers use diodes and controllable switches with turn-off capabilities. Depending on power ratings, the devices can be BJTs, MOSFETs, GTOs, IGBTs, or MCTs.

Field Exciters

Field exciters provide dc excitation currents for separately excited dc motors. They themselves are usually phase-controlled ac-to-dc rectifiers with current regulating capability.

AC DRIVES

Ac Motor Speed Control

Although there are many types of ac VSDs, invariably they are some type of variable-frequency and variable-voltage (or current) converter because ac motor speed control always involves frequency control and voltage (or current) control.

Ac Induction Motor Speed Control. Induction motors are electrically made up of balanced multiphase stator windings and shorted rotor windings. A typical induction motor can be represented by the equivalent circuit in Fig. 5, in which, R_s and L_{ls} are stator winding resistance and leakage inductance, R_r and L_{lr} are rotor winding resistance and leakage inductance referred to the stator winding, L_m is the equivalent air-gap magnetizing inductance, f is the stator source frequency, and f_{sl} is the slip frequency. For a motor with p poles, the slip frequency is given by

$$f_{sl} = \frac{\omega_s - \omega_m}{\omega_s} f = sf \tag{7}$$

where

$$\omega_s = \frac{p}{2}\,\omega_e = \frac{p}{2} 2\pi f$$

is the synchronous mechanical speed, ω_e is the angular electrical frequency, ω_m is the rotor speed, and s is the per unit slip.

Induction motors operate through magnetic fields rotating at ω_s that induce current in the rotor winding rotating at ω_m. It is necessary to maintain slip for an induction motor to generate torque.

The resistance $((f - f_{sl})/f_{sl})R_r$ in Fig. 5 is the equivalent motor load. Neglecting magnetizing branch in Fig. 5, the torque and speed relationship for a three-phase motor is given by

$$T = \frac{2}{p\omega_e} \frac{3V_s^2 \dfrac{R_r}{s}}{\left(R_s + \dfrac{R_r}{s}\right)^2 + \omega_e^2 (L_{ls} + L_{lr})^2} \tag{8}$$

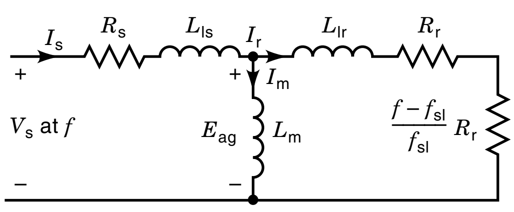

Figure 5. Steady-state induction motor equivalent circuit.

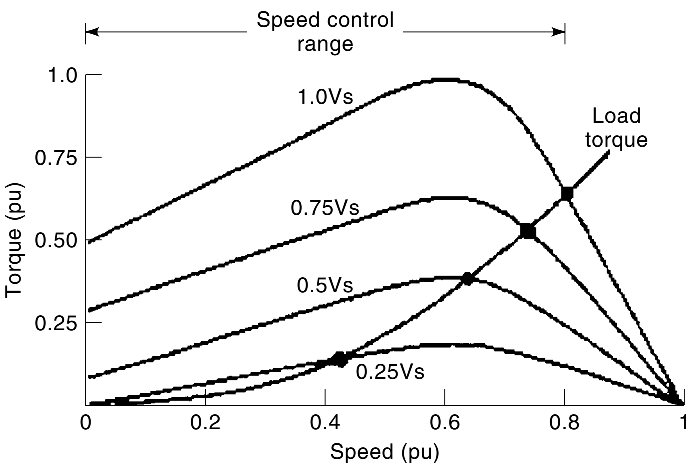

Figure 6. Induction motor torque–speed curves with stator voltage speed control (3).

Figure 6 shows a family of torque-speed curves based on Eq. (8) for various stator voltages. The torque in the curves are normalized on maximum pull-out torque at rated voltage, and the speed is normalized on rated synchronous speed. Equation 8 clearly indicates that there are four basic means for ac induction motor speed control: pole switching, stator voltage control, rotor resistance or slip power control, and frequency control.

Pole switching physically alters the number of poles p for a motor through external switchgear. Because this changes the synchronous speed ω_s, the motor speed also changes for a given load. Pole switching is a discrete speed control method seldom used in VSDs.

Equation (8) shows that changing stator voltage changes speed. Figure 6 shows the speed control characteristics with a fan type load. Because motor flux is proportional to voltage at a given frequency, the voltage control method is flux-weakening control. It is of limited use in fan or pump type loads.

Slip power or rotor resistance control applies only to wound rotor induction motors whose rotor windings have external terminals. The basic idea is to change the slip speed by feeding the slip energy back to the supply, converting it to additional useful mechanical power, or dissipating it in a resistor bank (7). This method is used in special VSD applications.

Frequency control changes supply frequency f and therefore motor synchronous speed ω_s, to control motor speed. It is often called V/Hz control because motor voltage is adjusted proportionally as f changes to maintain constant motor flux and maximize motor utilization. It can be shown from Eq. 8 that the maximum torque under a constant V/Hz ratio is nearly independent of f. The principle of V/Hz speed control

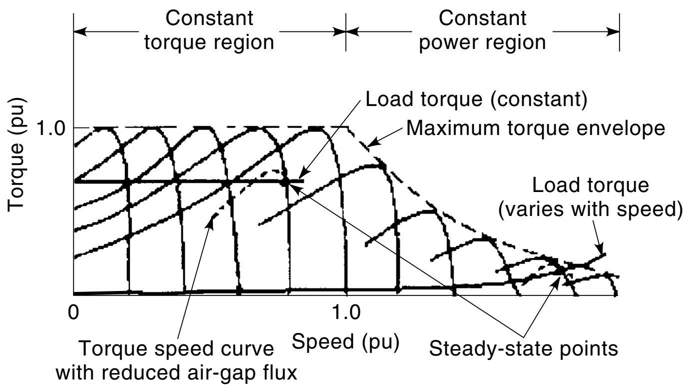

Figure 7. Induction motor torque-speed curves with V/Hz speed control (3).

is shown in Fig. 7. Below rated frequency, V/Hz ratio is maintained constant, and the motor operates in the constant torque region. Beyond the rated frequency, the voltage remains constant and the torque declines as frequency increases, forming a constant-power or field-weakening region. The V/Hz control and its variations are the most widely used methods in ac VSDs.

Ac Synchronous Motor Speed Control. Three types of synchronous motors based on rotor configuration are wound field winding, permanent magnet, and reluctance. The speed of a synchronous motor is determined solely by the stator supply frequency, that is, either it must run at synchronous speed or does not run at all. The torque of a synchronous motor can be written as (27)

$$T = \frac{3p}{2}\left[\frac{EV_s}{\omega_e^2 L_d}\sin\delta + \frac{V_s^2}{2\omega_e^2}\left(\frac{1}{L_q} - \frac{1}{L_d}\right)\sin 2\delta\right] \qquad (9)$$

where p is the number of poles, E is the motor internal emf produced by field current, V_s is the terminal voltage, ω_e is the electrical frequency, L_d and L_q are constant motor direct and quadrature inductances, and δ is the load angle between vectors $\boldsymbol{E}$ and $\boldsymbol{V}_s$. Because E and V_s are proportional to frequency ω_e under a given flux, the constant V/Hz speed control for induction motors applies to synchronous motors.

LCI Drives (1,7,8)

The topology of an LCI synchronous motor drive system is shown in Fig. 8. It has two two phase-controlled converter bridges and a dc link inductor. The source converter is line-commutated and produces a controlled dc voltage. The dc link inductor turns the line-side converter into a current source to the motor or load-side converter. The load converter operates normally in the inversion mode. The drives usually use standard SCRs as switching devices.

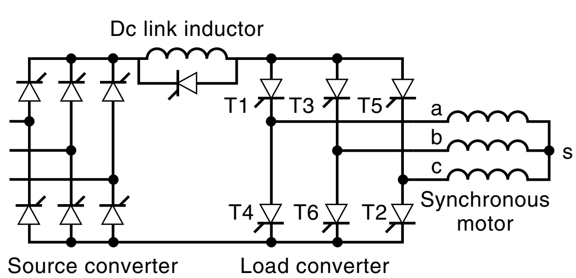

Figure 8. Typical LCI synchronous motor drive system.

Load commutation is made possible by the reactive power capability of synchronous motors. The motor must operate at a sufficient leading power factor to overcome the commutating reactance. Typical waveforms of an LCI load converter are shown in Fig. 9. The line-to-line voltages are motor internal emfs generated by the field exciter.

An LCI must be force-commutated at low speeds (usually less than 10% of rated speed) because there is not enough voltage to commutate the load converter (3). In this mode, commutation is done by switching off the load converter to shut off dc link current. As soon as the conducting SCRs in the load converter have turned off, the next pair can be selected and the source converter current can be restored.

Torque control for an LCI is by regulating the dc link current with the source converter. Operation above rated speed is possible by field-weakening control.

LCI drives are usually used in high-horsepower applications, such as turbo compressors, induced and forced draft fans, boiler feed pumps, blowers, turbine starting, extruders, mixers, and rolling mills. They have an inherent capability to provide regenerative braking and their four-quadrant operation is simple. LCI induction motor drives are possible with load capacitors (7).

The power factor and harmonics of LCIs are similar to phase-controlled dc drives.

Cycloconverter Drives (1,3,7,9–11)

A cycloconverter is a direct ac converter, that is, there is no intermediate energy storage. The configuration of a typical line-commutated cycloconverter drive is shown in Fig. 10. It uses three SCR-based, four-quadrant dc bridges. With a current balancing reactor between positive and negative bridges, the cycloconverter is a circulating current type. Otherwise it is a noncirculating type. Each dc bridge supplies one phase of a three-phase induction or synchronous motor.

The operating principle of a cycloconverter is shown in Fig. 11. VSD motor control generates a sinusoidal reference phase voltage of a certain amplitude and frequency. By properly controlling the firing of each SCR, the cycloconverter cuts small segments from the incoming line voltage waveforms closest to the reference waveform. The synthesized output voltage has rich harmonic ripples, but its fundamental component equals the sinusoidal reference voltage. A cycloconverter converts a fixed voltage and frequency source directly into a variable-voltage, variable-frequency source. The cycloconverter shown in Fig. 11 is a noncirculating current type and must not allow simultaneous conduction of forward and reverse bridges. With sufficient link reactors, cycloconverters can also operate in circulating current mode to eliminate "dead zones" between two bridges' conduction and to improve output voltage characteristics.

The output frequency of cycloconverter drives is limited to less than one-third of input line frequency, or in the case of circulating current type, to less than one-half of input line frequency. Cycloconverters require many switching devices with three-phase drives normally using at least 36 SCRs.

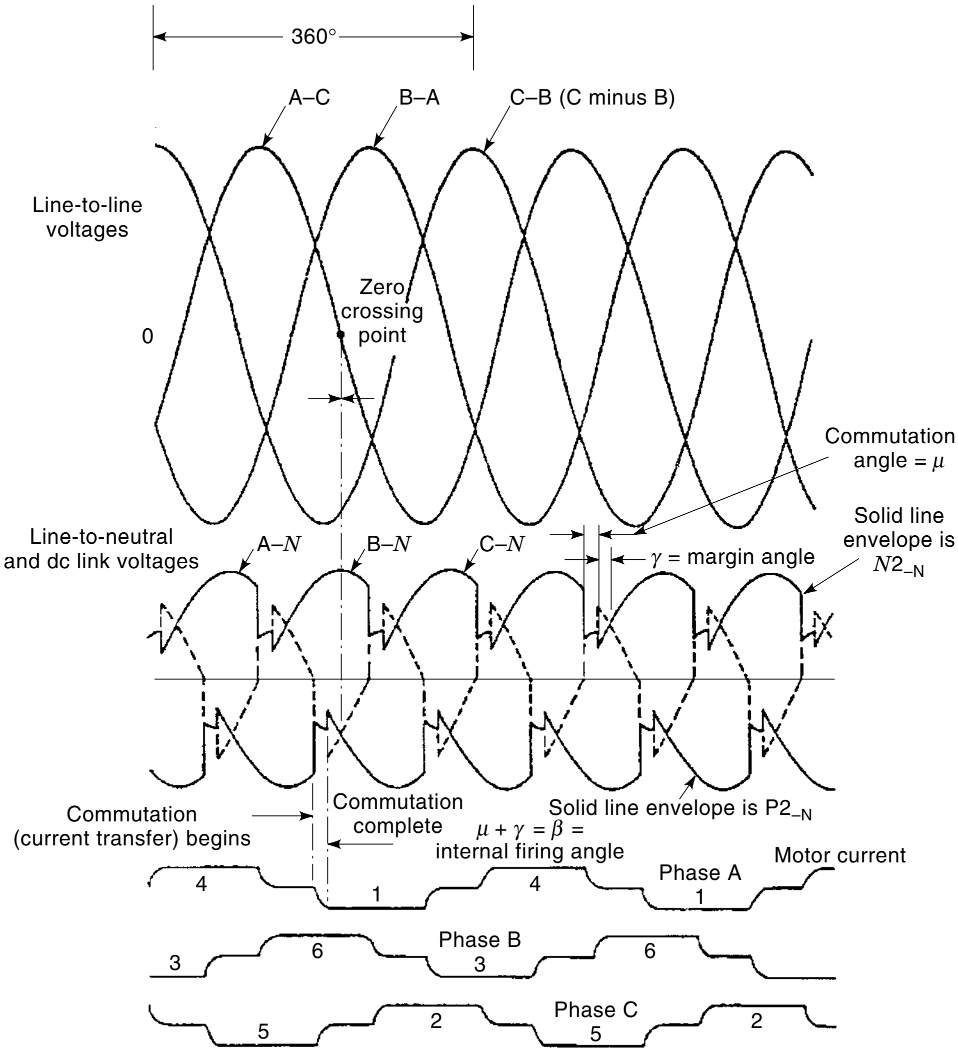

Figure 9. Typical waveforms of a LCI load converter.

Therefore, they are usually limited to low-speed, high-power applications. They have a simple, rugged converter structure, high efficiency, excellent controllability, good dynamic response, and full regenerative capability. Cycloconverter drives are suitable for both induction and synchronous motor applications and have been used in metal rolling mill main drives, cement mill, ball mill, ship propulsion, variable frequency generators, locomotive traction, mine winding, kilns, crushers, and large fans and pumps (3,7,9,10).

Cycloconverters are made up of phase-controlled DC bridges and therefore always draw lagging reactive power from the input. The input power factor worsens as the output voltage or the load power factor decreases. The maximum power factor for a cycloconverter is below 0.5 (12). To improve its power factor, a cycloconverter is operated in the trapezoidal mode rather than the standard sinusoidal mode. In the trapezoidal mode, a third harmonic component is added to the fundamental phase voltage reference so that the output voltage is higher for each bridge and this leads to a higher power factor. The added third harmonic component does not affect normal operation of a neutral floating Y-connected motor where the third harmonic current cannot flow.

Cycloconverters can have a very rich source-side current harmonic spectrum including a dc component due to normal dc bridge operation, cycloconverter operation directly sensed by the source, and their interaction (12). Line-side filters are usually needed and also transformers need to be designed to deal with possible dc saturation.

CSI Drives (1,2,3,7,9–11,13)

In a typical CSI drive, as shown in Fig. 12, the SCR-controlled source converter produces a variable dc voltage by firing the SCRs to maintain a proper V/Hz ratio. The inverter section uses SCRs to produce the required variable output frequency by forced commutation. The six capacitors and six diodes help achieve the forced commutation. The drive has a large link reactor to regulate the dc link current, making it appear to the inverter as a current source. It is usually packaged as a motor drive unit because proper inverter commutation depends on motor inductance. CSIs are usually for induction motor drives. Figure 13 shows the voltage and current waveforms of one phase. The current is square wave-shaped which can cause torque oscillation at low speed (cogging or torque pulsation) and harmonic heating in the motor. The voltage has notching caused by commutation.

The frequency of a CSI is controlled by controlling inverter SCR switching and commutation. Motor voltage is controlled

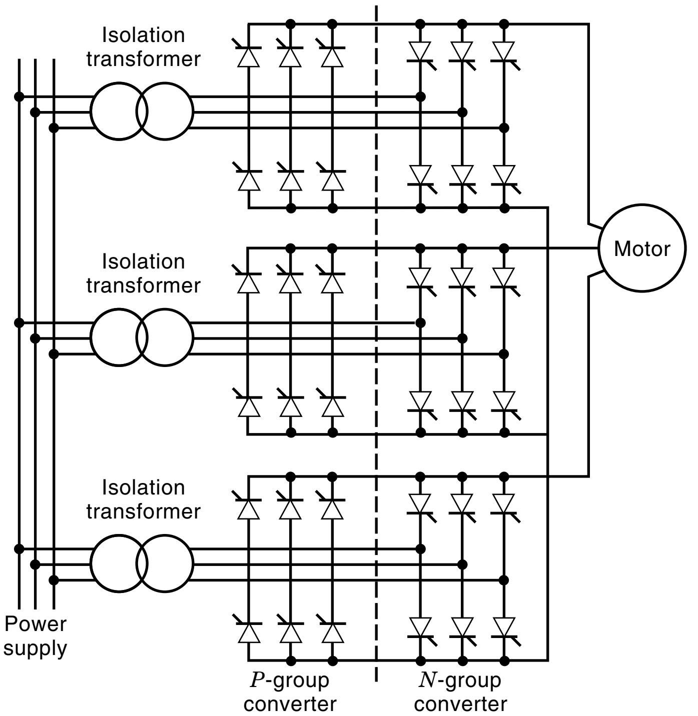

Figure 10. Configuration of cycloconverter drives.

by regulating dc link current. In general, voltage and current feedback control are required in a CSI VSD application.

CSI drives are robust and reliable because of their inherent current-limiting operation. They have simple circuitry, good dynamic behavior, inherent regenerating capability, and are easy to control. However, CSIs have large harmonics generated back to the source and poor power factor due to the SCR front end. They cannot work at no load and have a stability problem at light-load and high-speed conditions. Other disadvantages include the use of large and costly inductors, cogging due to square wave output current, voltage spikes on motor windings, and difficulty with multimotor applications (2,3,13).

CSI are usually found in medium to high power range, general industrial VSD applications, such as fans, blowers, centrifuges, compressors, pumps, mixers, kneeders, conveyors, and roller tables (9).

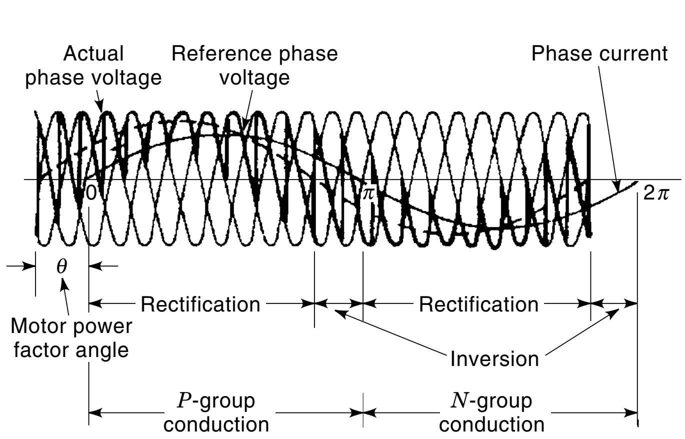

Figure 11. Operation principle of a cycloconverter (3).

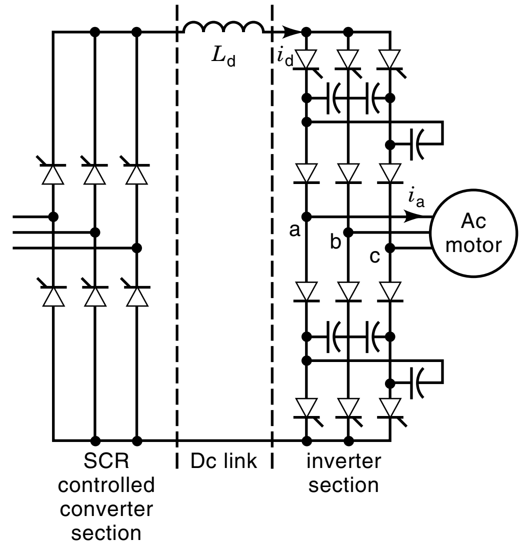

Figure 12. Basic configuration of CSI drives.

There are many CSI variations on Fig. 12, notably IGBT- or GTO-based CSIs and PWM-CSIs (26).

VSI Drives (1,2,3,7,10,11,13)

A VSI drive uses the same SCR-controlled source converter as a CSI drive. As shown in Fig. 14, its dc link and inverter section differ from those of a CSI drive. The dc link has a large filtering capacitor to provide a stiff, load-independent voltage making it appear to the inverter as a voltage source. The inverter uses BJTs, IGBTs, or GTOs to produce a variable-frequency, six-step voltage output to the motor load by forced commutation. Each inverter switch is on for half of the time during a period, and a total of three switches are on at any given time. The typical voltage and current waveforms are shown in Fig. 15. The voltage amplitude is controlled by SCRs in the converter section, and its frequency is controlled by commanded inverter device switching.

VSI have simple and rugged circuitry, are easy to control, and are applicable to multimotor installations. The disadvantages include poor input power factor, large source and motor harmonics, no inherent regenerating capability, and possible torque pulsation at low speed (2,3,10,13).

VSI drives usually have a speed ratio limited to 10 : 1 (3). They are general purpose industrial drives, normally used in low- to medium-horsepower industrial applications (several HP to several hundred HP).

VSIs have been superseded in performance and are rarely applied nowadays (10). They are being replaced by PWM-VSI drives.

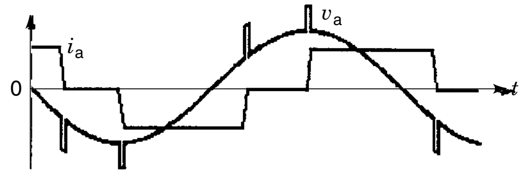

Figure 13. Motor voltage and current waveforms of CSI drives.

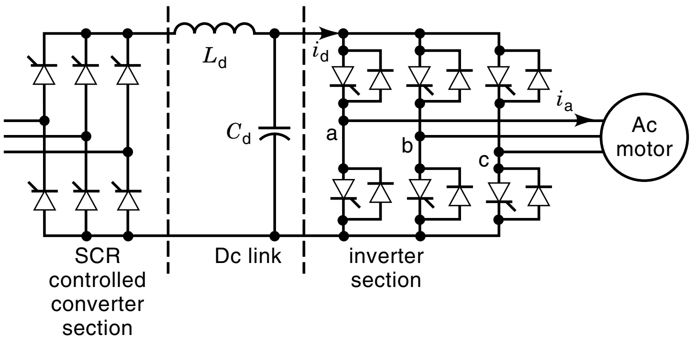

Figure 14. Basic configuration of VSI drives.

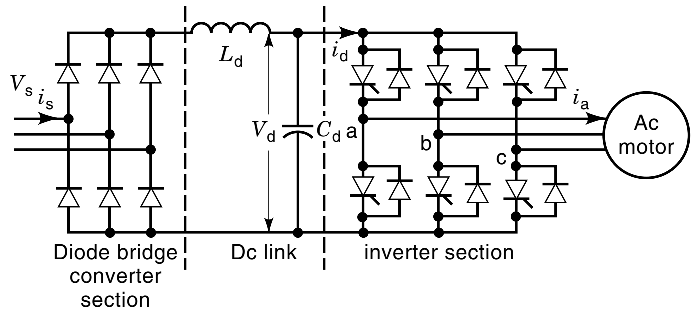

Figure 16. Typical configuration of PWM-VSI drives.

PWM-VSI Drives (1–3,7,9–11,13,14)

A typical PWM-VSI drive, shown in Fig. 16, uses a diode bridge for a source converter to produce a fixed dc bus voltage. The inverter uses high-frequency switching devices, usually IGBTs, MCTs or GTOs, to generate pulse-width-modulated square wave voltage outputs. Both the amplitude and frequency of the equivalent output voltage can be controlled. Inverter control signals are generated by a PWM modulator. In the case of a sine-triangle modulator as shown in Fig. 17 (1), three balanced sinusoidal reference voltages at desired frequency and amplitude are compared with a triangle signal at a selected switching frequency whose amplitude is determined by the dc link voltage. Depending on whether the sinusoidal reference voltage for a given phase is greater or less than the triangle voltage, the upper and lower switches of the phase leg turn on and off alternately. Figure 17 also shows waveforms of two phase voltages referenced to negative dc link and one line-to-line voltage. Depending on devices, PWM switching frequency ranges from 500 Hz for GTOs to 20 kHz for MOSFETs and IGBTs (15). Higher switching frequency leads to higher speed range, better dynamic performance, and less harmonics in motor voltages and currents but higher inverter losses.

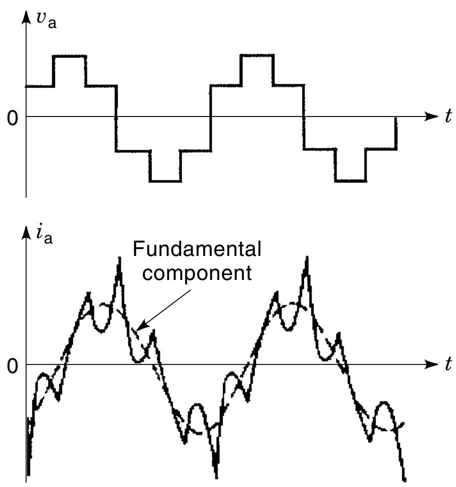

Figure 15. Motor voltage and current waveforms of VSI drives (1).

PWM-VSI drives are a relatively new member in the ac drive family. They are gaining popularity because they have many good features. They have very good input power factors with diode bridge front-end and relatively small line-side harmonics because the load current for the source bridge is nearly dc. Properly switched PWM-VSIs produce nearly sinusoidal motor currents, causing no torque pulsation and little harmonic heating in motors. They are easy to control, have excellent dynamic performance, and are compatible with multimotor applications (2,13). Possible application issues include motor insulation overstress caused by high dV/dt due to high-frequency switching and motor bearing currents caused by high common-mode voltages due to PWM switching (15–17).

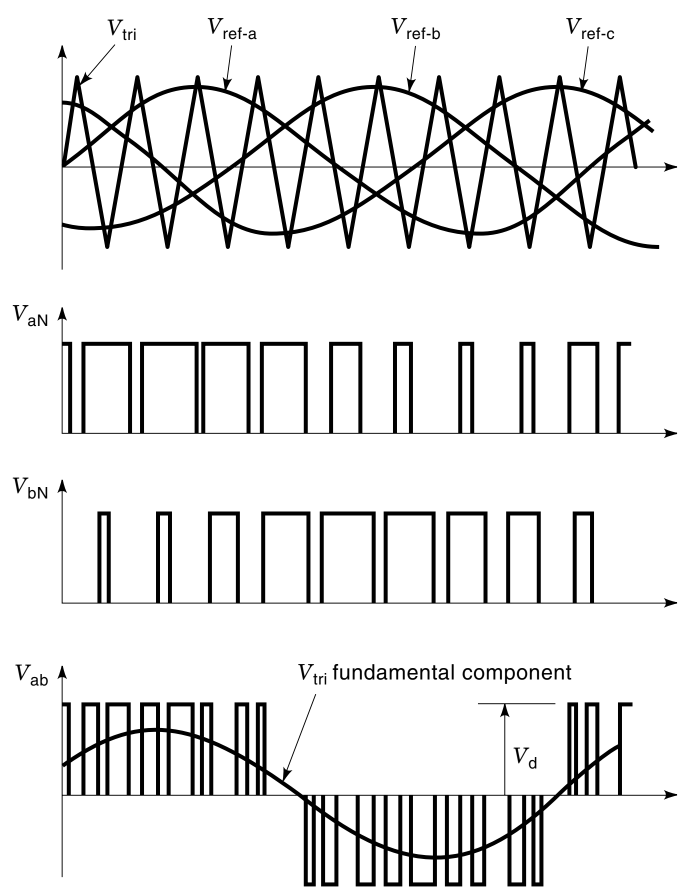

Figure 17. Waveforms of PWM-VSI drives (1).

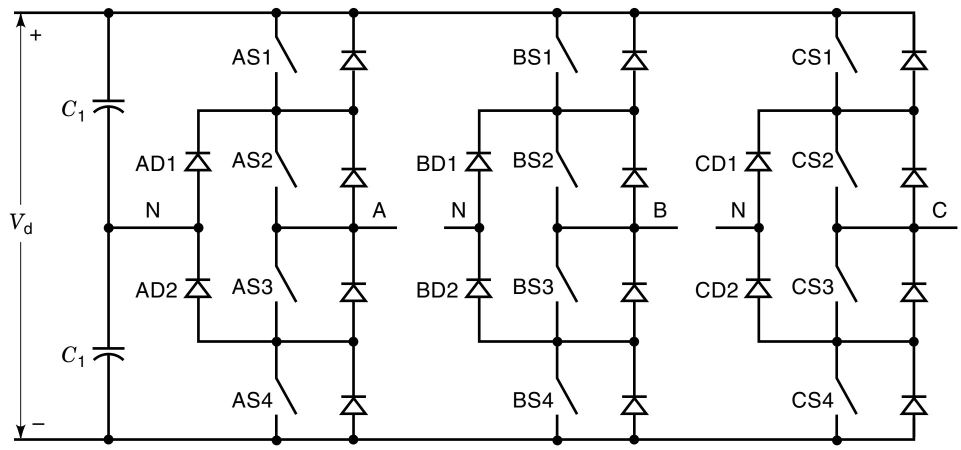

Figure 18. The topology of a neutral point clamped PWM-VSI.

For medium-voltage high-power applications, the neutral point clamped (NPC) PWM-VSI is often used. As shown in Fig. 18, it uses four switching devices and two clamping diodes per phase, and the clamping diodes midpoint are tied to the dc link capacitor neutral point. Phase potential is at a positive dc link when S1 and S2 are on, at a negative dc link when S3 and S4 are on, and at midpoint of the dc link when S2 and S3 are on. Therefore, NPC PWM-VSI is a three-level inverter compared with the two-level PWM-VSI in Fig. 16. Although the peak voltage on a switching device in a two-level PWM-VSI equals the full dc link voltage, the peak voltage on a switching device in a three-level is only one-half the dc link voltage. The line-to-line voltage waveforms of NPC PWM-VSI have five levels, as shown in Fig. 19 as compared to three levels in Fig. 17, resulting in less motor harmonics and less motor insulation stress at a given switching frequency.

PWM-VSIs can also be stacked to build higher voltage, higher power drives, as shown in Fig. 20. Each module has its own dc link and diode source bridge that must be isolated through a transformer. The inverter outputs are connected in series to achieve higher voltages. Properly modulated switching produces multilevel output voltage waveforms. Both two-level and three-level PWM-VSIs can be used as building modules for this configuration.

PWM-VSIs fed by diode bridge frontends have no regenerative capability. For regenerating applications, a back-to-back PWM-VSI topology can be used. The dc link voltage is regulated by the PWM source bridge. With back-to-back topology, the input power factor can be controlled and the ac line harmonics are small.

PWM-VSIs range from MOSFET-based fractional horsepower drives to GTO-based 20 MW drives. They are widely

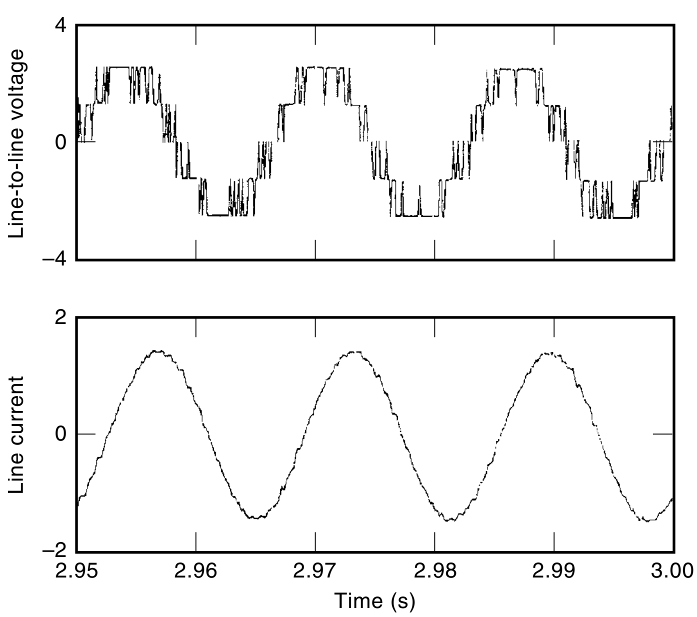

Figure 19. Waveforms of a neutral point clamped PWM-VSI.

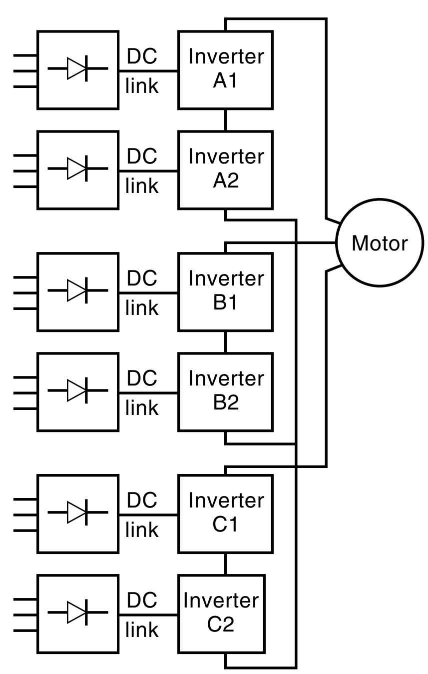

Figure 20. Stacking PWM-VSIs to build higher voltage and higher power drives.

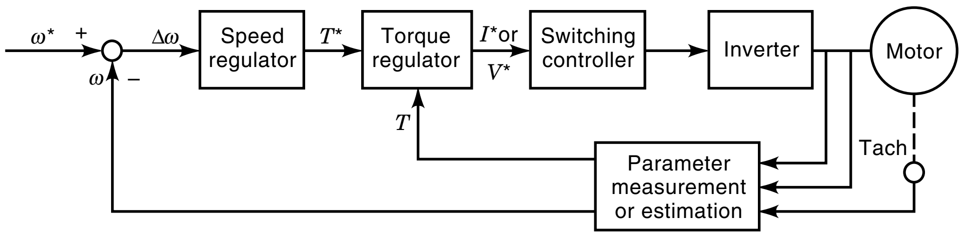

Figure 21. Typical control loops of VSD.

used as system drives and general purpose stand-alone drives.

Ac Wound Rotor Induction Motor Drives

- A variable resistance connected to the induction motor rotor winding can adjust motor speed. One way to achieve a variable resistance is by connecting the rotor to a diode rectifier, which feeds a chopper that has a fixed-load resistor (7).
- A static Kramer drive converts the slip power of a wound-rotor induction motor to useful mechanical power. The rotor voltage is rectified through a diode bridge and then fed to a dc motor on the same shaft (3,7,9,10).
- A static Scherbius drive converts the slip power back to an ac source. The rotor voltages are fed back to an ac source through a cycloconverter (3,7).

VSD CONTROL

Modern VSDs are complex power electronic equipment that require sophisticated and coordinated control for their operation. Different drive controllers can be on various hardware or software platforms, of various architectures, digital or analog, centralized or distributed. However, they all perform the same basic control functions that can be divided into four hierarchical layers: (1) process control; (2) speed control; (3) torque control; (4) converter switching control.

Process Control

Process control generates speed (or position, torque, power, etc.) command for VSDs based on process requirements. Process controllers are external to VSDs. They can be interfaced with digitally controlled VSDs through programmable logic controllers (PLCs) or computer-based controller stations. The communication network can be a local area network (LAN) linked via RS422, Ethernet, or other standard industrial bus protocols (18–21).

Speed Control

VSD speed control is often identified as outer loop control because in the language of control block diagrams it is a control loop outside of a torque controller as shown in Fig. 21. The input to the speed regulator is the speed error, and the output of the speed regulator is the command to the inner torque control loop. Because the torque regulator normally has much faster response than the speed regulator, the tuning of the speed regulator need only be concerned with mechanical load characteristics, such as system inertia. A first- or second-order proportional and integral regulator is usually used in VSD speed regulation.

The speed feedback used in speed regulator can be directly measured with a speed sensor or estimated on the basis of motor electrical measurements in sensorless VSDs (22).

Torque Control

Torque control is the inner loop control because it is inside the speed control loop as in Fig. 21. It receives torque command from the speed regulator and then commands and regulates motor stator voltages, currents, and/or field currents to achieve the desired torque. The output of the torque control is usually some reference voltage or current for converter switching control. The essence of torque control is motor current and voltage control.

Dc Drive Torque Control. Equation (2) indicates that the torque for a dc motor is directly proportional to the product of armature current and field current. Therefore, it is very easy to control torque in a dc drive through either the armature current or field current, resulting in excellent dynamic performance for dc drives. The physical reason behind this is the decoupling of field winding and armature magnetic fields due to their mechanical orthogonality. As a result, dc drive torque controllers consist simply of decoupled armature and field current regulators.

Induction Motor Drive Torque Control. Figure 5 shows that the induction motor stator current I_s consists of two current vectors, magnetizing current I_m and rotor current I_r, and δ is the angle between them, where $\delta = \tan^{-1}(R_r/(s\omega_s L_{lr}))$. The torque for a three-phase p pole induction motor can be derived as (27)

$$T = \frac{3p}{2} L_m I_m I_r \sin\delta \tag{10}$$

Equation (10) states that induction motor torque is the result of air-gap flux and rotor current interaction. It also states that to control the motor torque through stator current, I_m and I_r, as well as δ angle must be controlled. In other words, a vector control scheme is needed. The actual implementation of vector control uses rotor flux and corresponding magnetizing current I_y, as well as the torque producing current I_x that is orthogonal to I_y. Therefore, it is field-oriented control. Then,

$$T = \frac{3p}{2} \frac{L_m^2}{L_{lr} + L_m} I_y I_x \tag{11}$$

which is similar in form to Eq. (2) for dc motors.

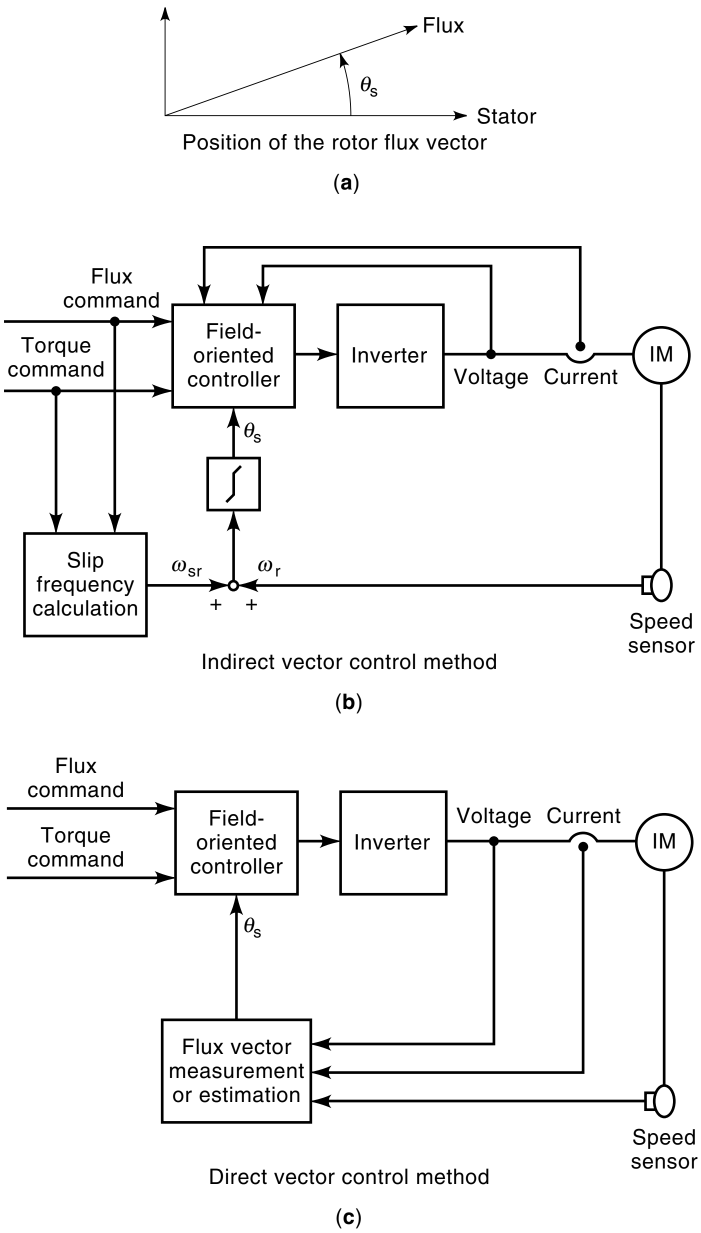

Figure 22. Two generic types of motor field vector control schemes (22).

There are two basic approaches for implementing field-oriented control in induction motor drives, as shown in Fig. 22. The direct method estimates the rotor flux position using flux observers. The more common indirect method first determines the slip s based on the relationship

$$s = \frac{1}{\omega_e}\frac{R_r}{L_{lr}+L_m}\frac{I_x}{I_y}$$

and then adds to the rotor speed to determine the rotor flux position. Both methods orient I_y to rotor flux and I_x to its quadrature. Through decoupled I_x and I_y, motor torque can be controlled.

Field-oriented control relies on knowledge about motor parameters. A properly tuned control can result in high induction motor performance comparable to that of dc motors.

Synchronous Motor Drive Torque Control. Torque control for synchronous motors also requires controlling current magnitude and phase angle. The principle of field-oriented vector control also applies to synchronous motors. The rotor position information needed in the control can be obtained by sensors, such as resolvers, absolute position encoders, and Hall sensors, or through sensorless estimation from motor terminal quantities (22).

For wound-field synchronous motors, field current control is part of torque control. The command current for a field current regulator is determined in a torque controller by the flux requirement in the motor direct axis.

Converter Switching Control

The converter switching control is usually accomplished through a modulator either digitally or by hardware analog circuitry. The input to a modulator is the reference voltage or current signal generated as output of the drive torque controller. The output of the modulator is the actual gating or firing command for switching devices. The carrier signal of the modulator depends on the drive converter, its topology, device switching frequency, dc link voltage or current, ac source voltage and frequency, etc. An example of a modulator for PWM-VSI is shown in Fig. 17.

There are a variety of modulator techniques for different drives, especially, for PWM drives. The basic requirements for a modulator include

- accuracy: discrete switching should yield continuous voltage or current as close as possible to its reference
- linearity between output and modulation index (the ratio between reference signal and carrier signal amplitude)
- minimum waveform distortion
- minimum switching losses
- prevention of commutative failure

VSD EVALUATION AND APPLICATION ISSUES

Ac Drives Versus dc Drives

Dc drives traditionally dominated VSD applications because of their superior dynamic performance, low initial cost, and simple control scheme. The disadvantage of dc drives mainly lies in the maintenance difficulties with dc motors because of their mechanical commutators.

Ac drives are progressing rapidly and already have become the drive of choice in today's VSD applications. Because of advancements in power electronics and digital control, it has become possible to build cost-effective ac drive power converters and to implement sophisticated control, making the performance of ac drives comparable to dc drives. In many cases, ac drives are superior because of the more robust ac motors. For example, ac drives have higher power ratings, operate at higher speeds, and have faster speed regulator response.

Ac Drive Evaluation

Comparisons of ac drives are summarized in Table 2.

Table 2. Summary Comparison of ac Drives

	Speed Range	Regeneration	Ac Line Harmonics	Motor Harmonics	Input PF[a]	Power Ratings	Multimotor Applications	Power Dip Ride-Through
VSI	Medium to high	DBO[b] possible RGN[c] needs extra CNVT	High	Medium	Medium	Low to medium	Possible	Possible
PWM-VSI	Very wide, down to zero	DBO possible RGN needs extra CNVT[d]	Moderate	Low	Close to unity	Low to very high	Possible	Good
CSI	Very wide, down to zero	4-quadrant operation	Severe	High	Low	Medium to high	Difficult	None
LCI	Above 0.1 ω_0[e]	4-quadrant operation	Severe	High	Low	Medium to very high	Difficult	None
CCV[f]	Zero to 1/3 or 1/2 of ω_s[g]	4-quadrant operation	Severe	Low	Poor	High power	Difficult	None

[a] PF: power factor.
[b] DBO: dynamic braking operation.
[c] RGN: regeneration operation.
[d] CNVT: converter.
[e] ω_0: rated speed.
[f] CCV: cycloconverter.
[g] ω_s: synchronous speed.

Drive Interface with Power Systems

Ac Input Power Factors. VSDs with phase-controlled source converters usually have poor power factors, and the cycloconverter is the extreme case. To boost system power factors, correction devices, such as capacitor banks and other types of filters, are required which add to system complexity and cost. On the other hand, VSDs with diode bridge front ends usually have power factors close to unity. In the case of a back-to-back VSI, CSI, or PWM, the drive can run at any controlled power factor, making them var compensators for power systems.

Ac Line Harmonics. Operating in the switching mode, VSDs are nonlinear equipment and generate undesirable current and voltage harmonics back to the ac line (23–25). Without mitigation, harmonics levels from VSDs in their basic topologies may exceed the harmonics limits set by industrial standards, such as IEEE-519-1992. Possible mitigation methods include (1) harmonic filters, which are usually bulky, expensive, vulnerable to line resonance, and generally undesirable; (2) PWM rather than a phase-controlled front end where possible; and (3) multipulse techniques.

Multipulsing is very effective in reducing harmonics. A basic dc rectifier bridge has six switching devices, commutates six times per period and therefore is a six-pulse converter. Two six-pulse bridges combined can be a 12-pulse bridge if their device switching times are evenly displaced. Transformers with isolated and properly phase-shifted secondaries are necessary for multipulsing. Figure 23 shows an 18-pulse diode rectifier bridge with three 20° phase-shifted transformer secondaries. The current harmonics for this configuration is only a quarter of its six-pulse counterpart.

Drive Interface with Motors

Motor Current Harmonics. VSDs generate harmonics in motor currents and cause overheating, torque pulsation, and mechanical resonance. Depending on motors, derating or oversizing may be necessary. Other solutions include drive output filters (15). Certain drives have much better harmonic performance than others. For example, with PWM-VSIs at adequate switching frequency, motor current harmonics are negligible.

Motor Insulation. Voltage waveforms with high dv/dt, especially for fast switching PWM-VSI drives, can overstress motor insulation. The reflected wave phenomenon due to the cable connection between the inverter and the motor worsens the problem (15). Mitigation methods include (1) specially designed motors; (2) drive output filters; (3) motor terminal filters that match the cable characteristic impedance; (4) motor terminal dV/dt filters.

Motor Bearing Currents. VSD switching mode operation can cause high common-mode voltages in motor windings. These

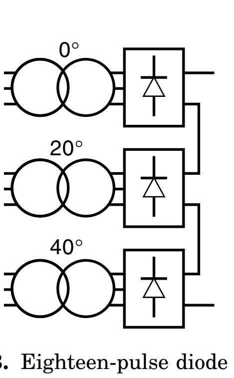

Figure 23. Eighteen-pulse diode rectifier.

common voltages can be capacitively coupled to the motor shaft. The accumulated charge on the shaft can eventually lead to flashover and arcing through motor bearings (16,17). Possible mitigation methods include (1) shaft grounding brushes; (2) electrostatic shield between stator and rotor; (3) proper grounding schemes for motors and drives; and (4) common-mode filters.

FUTURE TRENDS FOR VSDs

Power semiconductor, digital control, and computer technologies will continue to be the technological driving forces behind VSD development. As bigger and cheaper devices become available, bigger and better VSDs will be developed and applied. Packaged, integrated power electronic devices will be devices of choice. We are already seeing that VSDs based on an integrated gate commutated thyristor (IGCT), a packaged GTO, are beginning to dominate the medium-voltage, high-power VSD market.

In power converter areas, PWM-VSI and its variants will continue to dominate in ac VSDs and will be extended to a very high power range because of its overall performance. New topologies, such as matrix converters, could emerge. Soft switching concepts and techniques (1) will be applied more in VSD converter designs. More emphasis will be on friendly interfaces to power systems and motors.

In control areas, integrated control implemented on a single dedicated chip will be prevalent. On-line adaptive drive and motor control will be a standard approach perhaps based on some type of artificial intelligence techniques. Sensorless control will be improved and perfected and will become the norm for most VSD applications. Auto-tuning and self-commissioning will become the norm. Drive communication interfaces will be improved and standardized.

In application areas, VSDs will be offered as total system solutions, as drives, var compensators, harmonic filters, and mechanical resonance eliminators. Utility and motor friendly drives will win in the marketplace. Overall VSD applications will continue to grow in the forseeable future.

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Virginia Tech

VARIABLE SPEED GENERATION. See WIND TURBINES.
VDM. See VIENNA DEVELOPMENT METHOD.
VECTOR CONTROL. See MAGNETIC VARIABLES CONTROL.