J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

LARGE MOTOR DRIVES

Large motor drives are needed in many industrial processes, such as pipelines and petrochemical, pulp and paper, cement, mining and metals, water and wastewater treatment, and power utilities. There are two types of motor drives: dc motor drives and ac motor drives. Typically, a motor drive system consists of an ac-dc or ac-ac power converter (see the article “AC-AC Power Converters”) and one or multiple driven dc or ac motors. The power converter transforms utility or standalone ac power to a desirable variable voltage and variable frequency form of power that feeds the motors for torque, speed, and/or position control. Figure 1 shows the basic block diagrams of large dc and ac motor drives. The scope of this article is limited to large motor drives with a medium voltage, which is larger than 600 V and less than 13.8 kV, and power ratings of over 350 kW. The typical voltage levels include 750 V, 2300 V, 3300 V, 4160 V, and 6000/6600/6900 V.

For large motor drives, large VA rated power converters are required. The commonly used converter-inverter topologies have been thyristor [silicon-controlled rectifier (*SCR*)] converters, gate-turn-off thyristor (GTO) current-source inverters, GTO choppers (dc-dc converters), GTO voltage-source inverters, thyristor cycloconverters, and recent device technology advances have spawned insulated gate bipolar transistor (IGBT)–based multipulse and multilevel inverters. Up to 6 kV/6 kA GTO thyristors, 3.3 kV/1.2 kA high-voltage IGBTs, and 4.5 kV/4 kA integrated gate commutated thyristors (IGCTs) are available for such high-power applications.

With increasing rapidity, many industrial processes formerly operated at constant speed are converted into adjustable speed to accelerate the throughput, to save energy, and to enhance productivity and automation. Especially in large-motor-drive applications, energy savings and productivity improvement are significant from adjustable speed drives (ASDs).

Large DC Motor Drives

Because of the excellent speed controllability of dc motors, dc motor drives have been widespread in many applications, such as automatic tracking systems of weapons, robots, machine tools, and rolling mills, in a power range of mW to over 10 MW. In addition, dc motor drives have been used for traction drives of electric railroad systems, engine starters of airplanes and automotives, etc., where large starting torque is required.

Basic Structures, Equivalent Circuits, and Speed Control of DC Motors.

There are two basic structures in dc motors, homopolar dc motors and heteropolar dc motors, both based on Fleming’s law. Homopolar dc motors have no commutators and produce low back emf voltage. Most commonly used dc motors are heteropolar, whereas homopolar dc motors have been used in very special applications. The following discussion is limited to heteropolar dc motors.

A dc motor consists of three main parts: field winding, armature, and commutator or brush. Based on different excitation methods, dc motors can be divided into four major categories: (1) separately excited, (2) shunt excited, (3) series excited, and (4) compound excited. The shunt-excitation method has been used in dc generators in which a residual voltage in the winding can start generation. Series-excited motors are widely used for engine starters because they can generate large starting torque. The compound-excited motors

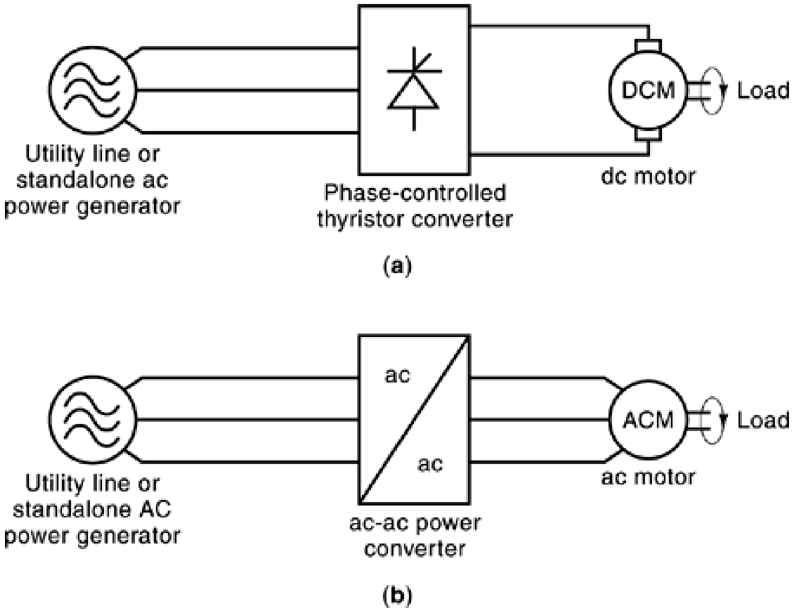


Fig. 1. Basic block diagrams of large motor drives.

combine the features of both the shunt- and series-excited motors. Figure 2 shows their basic configurations. In compound dc motors, there are cumulative compounds and differential compounds.

Figure 3 shows the basic equivalent circuit of a dc motor. Equation (1) gives the basic expression of the equivalent circuit.

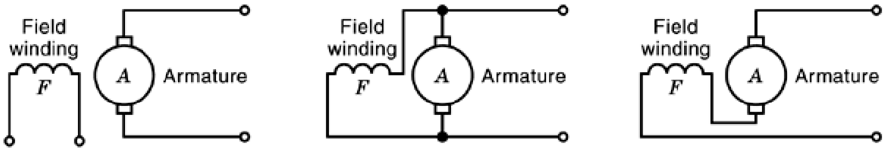
$$\begin{bmatrix} v_f \\ v_a \end{bmatrix} = \begin{bmatrix} R_f + L_f \dfrac{d}{dt} & 0 \\ p\omega_m M & R_a + L_a \dfrac{d}{dt} \end{bmatrix} \begin{bmatrix} i_f \\ i_a \end{bmatrix} \tag{1}$$

where R_f and L_f are the resistance and inductance of the field winding, R_a and L_a are the resistance and inductance of the armature winding, M is the mutual inductance of between the field and armature windings, ω_m is the rotor speed, and p is the number of pole pairs. The torque produced τ can be expressed as

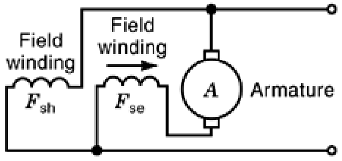
$$\tau = pMi_f i_a \tag{2}$$

In steady state, d/dt becomes zero. Therefore, Eqs. (1) and (2) can be reduced as follows:

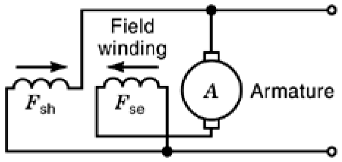
$$\begin{bmatrix} V_f \\ V_a \end{bmatrix} = \begin{bmatrix} R_f & 0 \\ p\omega_m M & R_a \end{bmatrix} \begin{bmatrix} I_f \\ I_a \end{bmatrix} \tag{3}$$



(**a**) Separately excited (**b**) Shunt excited (**c**) Series excited



Cumulative compound



Differential compound

(**d**) Compound excited

Fig. 2. Structures of dc motors.

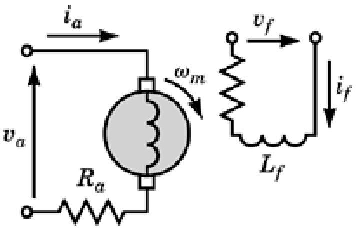
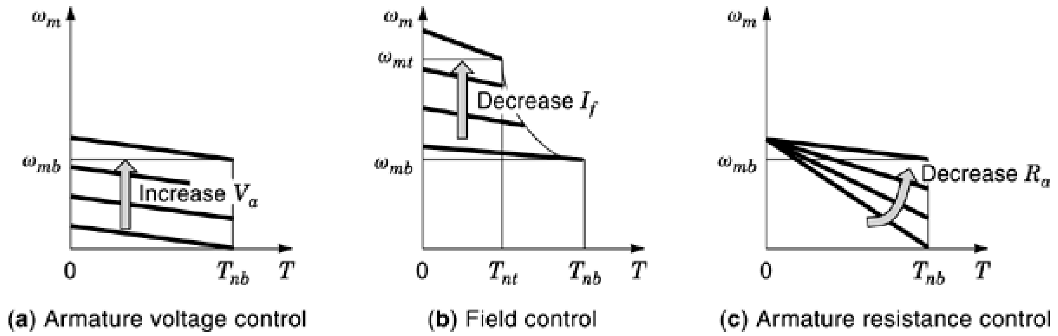


Fig. 3. Equivalent circuit of a dc motor.

$$T = pMI_f I_a \tag{4}$$

It is noted that all variables in Eqs. (1) and (2) are instantaneous value, whereas the variables in Eqs. (3) and (4) are capitalized to express the steady-state value, respectively. From Eqs. (3) and (4), the rotor speed is given by

$$\omega_m = \frac{V_a - R_a I_a}{pMI_f} = \frac{V_a}{pMI_f} - \frac{R_a}{(pMI_f)^2}T. \tag{5}$$



(a) Armature voltage control **(b)** Field control **(c)** Armature resistance control

Fig. 4. Control methods of dc motors.

It is obvious from Eq. (5) that the motor speed can be controlled by changing (1) armature voltage V_a, (2) field current I_f, or (3) armature circuit resistance R_a. Therefore, there are three methods to control the motor speed. Figure 4 shows the three control methods: armature voltage control, field control, and armature resistance control. The armature voltage control is the most commonly used method, whereas the field control is used in conjunction with the armature voltage control to provide wider speed control ranges. The armature resistance control method is only used for starting torque boosting because increasing armature resistance causes power loss.

Armature Voltage Control of DC Motors. As an armature voltage control method, the Ward-Leonard system is the most traditional dc motor drive. Figure 5 shows the system configuration. The dc motor (*DCM*) is directly fed by a dc generator (*DCG*). Therefore, the motor speed is controlled by the generator's output voltage according to the armature voltage control. The generator is driven by an ac motor (*ACM*) that is fed from an ac power source or utility. The generator's output voltage is controlled by the field current I_{fg}. By controlling the direction and magnitude of the generator field current I_{fg}, the generator can produce any positive or negative voltage, which in turn controls the motor's rotation direction and speed as desired. Constant torque control and regenerative braking are possible. The Ward-Leonard system had been widely used in large-motor-drive applications, such as steel rolling mills. It has been replaced by the thyristor converter and dc chopper systems since the 1970s. The Ward-Leonard system, however, is the basic dc motor drive. The thyristor converter and dc chopper systems as shown in Figs. 6 and 7 are called static Leonard systems. In Fig. 6, a thyristor converter is used to provide a variable dc voltage to the armature for speed control, whereas the field winding is fed by a small thyristor converter. Both thyristor converters are controlled by firing phase angles. Such static Leonard systems or thyristor Leonard systems have been widely used since the 1970s in many applications such as rolling mills where high-performance adjustable speed drives are required. The static Leonard control system has the following four advantages and three disadvantages over the traditional Ward-Leonard system:

Smaller control power, higher performance, and faster response

Lower power losses and higher efficiency

Easier maintenance

Less civil engineering

Lower power factor

Harmonic generation

Second set of thyristor converters needed for reverse speed operation

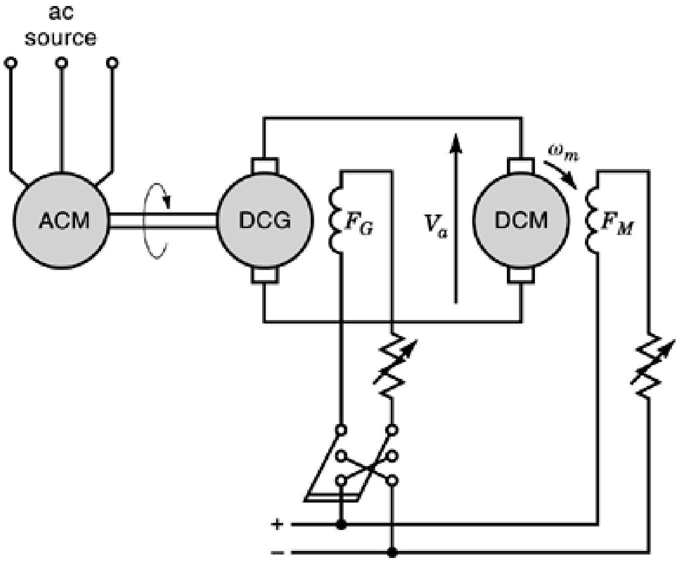


Fig. 5. Ward-Leonard system of dc motor drives.

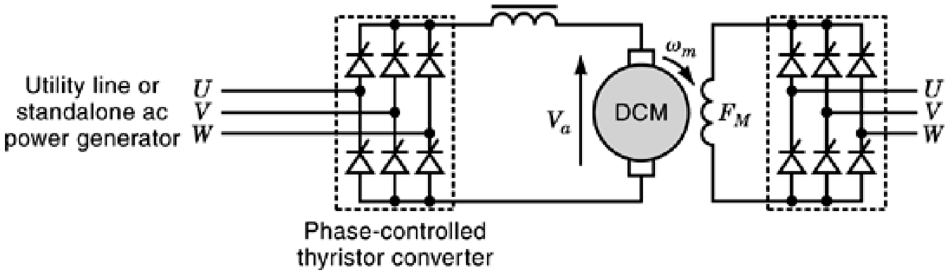


Fig. 6. Configuration of thyristor Leonard system.

The dc chopper system is used for some applications such as electric railroads where dc power is supplied. A dc chopper motor drive system is shown in Fig. 7. A variable dc voltage is provided to the armature by the chopper GTO's turn-on and turn-off. The average dc voltage is proportional to the duty cycle, which is the ratio of the GTO's turn-on period to its turn-off period. Accordingly, the armature voltage is controlled.

Field Control of DC Motors. A dc motor's speed can be also controlled by changing the field current I_f, as shown in Eq. (5). Changing the field current I_f also causes the torque T to change. The output power, which equals the product of the torque and the speed, $T\omega_m = (V_{\mathrm{a}}\text{-}RI_a)I_a$, however, is constant regardless of speed as long as the armature voltage and current are unchanged. This constant-power property or constant-power drive is used to drive motors above the base speed and widen speed drive ranges.

Figure 8 illustrates the common combination of armature voltage and field control of dc motors. Usually, the armature voltage control by a thyristor converter is used to produce a constant torque drive while keeping the field current constant at speeds below the base speed. At the base speed, the full dc voltage of the thyristor converter is reached. After the thyristor converter reaches the full available voltage, over-base-speed drive can be implemented by weakening the field current I_f. This field-weakening control is commonly used to achieve a wide speed range. That is, the armature voltage control is used to produce constant-torque drive for speeds

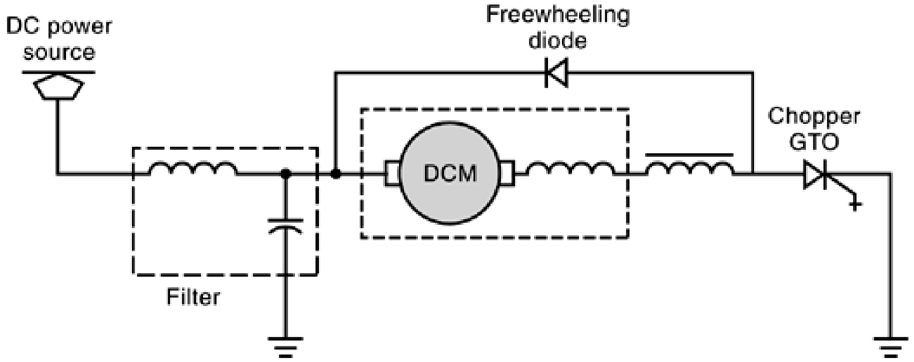


Fig. 7. Chopper system for dc motor drives.

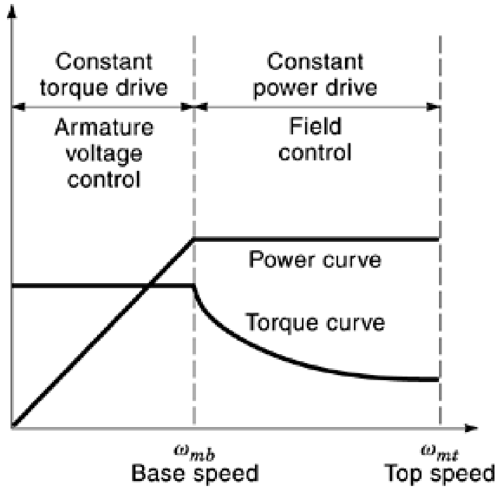


Fig. 8. Armature and field control of a dc motor.

from zero to the base speed, whereas the field control is used to produce constant-power drive for speeds from the base to top speed. The ratio of the top speed over the base speed is called the constant-power speed ratio (*CPSR*). Figure 9 shows a control diagram commonly used in large dc motor drives. The two thyristor converters connected in antiparallel provide forward and reverse speed control. Two inner control loops, a current control loop and voltage control loop, are employed to (1) keep current below the thyristor and motor ratings and (2) provide fast speed response. In the field control loop, an automatic field weakening control is added by feeding back the armature voltage signal.

Resistance Control of DC Motors. A series resistor can be inserted into the armature terminal of a dc motor to change the total armature circuit resistance, which in turn achieves speed control according to Eq. (5). However, this method has the following disadvantages:

At light or no load speed control becomes difficult or impossible
Power loss becomes excessive because of the series resistor

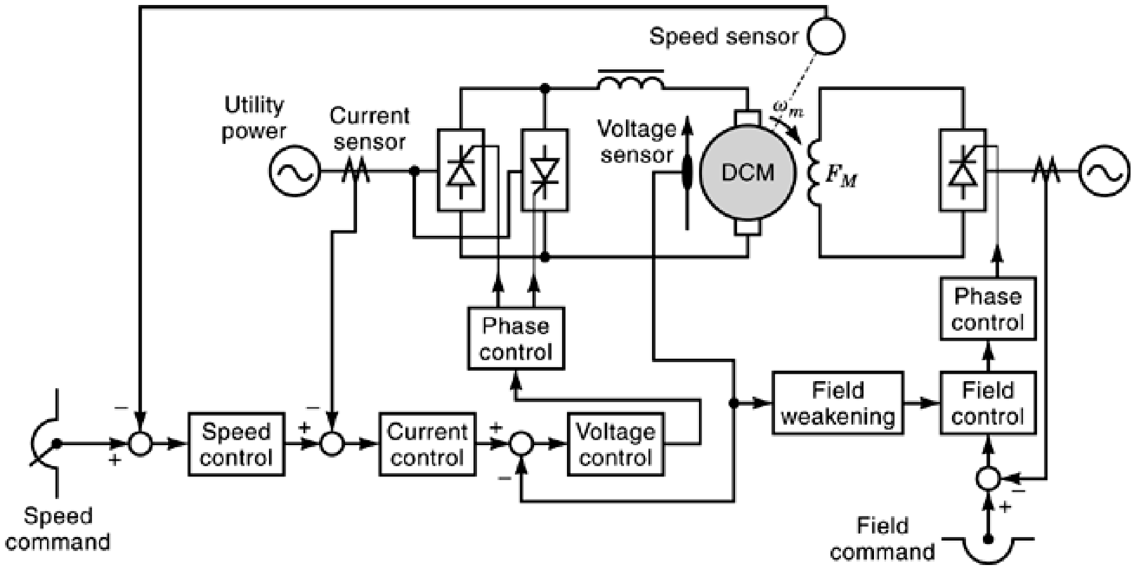


Fig. 9. Speed-control block diagram of a thyristor Leonard dc motor drive system, which has replaced the traditional Ward-Leonard system of dc motor drives, (Fig. 5). Two thyristor rectifiers connected in parallel with opposite directions are used to replace the dc generator, DCG, and another thyristor rectifier for field current control.

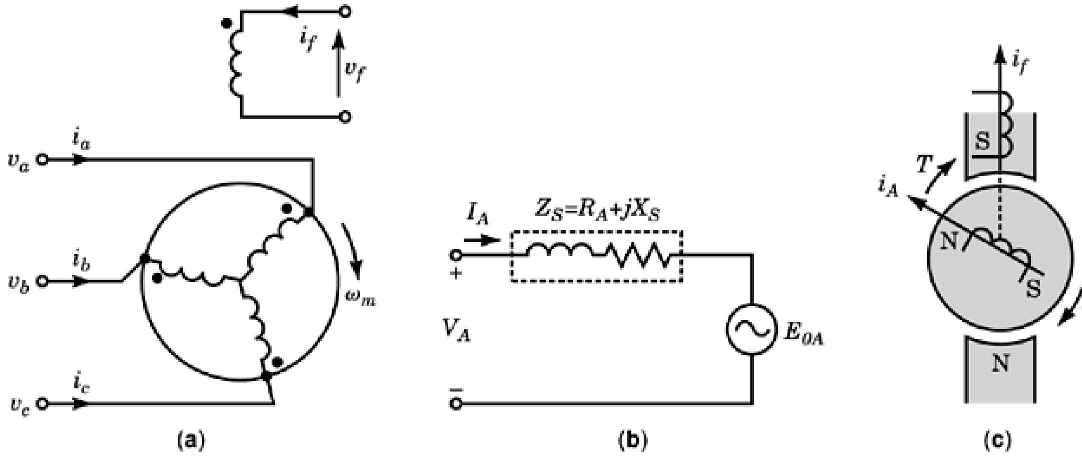


Fig. 10. A three-phase synchronous motor: (a) circuital model, (b) the equivalent circuit, and (c) operating principle.

Therefore, the resistance control is only used at low speeds or start-ups where a simple speed control is desired.

Large AC Synchronous Motor Drives

A synchronous motor usually consists of a dc excitation (field) winding and an armature winding and rotates at exactly the same speed as the supply frequency. There are revolving-armature and revolving-field types of

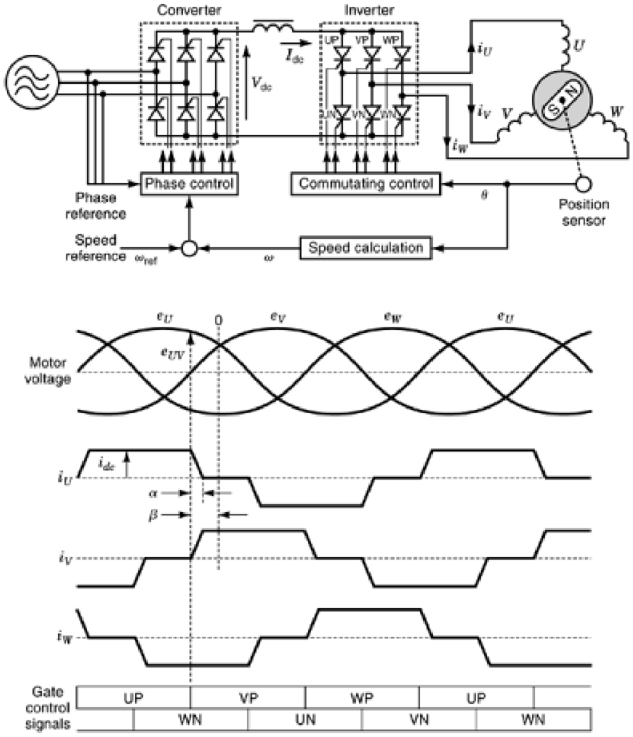


Fig. 11. System configuration, control, and waveforms of a dc thyristor motor system.

synchronous motors. Large synchronous motors usually are the revolving-field type, because field windings are simpler and consume much less power (i.e., less voltage and current) than armature windings. Figure 10 shows (a) a three-phase synchronous motor's circuital model, (b) the equivalent circuit, and (c) the operating principle (1, 2)

Ac synchronous motors have been traditionally used in large power applications with constant speed. As the enabling technology power electronics makes it possible to use ac synchronous motors in adjustable speed drives (ASDs). A variable-frequency power supply is needed for such ASD applications and the power supply has to be synchronized with the mechanical or shaft speed of the motor; therefore, a position sensor is usually required. Some ac synchronous motors that are made for ASD purposes are equipped with position sensors. They are driven by thyristor converters and are therefore called thyristor motors or commutatorless motors in some literature to distinguish them from dc motors. Some ac synchronous motors use permanent magnets or rotary transformers to eliminate brushes and slip rings and are therefore called brushless thyristor motors or brushless dc motors. There are several thyristor motor structures that are commonly used in the ASD applications.

Dc Thyristor Motors. Figure 11 illustrates the system structure, control, and waveforms of dc thyristor motors. It is the simplest structure to drive a synchronous motor. The system consists of a phase-controlled thyristor converter, a dc inductor for smoothing current, and a thyristor inverter. The dc current I_{dc} is regulated by phase control according to the torque command, thereby controlling the motor torque, which is proportional to the dc current. The thyristor inverter produces a 120° trapezoidal current wave at a desired motor speed. In order to generate such trapezoidal waves, the inverter has to commutate current from one phase to another by using help from the motor's induced (back emf) voltage, e_U, e_V, and e_W. Because of the motor inductance

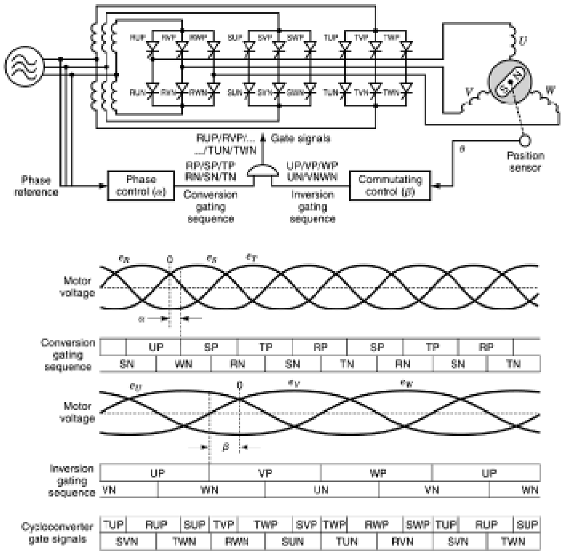


Fig. 12. System configuration, control, and waveforms of an ac thyristor motor system.

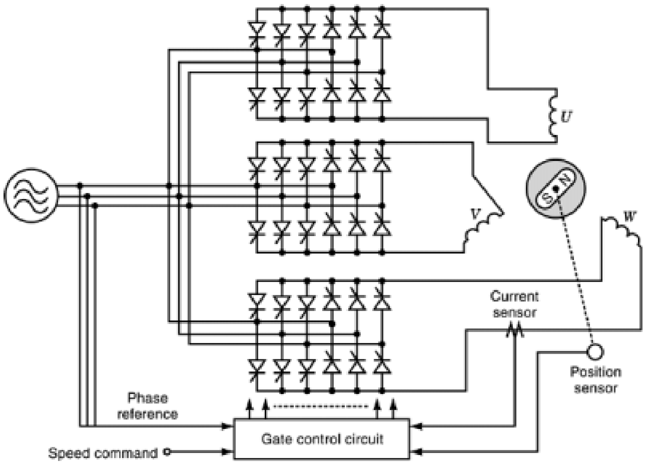


Fig. 13. System configuration of voltage-source type thyristor motors.

commutation takes time, which is called commutation overlapping angle, α, as indicated in the figure when a commutation is taking place from phase U to phase V. The commutation must be completed during $e_U > e_V$, therefore a leading angle β from time 0 should be guaranteed. Such a leading angle β is called the commutation leading angle. As explained here, this drive system that uses a dc link and provides the simplest structure is commonly called a dc thyristor motor. However, the dc thyristor motor has difficulties at start-up because the motor-induced voltage is zero at start-up and the inverter commutation relies on appreciable motor voltages. In order to start up, dc thyristor motors require special means such as using a commutation transformer to assist inverter commutation. To overcome this drawback of the dc thyristor motor, ac thyristor motors [or called SCR commutatorless motor (3)] are commonly used in large-drive applications.

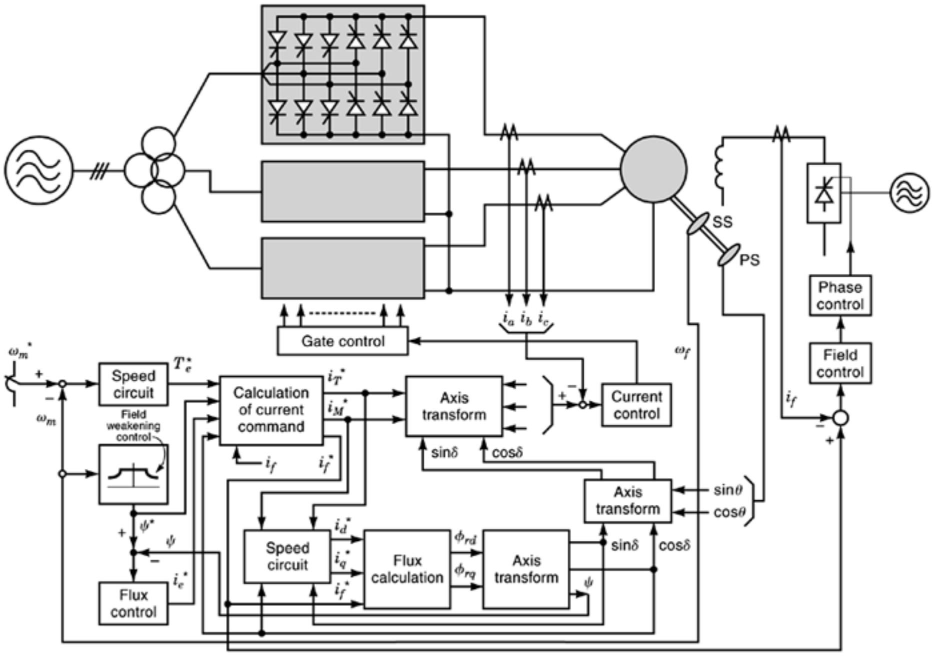


Fig. 14. Configuration and control block diagram of a 2.5-MW synchronous motor drive system used for steel rolling mills.

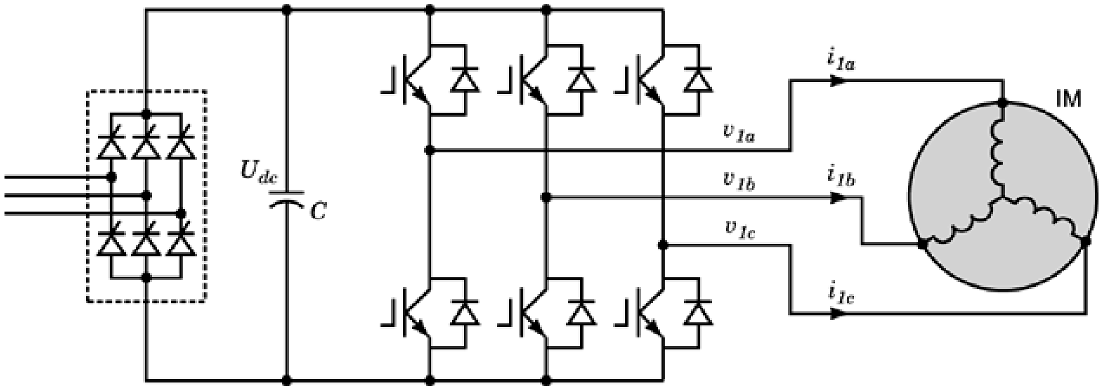


Fig. 15. Voltage-source inverter (VSI) for induction motor (*IM*) drives.

AC Thyristor Motors. Figure 12 illustrates one system structure, its control, and waveforms of ac thyristor motors. The thyristor converter as shown directly connects an ac synchronous motor to the power source and provides direct frequency change from ac to ac without dc links. This type of ac-ac power converter is a combination of the converter and inverter, known as the cycloconverter (see the article "AC-AC Power Converters" for more information) and is commonly used in large motor drive applications. The ac thyristor motor does not have the start-up problem because either the source voltage or motor voltage can be used for commutation (i.e., line commutation or load commutation). Since the cycloconverter as shown in Fig. 12 is a combination of a thyristor converter and an inverter, the cycloconverter gate signals are the logic AND of the conversion gating sequence and inversion gating sequence. Fig. 12 illustrates the gating (or firing) sequence and signals. The control angle α is referenced from the source and used for line commutation, whereas the control angle β is referenced from the load (or motor) and used for load commutation. Both line and load commutations should be completed within $(0, \pi)$, i.e., $0<\alpha<\pi$ and $0<\beta<\pi$.

The ac thyristor motor of Fig. 12 behaves exactly like the dc thyristor motor without its start-up problem. Both circuits have large current-smoothing inductors and produce 120° trapezoidal wave motor current. Therefore both systems (Figs. 11 and 12) are sometimes known as current-source thyristor motors, having the following features:

Large torque ripples due to trapezoidal current waveforms
Four-quadrant operation
Wide operation (output) frequency

Voltage-Source ac Thyristor Motors and Application Examples. As stated above, current-source thyristor motors are simple but produce high torque ripples, and thus are not suitable for high-performance and high-precision control. To achieve high-performance torque control, voltage-source cycloconverters and pulse-width-modulated (*PWM*) inverters are used. Figure 13 illustrates a system structure of voltage-source ac thyristor motors, where a cycloconverter is used for each phase (see Figs. 13 and 14 of the article "AC-AC Power Converters" for more information and the operating principle). This type of cycloconverter provides almost sine-wave current and less distorted voltage to the motor and is thus suited for applications demanding high-performance and high-precision control. The output maximum frequency is about 1/3 to 1/2 of the line frequency. For low speed and large motor drives, cycloconverters are widely used. For higher-speed applications, forced-commutated thyristor inverters and GTO inverters (see Figs. 15, 16, 17 in the next section) are used. For example, Fig. 16 shows a current-source inverter (CSI) using thyristors and diodes. The CSI can be employed for an ac synchronous motor drive as well. The advantages of the CSI are that (1) both PWM and six-step operations are possible, (2) a large constant-power speed ratio (*CPSR*) such as 6× to 10× base speed is achievable without any other assistance from outside circuits, and (3) regeneration is possible. Figure 17 is another version of the CSI using GTOs.

Because of high efficiency, high reliability, and high performance, cycloconverter-based large-motor-drive systems are widely used in many industry applications, such as cement mills, steel rolling mills, mine blowers, and pumps. As an example, Fig. 14 shows the full configuration and control block diagram of a 2.5-MW synchronous motor drive used for steel rolling mills. The control is very similar to the dc motor control.

Large AC Induction Motor Drives

Induction motors having simpler structures, especially squirrel-cage induction motors, are more rugged and economical than dc and synchronous motors. They are widely used in almost every industry. Until the 1960s, however, induction motors were mainly used in constant-speed drive applications because their torque and speeds are much more difficult to control. In modern industries where high performance and high-precision torque, speed, and/or position control are required, dc motors were the choice. With the development and advance of power semiconductor devices and induction motor control theory, induction motors have became a major player in the variable-speed drives or adjustable speed drives (ASDs) because of their ruggedness and maintenance-free features.

Power Converters for Induction Motor ASDs. There are three major power converters that are commonly used in the induction motor drives. They are the voltage-source inverter (VSI, Fig. 15), the current-source inverter (CSI, Figure 16), and the cycloconverter (see Fig. 13). Figure 15 shows a typical voltage-source

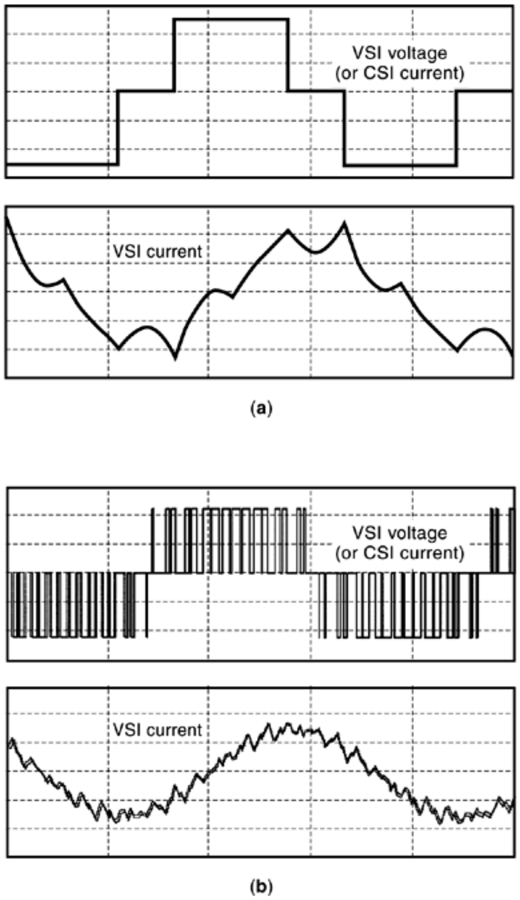


Fig. 16. Six-step and PWM waveforms of VSI and CSI.

inverter consisting of a diode rectifier bridge, a large dc capacitor for maintaining a constant dc voltage, and six switches. In the figure six IGBT-diode modules are shown. For larger motor drives, GTO thyristors may be used. A voltage-source inverter can produce either a 120° square-wave (or six-step) line-to-line voltage as shown in Fig. 16(a) or a PWM voltage waveform as shown in Fig. 16(b). A PWM inverter can produce almost sinusoidal currents. Figure 17 shows a current-source inverter, which is the dual circuit of the voltage-source inverter, Fig. 15. Recently, the current-source inverter (Fig. 16) has been simplified by using GTOs as shown in Fig. 18. A capacitor bank at the output is needed for current commutation. Unlike the voltage-source inverter, the current-source inverter can produce either a 120° square wave (or six-step) line current or a PWM current waveform as shown in Fig. 16. The voltage waveform becomes almost sinusoidal for PWM current-source inverters, which is similar to the PWM current waveform as shown in Fig. 16 for the VSI.

Speed Control Methods of Induction Motors. There are many speed-torque control methods for induction motor drives. However, they can be categorized into three basic methods: primary frequency control, primary voltage control, and slip power control. The primary frequency control includes constant volt/hertz (V/f) control, slip frequency control, and vector control. The slip power control has the secondary resistance control and static Scherbius control.

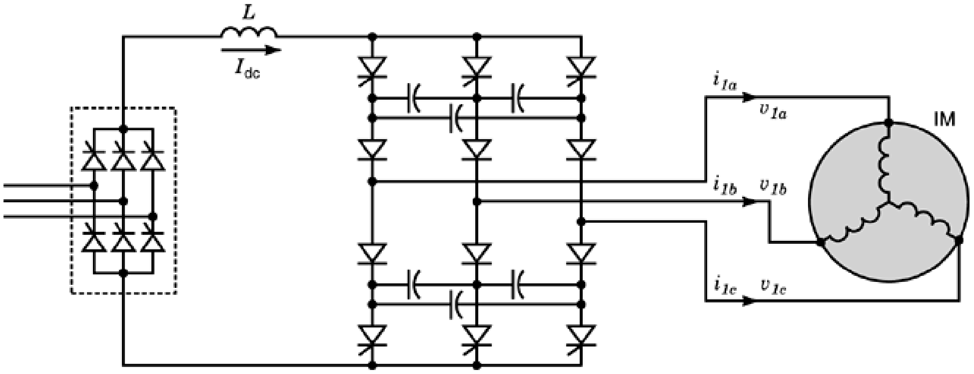


Fig. 17. Current-source inverter (CSI) using thyristors for induction motor drives, where a thyristor rectifier provides a desired dc current, I_{dc} and the CSI generates a desired frequency output.

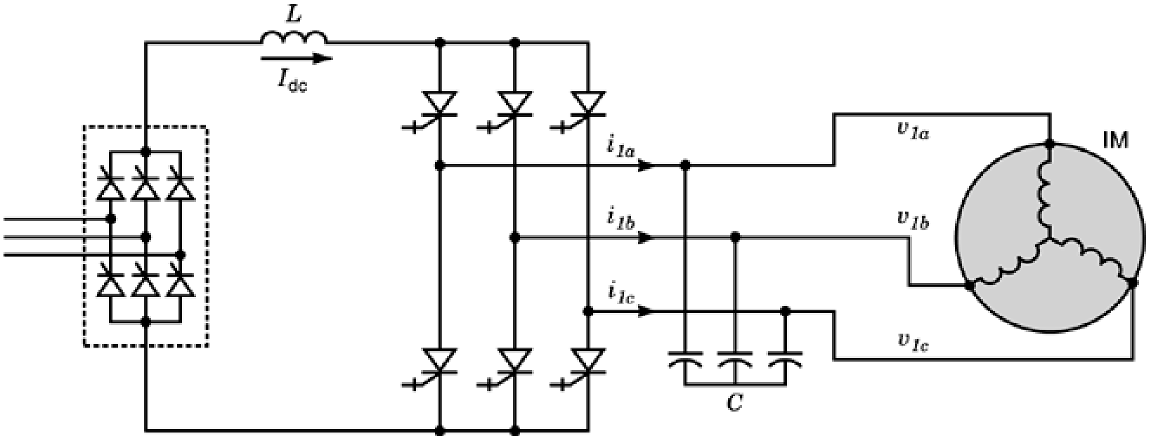


Fig. 18. Current-source inverter using GTO thyristors for induction motor drives.

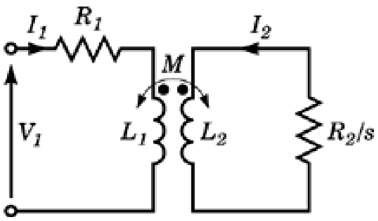


Fig. 19. Per-phase equivalent circuit of the induction motor.

Figure 19 shows the per-phase equivalent circuit of an induction motor in steady state. V_1 is the primary phase voltage, I_1 is the primary (or stator) current, I_2 is the secondary (or rotor) current, L_1 is the stator inductance, L_2 is the rotor inductance, R_1 is the stator resistance, R_2 is the rotor resistance, M is the mutual inductance, and s is the slip [i.e., $s=(\omega_1-\omega_m)/\omega_1$, where ω_1 is the primary voltage frequency and ω_m is the rotor

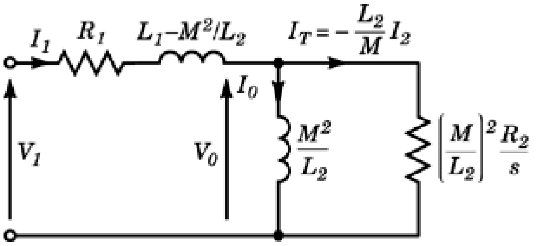


Fig. 20. Primary-referred equivalent circuit of the induction motor.

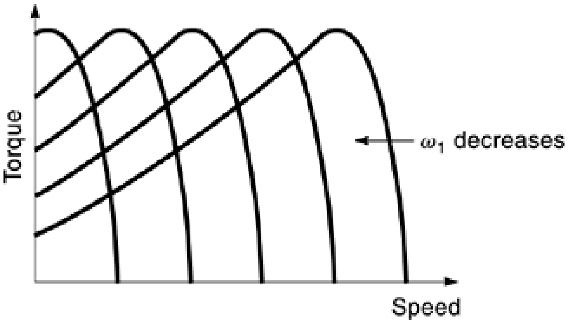


Fig. 21. Torque-versus-speed curves of constant V_0/ω_1 control.

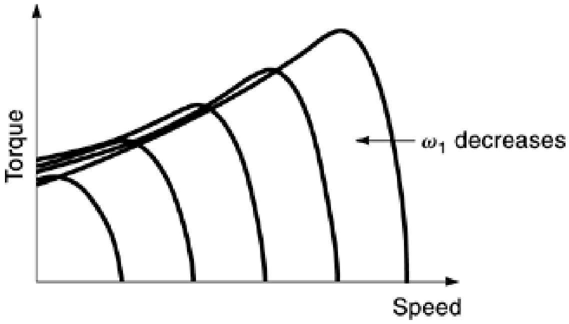


Fig. 22. Torque-versus-speed curves of constant V_1/ω_1 control, which shows less torque production at low speeds.

frequency]. The steady-state equations of an induction motor are as follows:

$$\begin{bmatrix} V_1 \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + j\omega_1 L_1 & j\omega_1 M \\ j\omega_1 M & \frac{R_2}{s} + j\omega_1 L_2 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}, \tag{6}$$

A primary-referred equivalent circuit as shown in Fig. 20 can be further derived from Fig. 19 and Eq. (6). In Fig. 20, V_0 is the back emf voltage induced from the rotor speed. For the constant volt/hertz (V/f) control, it is intended to keep V_0/ω_1 constant. By doing so, the exciting current (or current required to magnetize both core and leakage flux) I_0 becomes constant and the torque current I_T becomes proportional to slip, which in turn

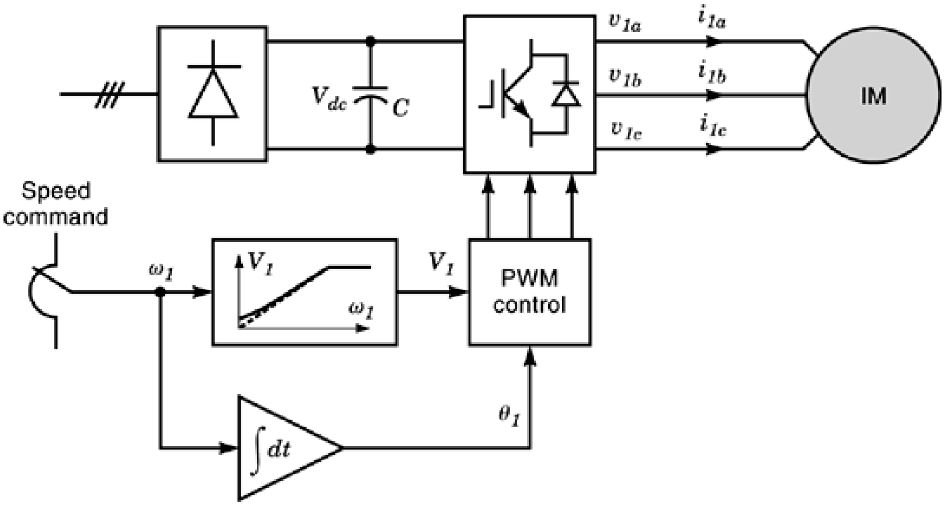


Fig. 23. Block diagram of the constant volt/hertz control. At low speeds, V_1 needs to be compensated for voltage drop due to the stator resistance.

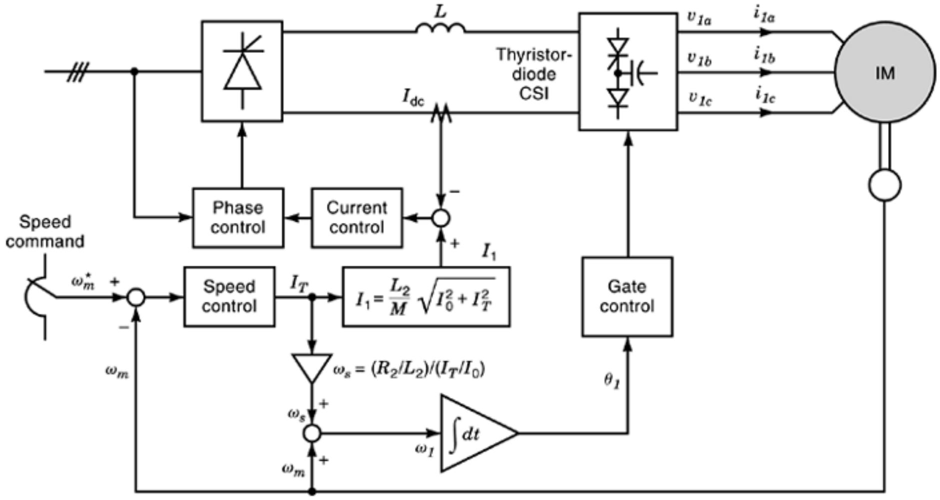


Fig. 24. Block diagram of the slip-frequency control using CSI.

makes the motor torque (T) be proportional to slip frequency. Their relations are expressed as follows:

$$V_0 = \omega_1 \frac{M^2}{L_2} I_0 = \left(\frac{M}{L_2}\right)^2 \frac{R_2}{s} I_T \qquad (7)$$

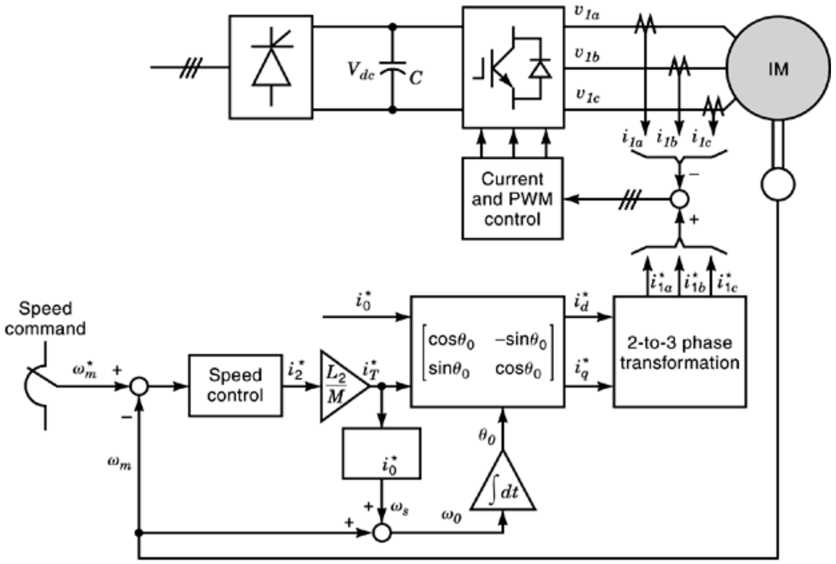


Fig. 25. Block diagram of indirect vector control of induction motors.

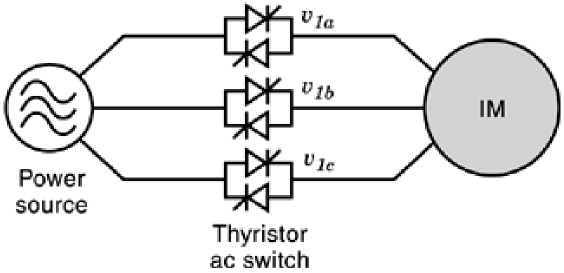


Fig. 26. Primary-voltage control circuit.

$$\frac{V_0}{\omega_1} = \frac{M^2}{L_2} I_0 = \text{const} \tag{8}$$

$$T = 3\frac{M^2}{L_2} I_0 I_T = 3\frac{M^2}{L_2} I_0 \frac{sV_0}{\left(\frac{M}{L_2}\right)^2 R_2} = 3\frac{L_2}{R_2} I_0 V_0 s = 3\frac{L_2}{R_2} I_0 \frac{V_0}{\omega_1} s\omega_1. \tag{9}$$

Figure 21 shows torque-versus-speed curves when V_0/ω_1 is kept constant. The curves are parallel to each other, which is desired for a good torque control. However, voltage V_0 is not directly accessible or controllable. In practical implementation, constant V_1/ω_1 is used instead. For the constant V_1/ω_1 control, the torque-versus-speed curves become Fig. 22, which is less desirable because of lower torque production and control at low

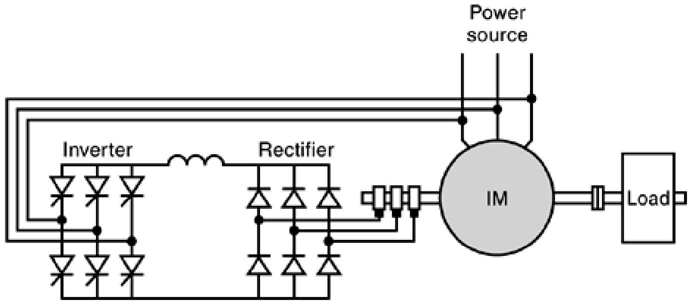


Fig. 27. Main circuit of the static Scherbius control.

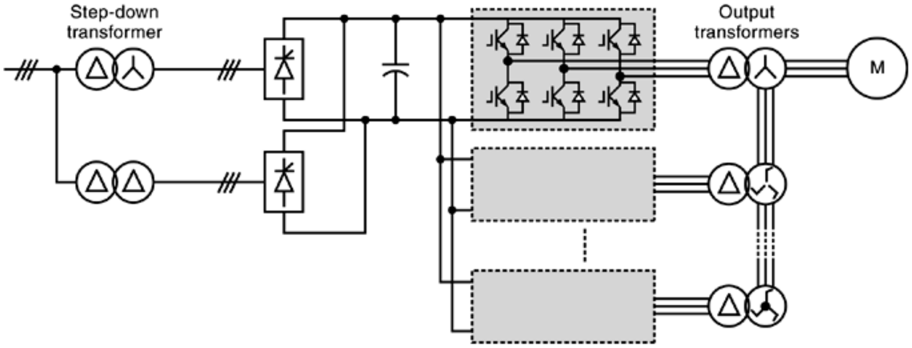


Fig. 28. Typical configuration of a multipulse inverter for large motor drives.

speeds. Therefore, constant volt/hertz (*V/f*) control is usually used for applications in which simple-open loop speed control is required. Figure 23 shows a block diagram of the constant volt/hertz (*V/f*) control.

From Eq. (9), it is evident that motor torque can be also controlled by the slip frequency. Figure 24 shows a block diagram of the slip frequency control using thyristor-diode CSI (Fig. 16). The constant volt/hertz (V/f) control (Fig. 23) and slip-frequency control (Fig. 24) provide steady-state torque and speed control. They are widely used in large induction motor drives for applications such as pumps and fans, etc.

Vector control (or field-oriented control), however, is used where high dynamic performance and high precision control are required. The vector control is based on the dynamic equation of induction motors, which can be expressed in the stationary *dq* frame as follows:

$$\begin{aligned} \mathbf{v}_1 &= \left(R_1 + L_1\frac{d}{dt}\right)\mathbf{i}_1 + M\frac{d}{dt}\mathbf{i}_2 \\ \mathbf{0} &= M\frac{d}{dt}\mathbf{i}_1 - M\omega_{\mathrm{m}} \times \mathbf{i}_1 + \left(R_2 + L_2\frac{d}{dt}\right)\mathbf{i}_2 - L_2\omega_{\mathrm{m}} \times \mathbf{i}_2 \end{aligned} \tag{10}$$

where $\mathbf{v}_1 = [v_{1\mathrm{d}}, v_{1\mathrm{q}}]^T$, $\mathbf{i}_1 = [i_{1\mathrm{d}}, i_{1\mathrm{q}}]^{\mathrm{T}}$, $\mathbf{i}_2 = [i_{2\mathrm{d}}, i_{2\mathrm{q}}]^T$, $\omega_{\mathbf{m}}$ is the rotor speed vector, and × denotes the vector (or cross) product. The vector control has direct and indirect control methods. The indirect vector control uses motor parameters to calculate slip frequency and PWM control to produce commanded current. Figure 25 shows the block diagram of the indirect vector control.

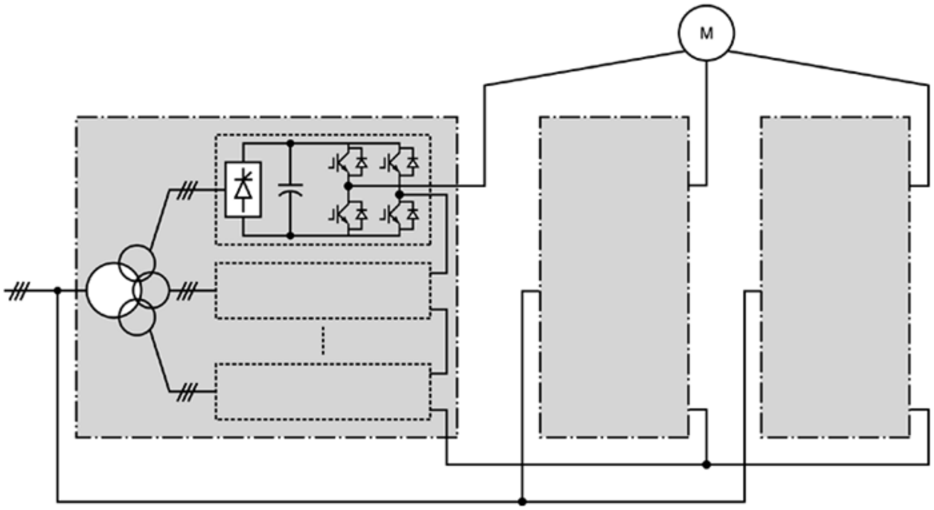


Fig. 29. A cascade multilevel inverter for large motor drives.

Another speed control method is the primary-voltage control. Figure 26 shows the primary-voltage control circuit, in which thyristor ac switches are used to control the motor primary voltage in magnitude without changing the frequency. The primary-voltage control provides the simplest method to control torque and speed. Motor efficiency decreases greatly at low speeds because of high slip. Therefore, this speed control method is only used in some special applications.

Another speed control method is the slip-power control. Slip power is the power consumed at the rotor resistance or its equivalent. For wound-rotor type induction motors, the slip power can be controlled by changing its equivalent rotor winding resistance. The equivalent rotor winding resistance is changed usually either by outside resistors connected to the rotor windings through slip rings or a static Scherbius circuit as shown in Fig. 27. In Fig. 27, instead of resistors the Scherbius circuit uses a rectifier-inverter circuit to control the dc link voltage that equivalently changes the rotor resistance and to regenerate slip power back to the line. Static Scherbius circuits have two major advantages: (1) required VA rating of the power converter is small when the motor is operated near the rated speed and (2) the motor can be operated at an over-synchronous speed when injecting power into the rotor by using a cycloconverter.

Multilevel Inverters for Large Motor Drives

Thyristor–based and GTO thyristor–based power converter technology such as cycloconverters and multipulse inverters using IGBTs has been traditionally used for large (medium-voltage) motor drives. A multipulse inverter connected through output transformers for medium-voltage large motor drives is typically configured as Fig. 28. Because of the output transformers' flux saturation, it is very difficult to operate and to achieve high performance at low speeds. In addition, a step-down front-end transformer is needed in such configurations. Transformers are bulky, costly, and lossy. Recently, multilevel inverters using IGBTs and high-voltage ($>$1700 V) IGBTs have been a hot topic in the research and development arena for large motor drives because of the following advantages:

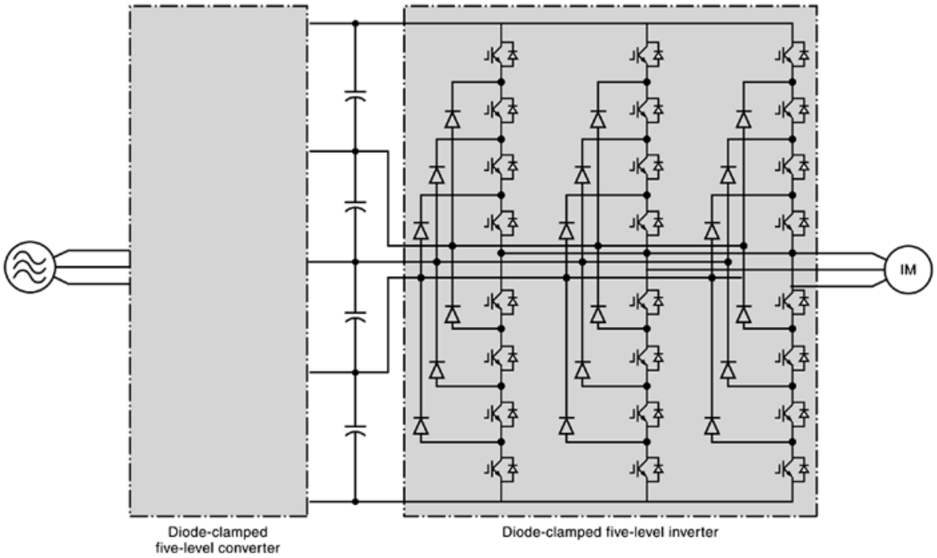


Fig. 30. A diode-clamped five-level converter-inverter for large motor drives.

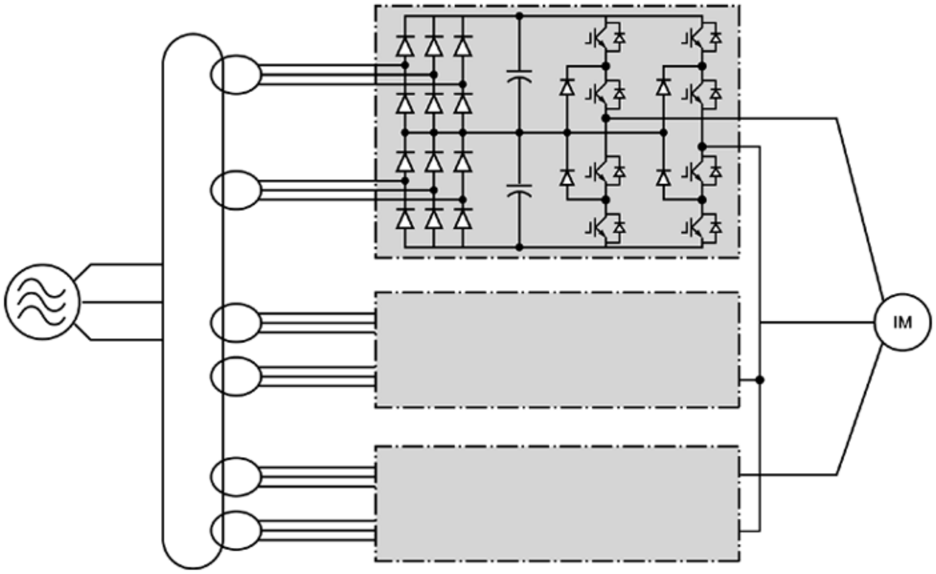


Fig. 31. A combination of cascade and diode-clamped nine-level (line-to-line) inverter for large motor drives.

- No need for output transformers that are required in multipulse inverters
- Higher inverter system efficiency
- No need for snubber circuits that are required in thyristor and GTO thyristor converters or inverters
- Sinusoidal current and almost sinusoidal voltage, resulting in lower harmonic power losses from the motor, and
- Almost distortion-free and unity-power-factor line current with multipulse diode rectifiers as the front end

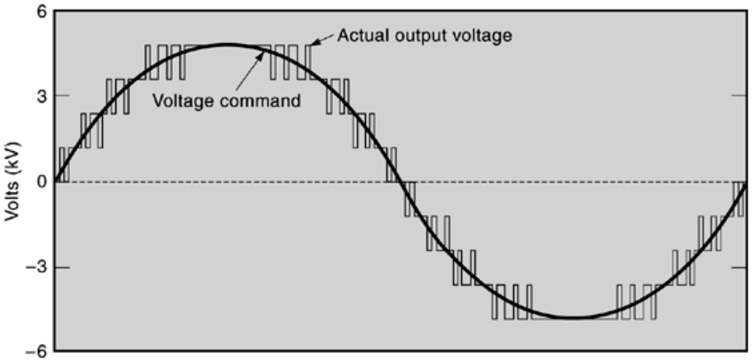


Fig. 32. Typical line-to-line voltage waveforms of a nine-level inverter. The staircase waveform incorporated with PWM provides a much better approximation to the command than the traditional two-level inverter.

Figure 29 shows a cascade multilevel inverter, where each phase consists of a series of H-bridge cells and a separate or isolated dc source is needed for each H-bridge cell. Figure 30 shows a diode-clamped multilevel converter-inverter system. The main feature of the diode-clamped multilevel inverter is the shared dc link that does not require a number of isolated dc sources. However, special considerations are necessary to balance each dc capacitor's voltage. Figure 31 shows a combination of the cascade and diode-clamped multilevel inverters. These multilevel inverters have emerged as a new generation of medium-voltage motor drives because they all generate relatively clean voltage waveforms as shown in Fig. 32, which are not achievable by the traditional thyristor and PWM inverters.

BIBLIOGRAPHY

1. M. H. Rashid *Power Electronics: Circuits, Devices, and Applications*, 2d ed., Englewood Cliffs, NJ: Prentice-Hall, 1993.
2. N. Mohan T. M. Undeland W. P. Robbins *Power Electronics: Converters, Applications, and Design*, 2d ed., New York: Wiley, 1995.
3. B. D. Bedford R. G. Hoft *Principles of Inverter Circuits*, New York: Wiley, 1964.

READING LIST

P. W. Hammond A new approach to enhance power quality for medium voltage AC drives, *IEEE Trans. Ind. Appl.*, **33**:202–208, 1997.
P. C. Sen *Thyristor DC Drives*, Toronto, Canada: Wiley, 1981.
L. M. Tolbert F. Z. Peng T. G. Habetler Multilevel converters for large electric drives, *IEEE Trans. Ind. Appl.*, **35**: 36–44,1999.

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