Module

7

Electrical Machine Drives

Lesson

34

Electrical Actuators: Induction Motor Drives

Instructional Objectives

After learning the lesson students should be able to understand

A. Concept of slip
B. Equivalent circuit of induction motor.
C. Torque-speed characteristics.
D. Methods of induction motor speed control.
E. Principles of PWM inverter.
F. Implementation of constant V/f control.

Introduction

For adjustible speed applications, the induction machine, particularly the cage rotor type, is most commonly used in industry. These machines are very cheap and rugged, and are available from fractional horsepower to multi-megawatt capacity, both in single-phase and poly-phase versions. In this lesson, the basic fundamentals of construction, operation and speed control for induction motors are presented.

In cage rotor type induction motors the rotor has a squirrel cage-like structure with shorted end rings. The stator has a three-phase winding, and embedded in slots distributed sinusoidally. It can be shown that a sinusoidal three-phase balanced set of ac voltages applied to the three-phase stator windings creates a magnetic field rotating at angular speed $\omega_s = 4\pi f_s /P$ where f_s is the supply frequency in Hz and P is the number of stator poles.

If the rotor is rotating at an angular speed ω_r, i.e. at an angular speed $(\omega_s - \omega_r)$ with respect to the rotating stator mmf, its conductors will be subjected to a sweeping magnetic field, inducing voltages and current and mmf in the short-circuited rotor bars at a frequency $(\omega_s - \omega_r)P/4\pi$, known as the slip speed. The interaction of air gap flux and rotor mmf produces torque. The per unit slip ω is defined as

$$S = \frac{\omega_s - \omega_r}{\omega_s}$$

Equivalent Circuit

Figure 34.1 shows the equivalent circuit with respect to the stator, where I_r is given as

$$I_r == \frac{V_m}{\left(\frac{R_r}{S}\right) + j\omega_e L_{lr}}$$

and parameters R_r and L_{lr} stand for the resistance and inductance parameters referred to to the stator.

Since the output power is the product of developed electrical torque T_e and speed ω_m, T_e can be expressed as

$$T_e = 3\left(\frac{P}{2}\right) I_r^2 \frac{R_r}{S\omega_e}$$

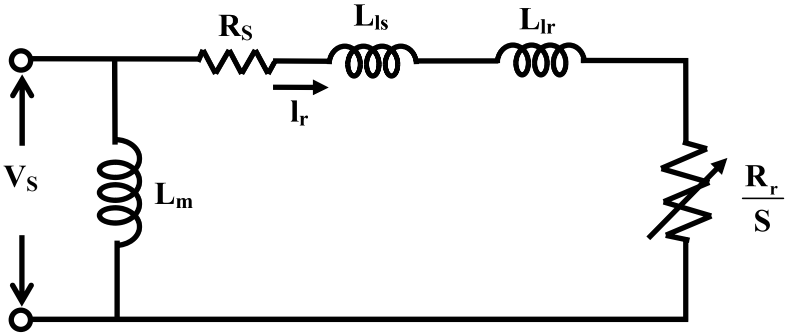

Fig. 34.1 Approximate per phase equivalent circuit

In Figure 34.1, the magnitude of the rotor current I_r can be written as

$$I_r = \frac{V_s}{\sqrt{\left(R_s + R_r/S\right)^2 + \omega_e^2\left(L_{ls} + L_{lr}\right)^2}}$$

This yields that,

$$T_e = 3\left(\frac{P}{2}\right)\frac{R_r}{S\omega_e}\cdot\frac{V_s^2}{\left(R_s + R_r/S\right)^2 + \omega_e^2\left(L_{ls} + L_{lr}\right)^2}$$

Torque-Speed Curve

The torque T_e can be calculated as a function of slip S from the equation 1. Figure 34.2 shows the torque-speed $\left(\omega_r/\omega_e = 1 - S\right)$ curve. The various operating zones in the figure can be defined as plugging ($1.0 < S < 2.0$), motoring ($0 < S < 1.0$), and regenerating ($S < 0$). In the normal motoring region, $T_e = 0$ at $S = 0$, and as S increases (i.e., speed decreases), T_e increases in a quasi-linear curve until breakdown, or maximum torque T_{em} is reached. Beyond this point, T_e decreases with the increase in S.

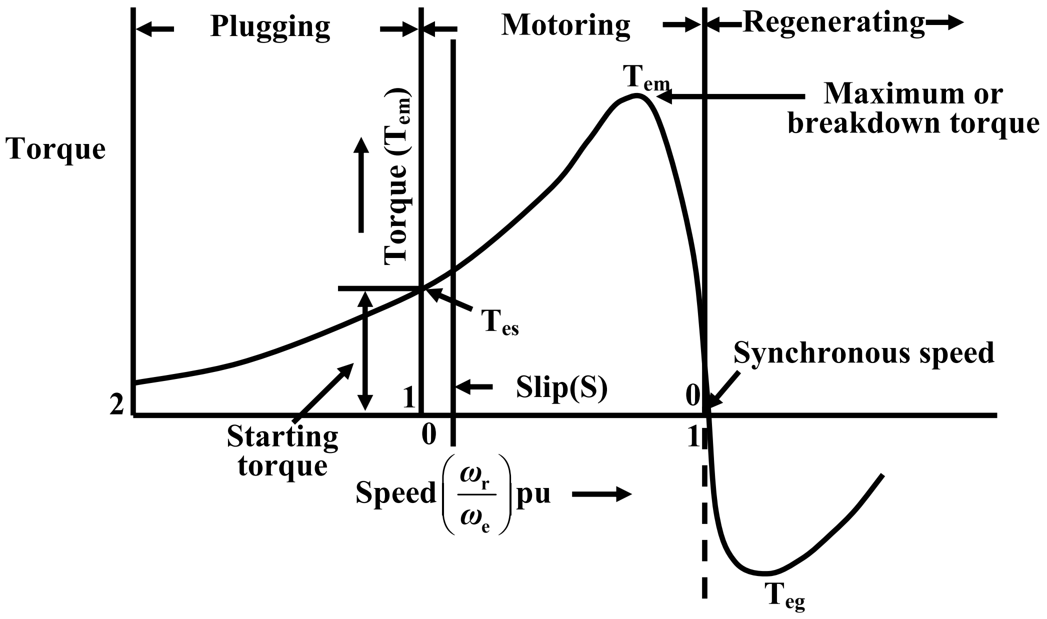

Fig. 34.2 Torque-speed curve of induction motor

In the regenerating region, as the name indicates, the machine acts as a generator. The rotor moves at supersynchronous speed in the same direction as that of the air gap flux so that the slip becomes negative, creating negative, or regenerating torque (Teg). With a variable-frequency power supply, the machine stator frequency can be controlled to be lower than the rotor speed ($\omega_e < \omega_r$) to obtain a regenerative braking effect.

Speed Control

From the torque speed characteristics in Fig. 34.2, it can be seen that at any rotor speed the magnitude and/or frequency of the supply voltage can be controlled for obtaining a desired torque. The three possible modes of speed control are discussed below.

Variable-Voltage, Constant-Frequency Operation

A simple method of controlling speed in a cage-type induction motor is by varying the stator voltage at constant supply frequency. Stator voltage control is also used for “soft start” to limit the stator current during periods of low rotor speeds.

Figure 34.3 shows the torque-speed curves with variable stator voltage. Often, low-power motor drives use this type of speed control due to the simplicity of the drive circuit.

Variable-Frequency Operation

Figure 34.4 shows the torque-speed curve, if the stator supply frequency is increased with constant supply voltage, where ω_e is the base angular speed. Note, however, that beyond the rated frequency ω_b , there is fall in maximum torque developed, while the speed rises.

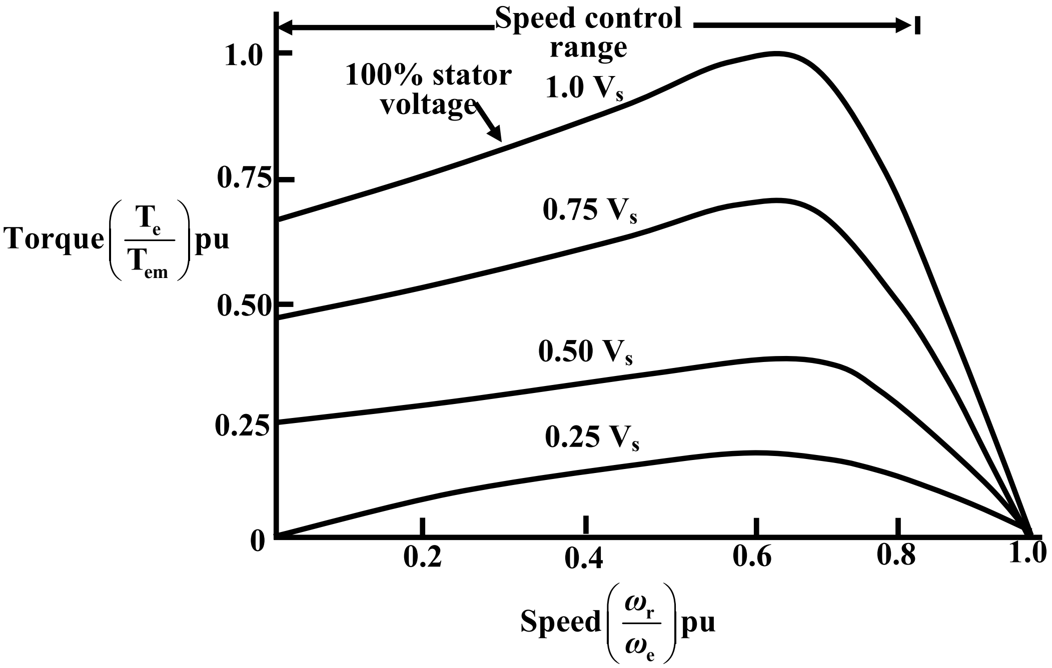

Fig. 34.3 Torque-speed curves at variable supply voltage

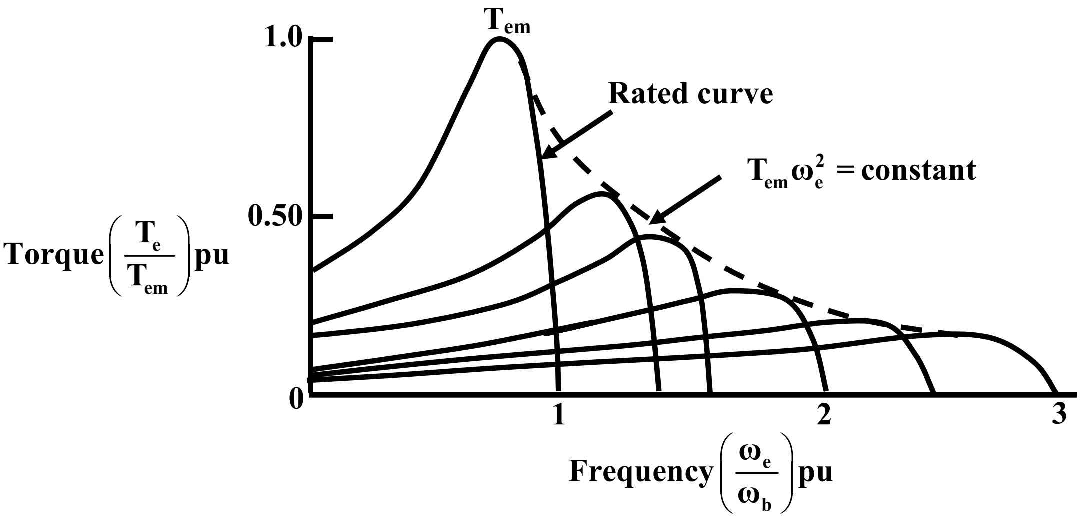

Fig. 34.4 Torque-speed curves at variable stator frequency

Variable voltage variable frequency operation with constant V/f

Figure 34.5 shows the torque-speed curves for constant V/f operation. Note that the maximum torque T_{em} remains approximately constant. Since the air gap flux of the machine is kept at the rated value, the torque per ampere is high. Therefore fast variations in acceleration can be achieved by stator current control. Since the supply frequency is lowered at low speeds, the machine operates at low slip always, so the energy efficiency does not suffer.

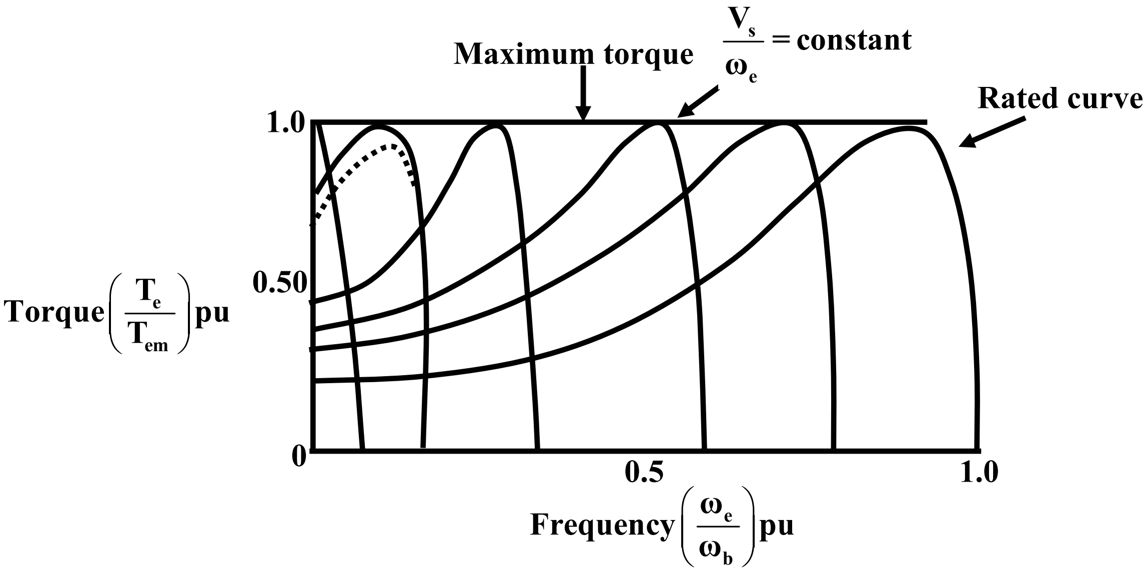

Fig. 34.5 Torque-speed curves at constant V/f

Majority of industrial variable-speed ac drives operate with a variable voltage variable frequency power supply.

Points to Ponder: 1

A. *In what type of applications, would it make sense to prefer a simple stator voltage control, rather than a constant V/f control ?*
B. *How can you be in the plugging region of the torque speed curve shown in Fig. 34.2 ?*

Variable Voltage Variable Frequency Supply

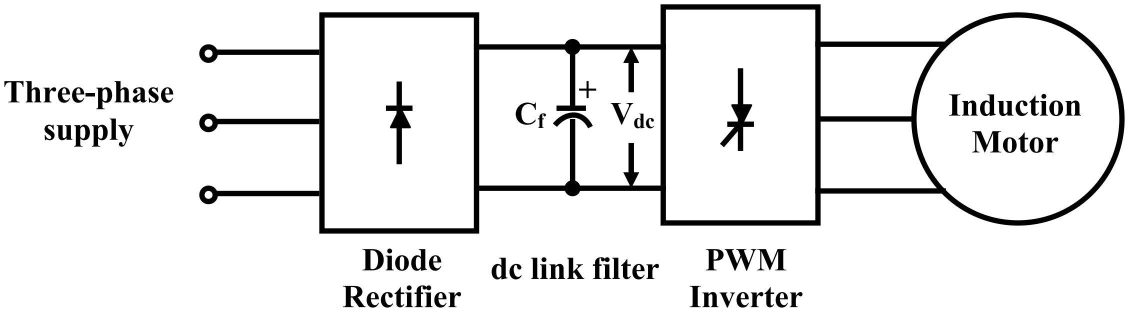

Fig. 34.6 PWM inverter fed induction motor drive

The variable voltage variable frequency supply for an induction motor drive consists of a uncontrolled (Fig. 34.6) or controlled rectifier (Fig. 34.7) (fixed voltage fixed frequency ac to variable/fixed voltage dc) and an inverter (dc to variable voltage/variable frequency ac). If rectification is uncontrolled, as in diode rectifiers, the voltage and frequency can both be controlled in a pulse-width-modulated (PWM) inverter as shown in Figure 34.6. The dc link filter consists of a capacitor to keep the input voltage to the inverter stable and ripple-free.

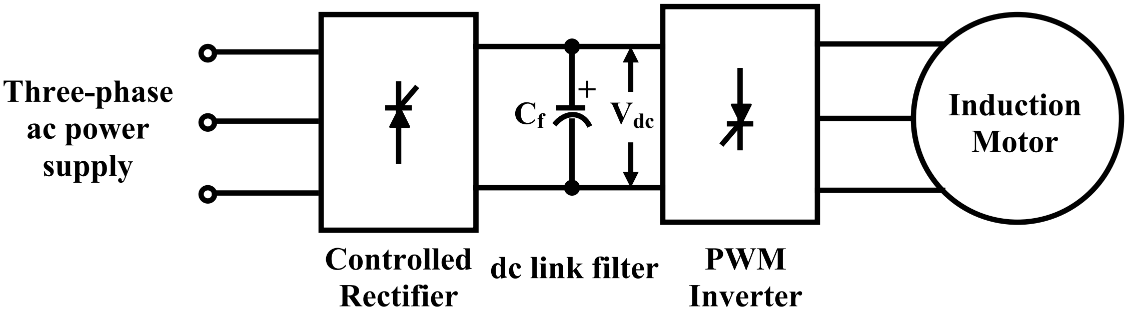

Fig. 34.7 Variable-voltage, variable-frequency (VVVF) induction motor drive

On the other hand, a controlled rectifier can be used to vary the dc link voltage, while a square wave inverter can be used to change the frequency. This configuration is shown in Fig. 34.7.

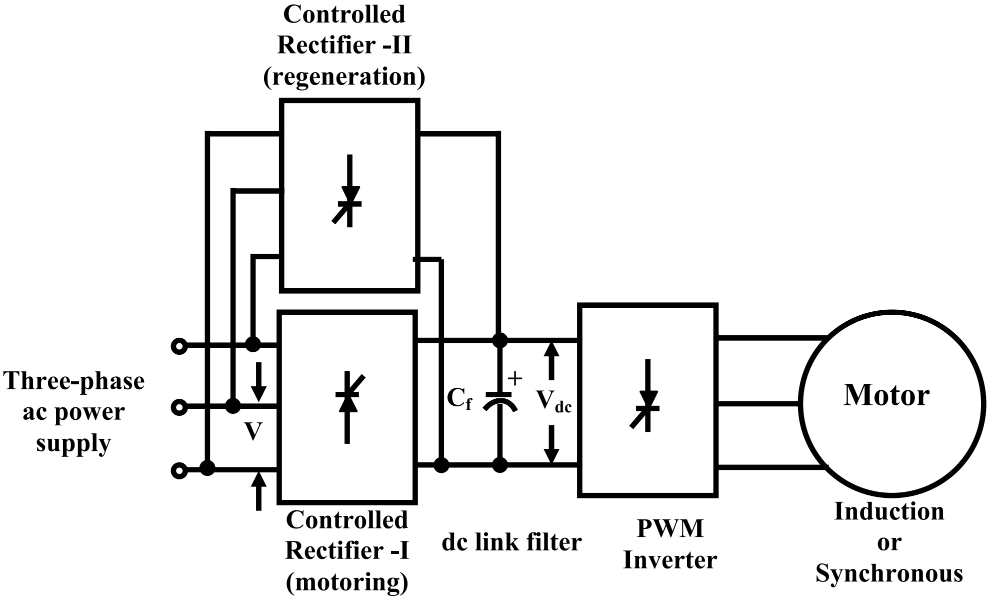

Fig. 34.8 Regenerative voltage-source inverter-fed ac drive.

To recover the regenerative energy in the dc link, an antiparallel-controlled rectifier is required to handle the regenerative energy, as shown in Fig. 34.8. The above are basically controlled voltage sources. These can however be operated as controlled current sources by incorporating an outer current feedback loop as shown in Fig. 34.9.

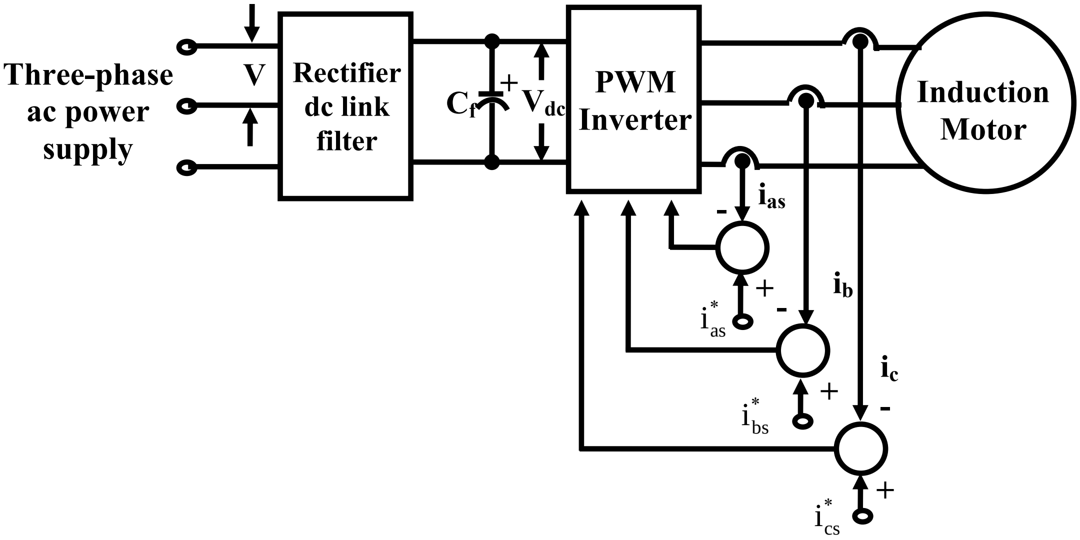

Fig. 34.9 Current-controlled voltage-source-driven induction motor drive

Points to Ponder: 2

A. *Why is it that drive with the single controlled rectifier shown in Fig. 34.7 cannot be used for regenerative braking?*
B. *How does one generate a controlled current source out of a voltage source inverter?*

Voltage-source Inverter-driven Induction Motor

A three-phase variable frequency inverter supplying an induction motor is shown in Figure 34.10. The power devices are assumed to be ideal switches. There are two major types of switching schemes for the inverters, namely, square wave switching and PWM switching.

Square wave inverters

The gating signals and the resulting line voltages for square wave switching are shown in Figure 34.11. The phase voltages are derived from the line voltages assuming a balanced three-phase system.

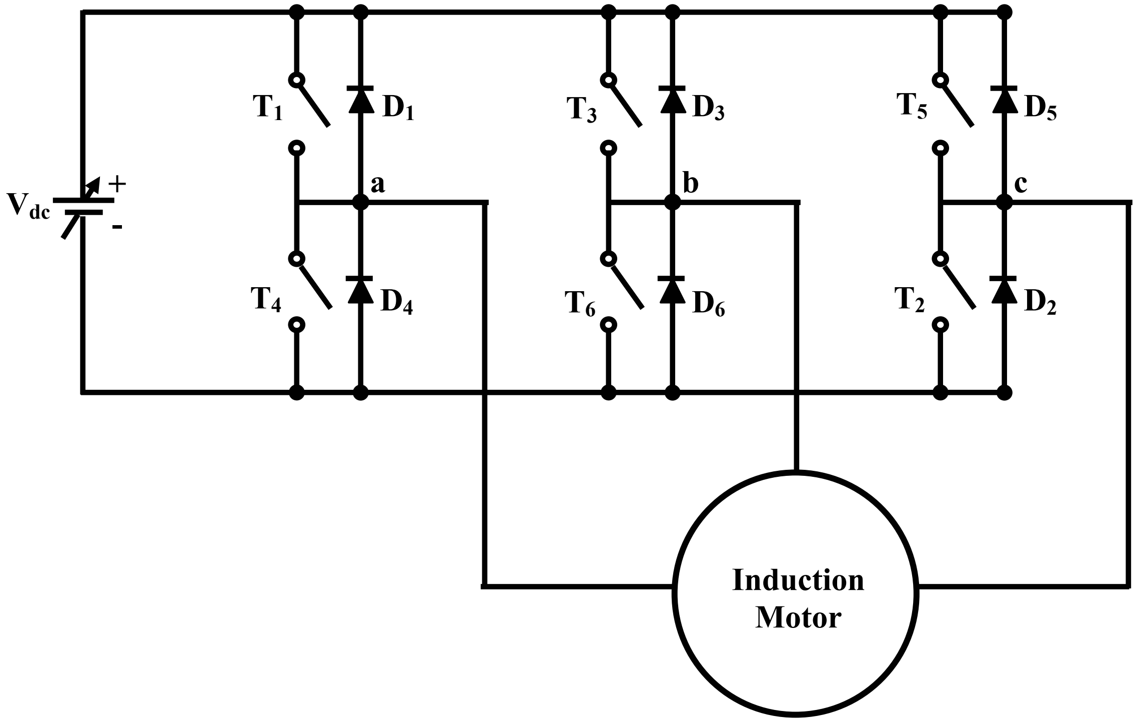

Fig. 34.10 A schematic of the generic inverter-fed induction motor drive.

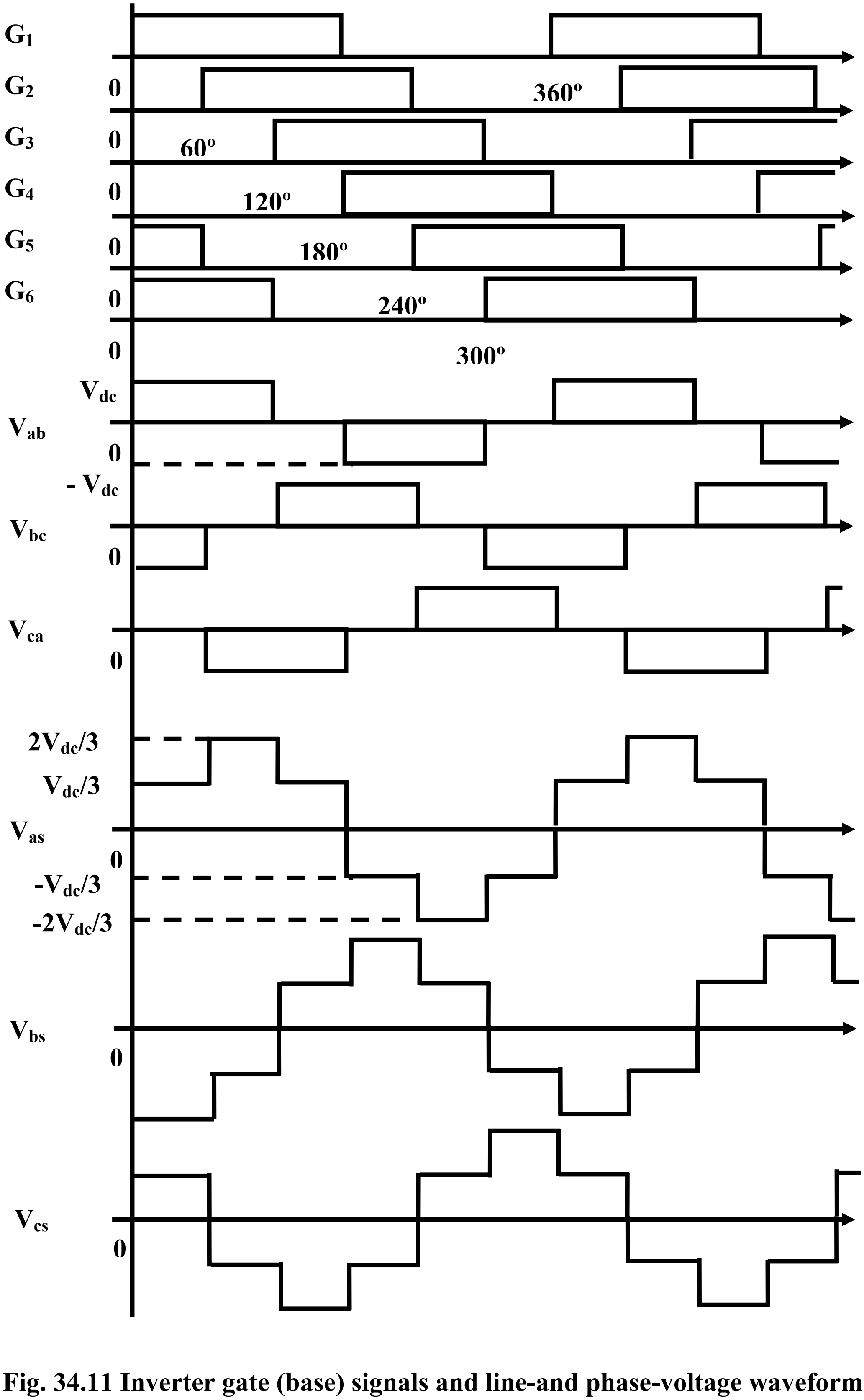

Fig. 34.11 Inverter gate (base) signals and line-and phase-voltage waveforms

The square wave inverter control is simple and the switching frequency and consequently, switching losses are low. However, significant energies of the lower order harmonics and large distortions in current wave require bulky low-pass filters. Moreover, this scheme can only achieve frequency control. For voltage control a controlled rectifier is needed, which offsets some of the cost advantages of the simple inverter.

PWM Principle

It is possible to control the output voltage and frequency of the PWM inverter simultaneously, as well as optimize the harmonics by performing multiple switching within the inverter major cycle which determines frequency. For example, the fundamental voltage for a square wave has the maximum amplitude ($4V_d/\pi$) but by intermediate switching, as shown in Fig. 34.12, the magnitude can be reduced. This determines the principle of simultaneous voltage control by PWM. Different possible strategies for PWM switching exist. They have different harmonic contents. In the following only a sinusoidal PWM is discussed.

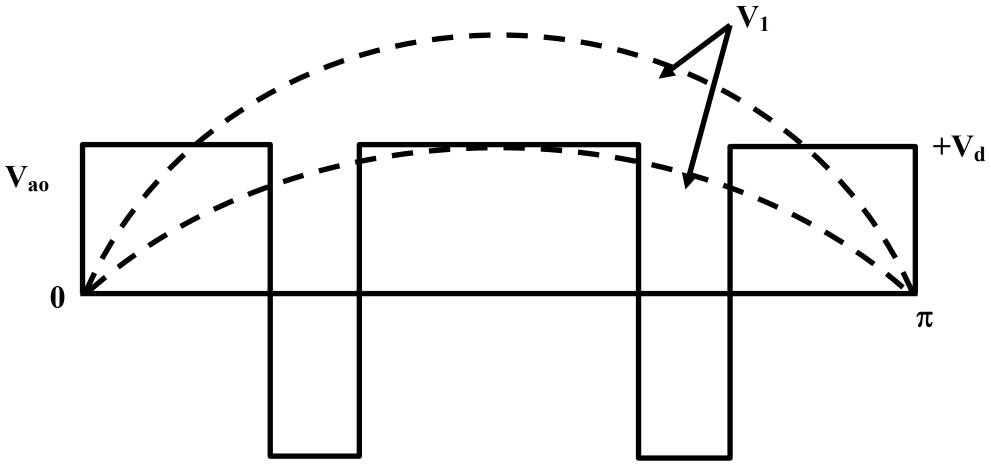

Fig. 34.12 PWM principle to control output voltage.

Sinusoidal PWM

Figure 34.13(a) explains the general principle of SPWM, where an isosceles triangle carrier wave of frequency f_c is compared with the sinusoidal modulating wave of fundamental frequency f, and the points of intersection determine the switching points of power devices. For example, for phase-a, voltage (V_{a0}) is obtained by switching ON Q_1 and Q_4 of half-bridge inverter, as shown in the figure 13. Assuming that $f << f_c$, the pulse widths of v_{a0} wave vary in a sinusoidal manner. Thus, the fundamental frequency is controlled by varying f and its amplitude is proportional to the command modulating voltage. The Fourier analysis of the v_{a0} wave can be shown to be of the form:

$$v_{a0} = 0.5mV_d \sin\left(2\pi ft + \phi\right) + \text{harmonic frequency terms}$$

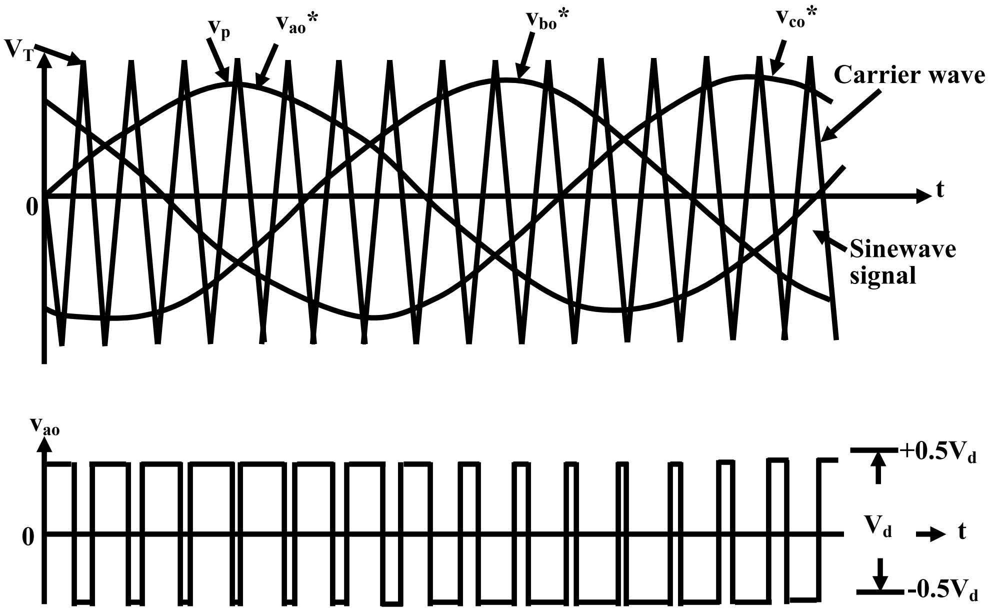

Fig. 34.13(a) Principle of sinusoidal PWM for three-phase bridge inverter.

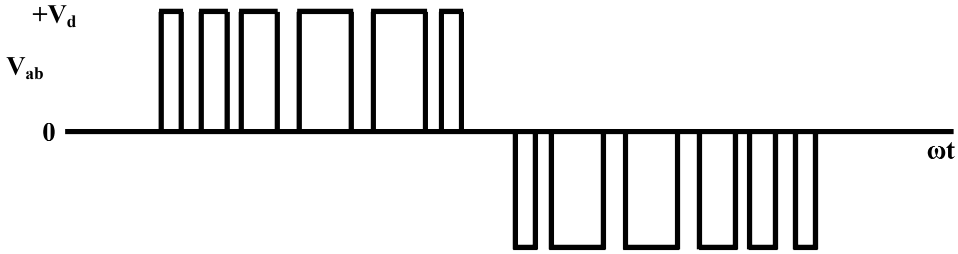

Fig. 34.13(b) Line voltage waves of PWM inverter

where m = modulation index and ϕ = phase shift of output, depending on the position of the modulating wave. The modulation index m is defined as

$$m = \frac{V_P}{V_T}$$

where V_p = peak value of the modulating wave and V_T = peak value of the carrier wave. Ideally, m can be varied between 0 and 1 to give a linear relation between the modulating and output wave. The inverter basically acts as a linear amplifier. The line voltage waveform is shown in Fig. 34.13(b).

Implementation of a constant voltage/constant frequency strategy

An implementation of the constant volts/Hz control strategy for the inverter-fed induction motor in close loop is shown in Figure 34.14. The frequency command f_s^* is enforced in the inverter and the corresponding dc link voltage is controlled through the front-end converter.

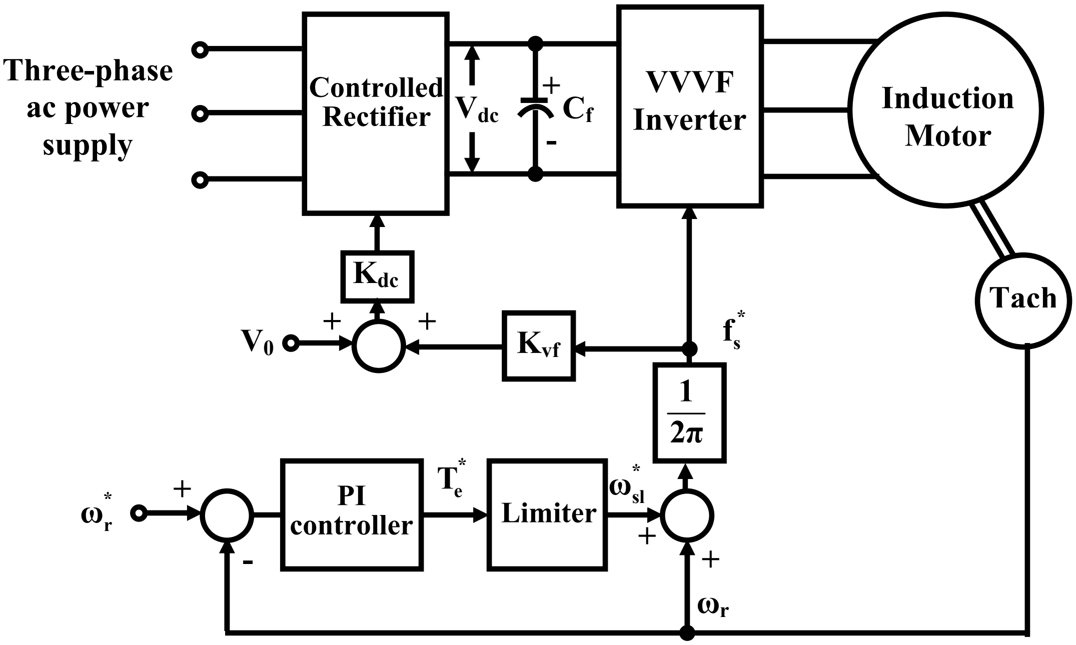

Fig. 34.14 Closed-loop induction motor drive with constant volts/Hz control strategy.

An outer speed PI control loop in the induction motor drive, shown in Figure 34.14 computes the frequency and voltage set points for the inverter and the converter respectively. The limiter ensures that the slip-speed command is within the maximum allowable slip speed of the induction motor. The slip-speed command is added to electrical rotor speed to obtain the stator frequency command. Thereafter, the stator frequency command is processed in an open-loop drive. K_{dc} is the constant of proportionality between the dc load voltage and the stator frequency.

Points to Ponder: 3

A. *Explain how the scheme in Fig. 34.10 achieves constant V/f.*
B. *Name two advantages and two disadvantages of a PWM inverter over a square wave inverter.*

Lesson Summary

In this lesson, the following topics related to Induction Motor Drives have been discussed.

a. Concept of slip
b. Equivalent circuit of induction motor.
c. Torque-speed characteristics.
d. Methods of induction motor speed control.
e. Principles of PWM inverter.
f. Implementation of constant V/f control.

Answers, Remarks and Hints to Points to Ponder

Points to Ponder: 1

A. *In what type of applications, would it make sense to prefer a simple stator voltage control, rather than a constant V/f control?*

Ans: For very simple applications with low torque demands and/or speed ranges a stator voltage control scheme would be adequate. Domestic fan controllers are of this type. Note that, for such applications, the cost of the controller is much more important than the improvement in efficiency, from a commercial point of view. The principle of stator voltage control is also used for soft starting of motors.

B. *How can you be in the plugging region of the torque speed curve shown in Fig. 34.2?*

Ans: Suppose the motor is rotating in the forward direction with a slip s. If suddenly the phase sequence of the three-phase supply is reversed, the slip would be equal to (1+(1-s)), or 2-s. Thus the motor would be in the plugging region of the torque speed curve.

Points to Ponder: 2

A. *Why is it that drives with the single controlled rectifier shown in Fig. 34.7 cannot be used for regenerative braking in the forward direction?*

Ans: Because the current through the controlled rectifiers cannot be reversed. One thus needs another rectifier connected in anti-parallel.

B. *How does one generate a controlled current source out of a voltage source inverter?*

Ans: By feedback control of the voltage input to the inverter. Thus the duty ratio of the PWM control input, which basically changes the voltage and thereby the current, is manipulated to make a current equal to the set point flow.

Points to Ponder: 3

A. *Explain how the scheme in Fig. 34.10 achieves constant V/f.*

Ans: Note that the voltage setpoint to the rectifier and the frequency setpoint to the inverter are related by a constant. Thus constant V/f is maintained.

B. *Name two advantages and two disadvantages of a PWM inverter over a square wave inverter.*

Ans: Advantages are simultaneous voltage and frequency control, and control over harmonic content. Disadvantages are complexity of switching law and requirement of fast switching.

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