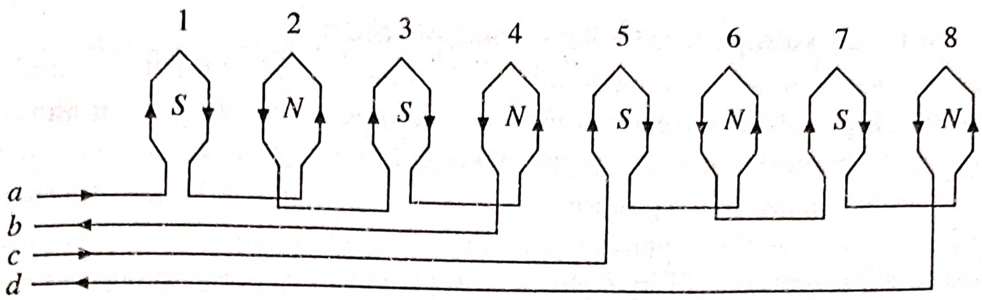
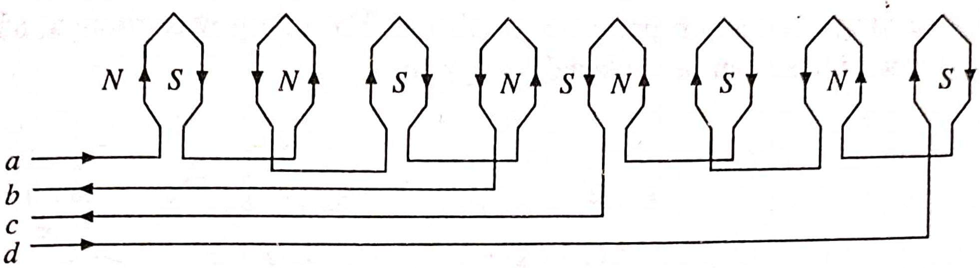


(a) Connection for 8 poles



(b) Connection for 10 poles

Fig. 6.30 Pole amplitude modulation by coil inversion

suffer from harmonic currents and voltages, and have lower power factor and efficiency than pole changing motors described in the earlier section. They find applications in fan, blower and pump drives.

6.11 STATOR VOLTAGE CONTROL

By reducing stator voltage, speed of a high-slip induction motor can be reduced by an amount which is sufficient for the speed control of some fan and pump drives (Fig. 6.31). While torque is proportional to voltage squared (Eq. (6.10)), current is proportional to voltage (Eq. (6.4)). Therefore, as voltage is reduced to reduce speed, for the same current motor develops lower torque. Consequently, method is suitable for applications where torque demand reduces with speed, which points towards its suitability for fan and pump drives.

If stator copper loss, core loss, and friction and windage loss are ignored, then from eqns (6.5) and (6.7), motor efficiency η is given by

$$\eta = \frac{P_m}{P_g} = (1 - s)$$

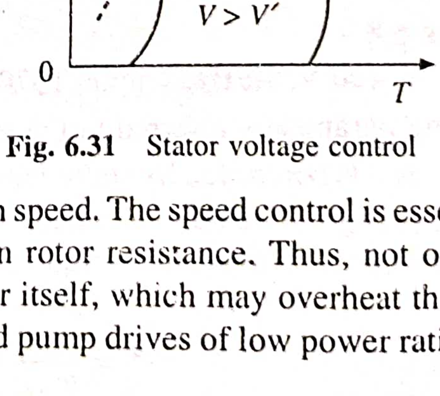


Fig. 6.31 Stator voltage control

The equation shows that the efficiency falls with decrease in speed. The speed control is essentially obtained by dissipating a portion of rotor input power in rotor resistance. Thus, not only the efficiency is low, the power dissipation occurs in the rotor itself, which may overheat the rotor. Because of these reasons, this drive is employed in fan and pump drives of low power rating and for narrow speed range.

Variable voltage for speed control is obtained using ac voltage controllers.

6.11.1 Control by ac Voltage Controllers and Soft Start

Domestic fan motors, which are always single-phase, are controlled by a single-phase triac voltage controller (Fig. 6.32(a)). Speed control is obtained by varying firng angle of the triac. These controllers, commonly known as solid state fan regulators, are now preferred over conventional variable resistance regulators because of higher efficiency. Industrial fans and pumps are usually driven by three-phase motors. Fig. 7.32(b) shows a commonly used thyristor voltage controller for speed control of 3-phase motors. Motor may be connected in star or delta. In delta connection, third harmonic voltage produced by motor back emf causes circulating current through the windings which increases losses and thermal loading of motor. Speed control is obtained by varying conduction period of thyristors. For low power ratings, anti-paralleled thyristor pair in each phase can be replaced by a triac.

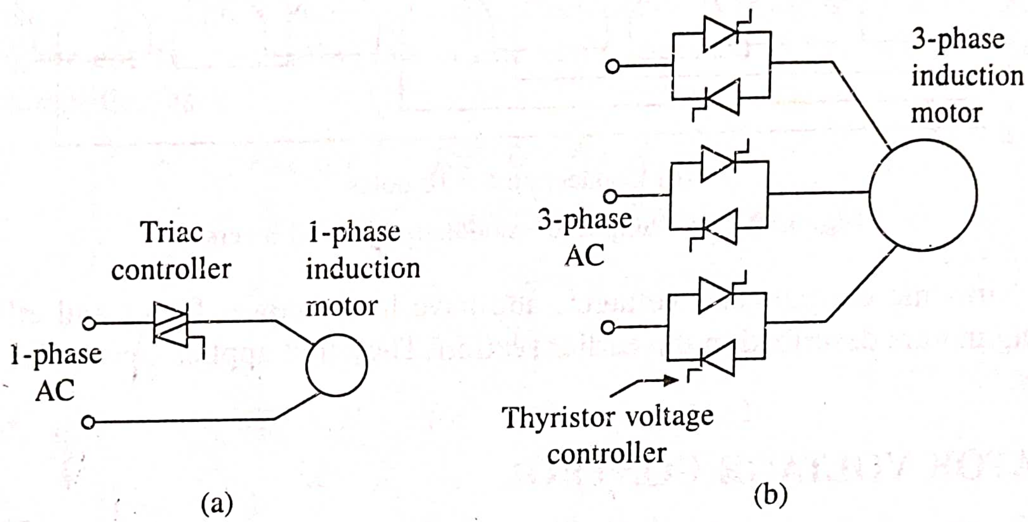


Fig. 6.32 Stator voltage control by semiconductor voltage controler

Since voltage controllers, both single- and three-phase, allow a stepless control of voltage from its zero value, they are also used for soft start of motors.

The power factor of an ac regulator is defined by eqn. (5.109). With increase in firing angle, both distortion factor and displacement factor reduce, giving a low power factor.

In fan and pump drives, the fluid flow has to be maintained constant against variations in pressure head and nature of pumped fluid. Therefore, it is always operated with closed-loop speed control. For closed-loop control, scheme of Fig. 3.5, consisting of inner current loop and outer speed loop is used. Braking is not used because fluid pressure provides adequate braking torque.

EXAMPLE 6.8

A 2.8 kW, 400 V, 50 Hz, 4 pole, 1370 rpm, delta connected squirrel-cage induction motor has following parameters referred to the stator: $R_s = 2\ \Omega$, $R_r' = 5\ \Omega$, $X_s = X_r' = 5\ \Omega$, $X_m = 80\ \Omega$. Motor speed is controlled by stator voltage control. When driving a fan load it runs at rated speed at rated voltage. Calculate (i) motor terminal voltage, current and torque at 1200 rpm and (ii) motor speed, current and torque for the terminal voltage of 300 V.

Solution

$$T = \frac{3}{\omega_{ms}} \times \frac{V^2 R_r'/s}{\left(R_s + \frac{R_r'}{s}\right)^2 + (X_s + X_r')^2}$$

$$\text{Synchronous speed} = \frac{120f}{p} = \frac{120 \times 50}{4} = 1500 \text{ rpm} = 50\,\pi \text{ rad/sec}$$

At full load
$$s = \frac{1500 - 1370}{1500} = 0.0867$$

At full load
$$T = \frac{3}{50\pi} \times \frac{400^2 \times 5/0.0867}{\left(2 + \dfrac{5}{0.0867}\right)^2 + (5+5)^2} = 48.13 \text{ N-m}$$

For a fan load torque is proportional to (speed)^2.

Thus
$$T_L = K(1-s)^2$$

At full load $T = T_L$

$$K(1 - 0.0867)^2 = 48.13$$

or
$$K = 57.7$$

Hence
$$T_L = 57.7(1-s)^2 \tag{i}$$

(i) At 1200 rpm

$$s = \frac{1500 - 1200}{1500} = 0.2$$

At this speed from Eq. (i)
$$T_L = 57.7(1 - 0.2)^2 = 36.9 \text{ N-m}$$

Since $T = T_L$, $T = 36.9$ N-m

$V_L = \sqrt{3} V_{ph}$ Y

$I_L = \sqrt{3} I_{ph}$ Δ

Now
$$\frac{3}{50\pi} \times \frac{V^2 \times 5/0.2}{\left(2 + \dfrac{5}{0.2}\right)^2 + (10)^2} = 36.9$$

which gives $V = 253.2$ V

$$\bar{I}_r' = \frac{253.2}{\left(2 + \dfrac{5}{0.2}\right) + j10} = 8.246 - j3.054$$

$$\bar{I}_m = \frac{V}{jX_m} = \frac{253.2}{j80}$$

$$\bar{I}_s = \bar{I}_r' + \bar{I}_m = 8.246 - j3.054 - j3.165 = 10.328 \angle -37°$$

$$\text{Line current} = \sqrt{3} \times 10.328 = 17.89 \text{ A}$$

(ii) At 300 V

$$T = \frac{3}{50\pi} \times \frac{300^2 \times 5/s}{\left(2 + \dfrac{5}{s}\right)^2 + (10)^2} = \frac{27 \times 10^4\, s}{10\pi(104s^2 + 20s + 25)} \tag{ii}$$

In steady state $T = T_L$. Therefore, from Eqs. (i) and (ii)

$$\frac{27 \times 10^4 s}{10\pi(104s^2 + 20s + 25)} = 57.7(1 - s)^2$$

or

$$104s^4 - 188s^3 + 89s^2 - 179s + 25 = 0$$

which gives $s = 0.147$.

Hence torque produced by the motor

$$T = 57.7\ (1 - 0.147)^2 = 41.94 \text{ N-m}$$

$$\text{Speed} = N_s\ (1 - s) = 1500\ (1 - 0.147) = 1279 \text{ rpm}$$

$$\bar{I}_s = \bar{I}_m + \bar{I}_r' = \frac{300}{j80} + \frac{300}{\left(2 + \dfrac{5}{0.147}\right) + j10} = 9.75 \angle -37.3^\circ$$

$$\text{Line current} = \sqrt{3} \times 9.75 = 16.88 \text{ A}$$

6.12 VARIABLE FREQUENCY CONTROL FROM VOLTAGE SOURCES

6.12.1 Variable Frequency Control of an Induction Motor

Synchronous speed, therefore, the motor speed can be controlled by varying supply frequency. Voltage induced in stator is proportional to the product of supply frequency and air-gap flux. If stator drop is neglected, terminal voltage can be considered proportional to the product of frequency and flux. $V \propto f\phi$

Any reduction in the supply frequency, without a change in the terminal voltage, causes an increase in the air-gap flux. Induction motors are designed to operate at the knee point of the magnetization characteristic to make full use of the magnetic material. Therefore, the increase in flux will saturate the motor. This will increase the magnetizing current, distort the line current and voltage, increase the core loss and the stator copper loss, and produce a high-pitch acoustic noise. While an increase in flux beyond the rated value is undesirable from the consideration of saturation effects, a decrease in flux is also avoided to retain the torque capability of the motor. Therefore, the variable frequency control below the rated frequency is generally carried out at rated air-gap flux by varying terminal voltage with frequency so as to maintain (V/f) ratio constant at the rated value. From Eq. (6.13)

$$T_{max} = \frac{K(V/f)^2}{\dfrac{R_s}{f} \pm \left[\left(\dfrac{R_s}{f}\right)^2 + 4\pi^2 (L_s + L_r')^2\right]^{1/2}} \tag{6.69}$$

where K is a constant, and L_s and L_r' are, respectively, the stator and stator referred rotor inductances. Positive sign is for motoring operation and negative sign is for braking operation.

When frequency is not low, $(R_s/f) << 2\pi(L_s + L_r')$ and therefore, from (6.69)

$$T_{max} = \pm \frac{K(V/f)^2}{2\pi(L_s + L_r')} \tag{6.70}$$

Equation (6.70) suggests that with a constant (V/f) ratio, motor develops a constant maximum torque, except at low speeds (or frequencies). Motor therefore operates in constant torque mode. According to Eq. (6.69), for low frequencies (or low speeds) due to stator resistance drop [i.e. when (R_s/f) is not negligible compared to $2\pi(L_s + L_r')$] the maximum torque will have lower value in motoring operation (+ve sign) and larger value in braking operation (–ve sign). This behavior is due to reduction in flux during motoring operation and increase in flux during braking operation. When it is required that the same maximum torque is retained at low speeds also in motoring operation, (V/f) ratio is increased at low frequencies. This causes further increase in maximum braking torque and considerable saturation of the machine in braking operation.

When either V saturates or reaches rated value at base speed, it cannot be increased with frequency. Therefore, above base speed, frequency is changed with V maintained constant. According to Eq. (6.70), with V maintained constant, maximum torque decreases with increase in frequency (or speed).

Variation in terminal voltage with frequency is therefore as shown in Fig. 6.33(a). V is kept constant above the base speed. Below the base speed (V/f) ratio is maintained constant, except at low frequencies where (V/f) ratio is increased to keep maximum torque constant. Corresponding speed torque curves are shown in Fig. 6.33(b) both for motoring and braking operations. The curves suggest that speed control and braking operation are available from nearly zero speed to above synchronous speed.

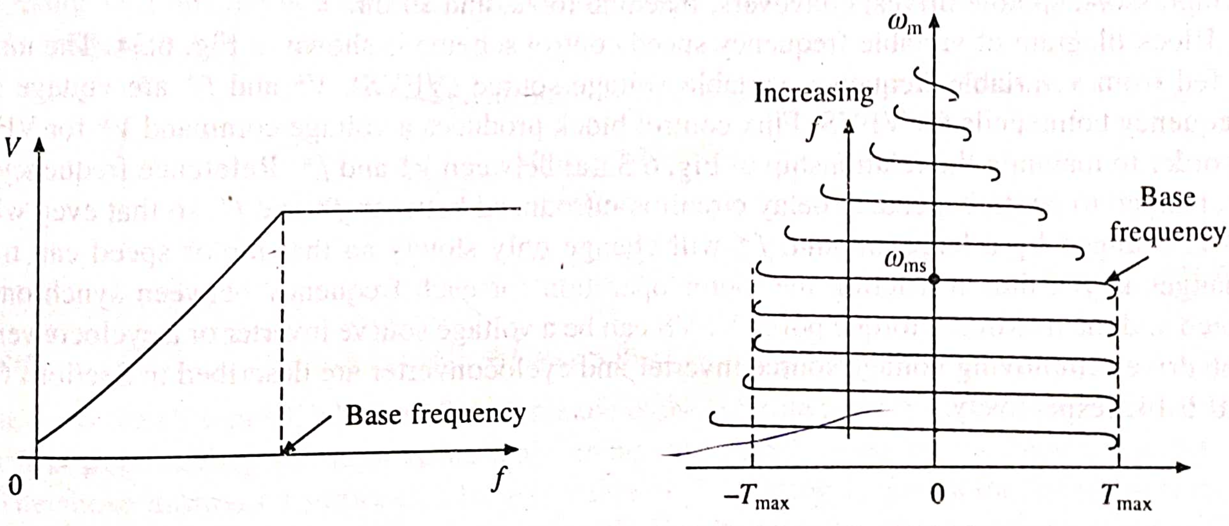


Fig. 6.33 Variable frequency control

A given torque is obtained with a lower current when the operation at any frequency is restricted between the synchronous speed and the maximum torque point, both for motoring and braking operations. Therefore, the motor operation for each frequency is restricted between the synchronous speed and maximum torque point as shown by solid lines in Fig. 6.33(b).

The variable frequency control provides good running and transient performance because of the following features:

(a) Speed control and braking operation are available from zero speed to above base speed.

(b) During transients (starting, braking and speed reversal) the operation can be carried out at the maximum torque with reduced current giving good dynamic response.
(c) Copper losses are low, and efficiency and power factor are high as the operation is restricted between synchronous speed and maximum torque point at all frequencies.
(d) Drop in speed from no load to full load is small.

The most important advantage of variable frequency control is that it allows a variable speed drive with above-mentioned good running and transient performance to be obtained from a squirrel cage induction motor. The squirrel cage motor has a number of advantages over a dc motor. It is cheap, rugged, reliable and longer lasting. Because of the absence of commutator and brushes, it requires practically no maintenance, it can be operated in an explosive and contaminated environment, and can be designed for higher speeds, voltage and power ratings. It also has lower inertia, volume and weight. Though the cost of a squirrel cage motor is much lower compared to that of a dc motor of the same rating, the overall cost of variable frequency induction motor drives, in general are higher. But because of the advantages listed above, variable frequency induction motor drives are preferred over dc motor drives for most applications. In special applications requiring maintenance free operation, such as underground and underwater installations, and also in applications involving explosive and contaminated environments, such as in mines and chemical industry, variable frequency induction motor drives are a natural choice. They have several other applications such as traction, mill run out tables, steel mills, pumps, fans, blowers, compressors, spindle drives, conveyers, machine tools, and so on.

Block diagram of variable frequency speed control scheme is shown in Fig. 6.34. The motor is fed from a variable frequency variable voltage source (VFVS). V^* and f^* are voltage and frequency commands for VFVS. Flux control block produces a voltage command V^* for VFVS in order to maintain the relationship of Fig. 6.33(a) between V^* and f^*. Reference frequency f^* is changed to control speed. A delay circuit is introduced between f^* and f^r, so that even when f^* is changed by a large amount, f^* will change only slowly so that motor speed can track changes in f^*, thus restricting the motor operation for each frequency between synchronous speed and the maximum torque point. VFVS can be a voltage sourve inverter or a cycloconverter. The drives employing voltage source inverter and cycloconverter are described in Sections 6.13 and 6.14, respectively.

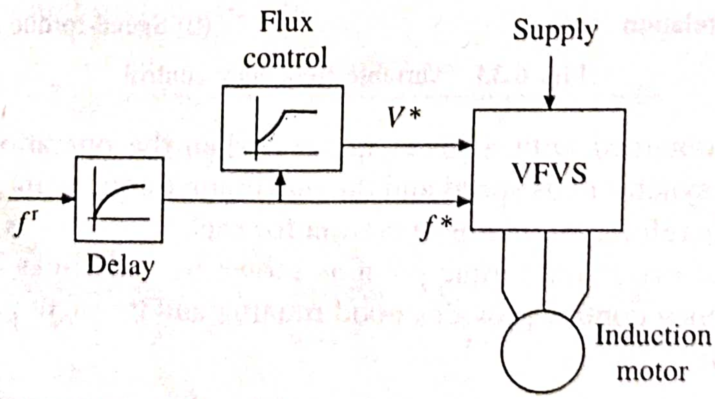


Fig. 6.34 Variable frequency control

6.12.2 Slip Speed Control

Let V and f denote the rated voltage and frequency of the machine. When the motor is operated below the base speed with constant (V/f) control, for a frequency, kf, the terminal voltage will be kV, where k is a factor such that, $0 \le k \le 1$. Thus, as frequency is changed from 0 to f, k changes from 0 to 1 and voltage changes from 0 to V.

Substituting for voltage kV and for frequency kf and neglecting stator resistance drop, from Eqs. (6.4) and (6.10)

$$I_r = \frac{V}{\sqrt{(R_r'/ks)^2 + (X_s + X_r')^2}} \tag{6.71}$$

$$T = \frac{3}{\omega_{ms}}\left[\frac{V^2 R_r'/ks}{(R_r'/ks)^2 + (X_s + X_r')^2}\right] \tag{6.72}$$

In Eqs. (6.71) and (6.72) if (ks) is maintained constant as k is varied, then rotor current I_r' and torque T will remain constant. Since the slip is small I_r' will be in phase with voltage. Since flux is constant I_m will also be constant. Now

$$I_s = \sqrt{I_r' + I_m^2} = \text{constant}$$

Thus if the motor operation is carried out at constant value of ks as the frequency is varied then the motor will operate at a constant current and torque. Let us examine the meaning of ks.

At frequency kf,

$$\text{Synchronous speed} = k\omega_{ms}$$

$$\text{Slip } s = \frac{k\omega_{ms} - \omega_m}{k\omega_{ms}}$$

and

$$ks = \frac{k\omega_{ms} - \omega_m}{\omega_{ms}} = \frac{\omega_{sl}}{\omega_{ms}} \tag{6.73}$$

where

$$\omega_{sl} = k\omega_{ms} - \omega_m \tag{6.74}$$

Note ω_{sl} is the slip speed, which is the difference in the rotating field speed $k\omega_{ms}$ and rotor speed ω_m. It is also the drop in motor speed from its no load speed, when the machine is loaded.

The above discussion shows that for any value of T, the drop in the motor speed from its no load speed $(k\omega_{ms})$ is the same for all frequencies. Hence, machine speed torque characteristics for $0 < s < s_m$ are approximately parallel curves.

Operation of the machine at a constant slip speed also implies the operation at a constant rotor frequency as shown below

$$ks = \frac{(kf)s}{f} = \frac{f_r}{f} = \frac{\omega_r}{\omega} \tag{6.75}$$

where f_r and ω_r are rotor frequency in Hz and rad/sec, respectively.

For $s < s_m$, $(R_r'/sk) >> (X_s + X_r')$, hence from Eqs. (6.72) and (6.73)

$$T = \frac{3V^2}{R_r'\omega_{ms}}(ks) = \text{constant} \cdot \omega_{sl} \tag{6.76}$$

Eqn. (6.76) suggests that for $s < s_m$, the speed torque curves are nearly straight lines. Since they are also parallel, the speed-torque curves are approximately parallel straight lines for $s < s_m$.

According to above discussion, for a gives slip speed, motor current and torque have same values at all frequencies. Thus, motor current and torque can be controlled by controlling the slip speed. Further the motor current can be restricted within a safe limit by limiting the slip speed. This behavior is utilized in closed loop speed control for limiting the current within a permissible limit.

Let us next consider the operation above base speed. As stated earlier, machine operates at a constant voltage V. Now

$$I'_r = \frac{V}{\sqrt{\left(R_s + \frac{R'_r}{s}\right)^2 + k^2(X_s + X'_r)^2}}$$

As the frequency is higher than the rated $k > 1$. Since the operation is again constrained between the synchronous speed and the maximum torque, slip has a small value, hence

$$I'_r = \frac{sV}{R'_r} = \frac{V}{R'_r}\left(\frac{k\omega_{ms} - \omega_m}{k\omega_{ms}}\right)$$

or

$$(k\omega_{ms} - \omega_m) = \omega_{sl} = \frac{R'_r}{V}\omega_{ms}(kI'_r)$$

Thus for speeds above the base speed, at a given I'_r and hence approximately at a given I_s, the slip speed ω_{sl} increases linearly with k (or frequency). This behavior is utilized in closed-loop speed control for limiting the current within permissible value above base speed.

Since the slip is small, I'_r is in phase with V. If the machine copper loss is neglected, the developed power P_m is given by

$$P_m = 3VI'_r$$

Consequently, P_m is constant for a given I'_r, and therefore for a given I_s. The drive, therefore, operates in constant power mode.

6.12.3 Torque and Power Limitations, and Modes of Operation

The torque and power variations for a given stator current and for frequencies below and above the rated frequency are shown by dots in Fig. 6.35. When the stator current has the maximum permissible value, these will represent the maximum torque and power capabilities of the motor in variable frequency control. Variation of maximum torque and power capabilities with frequency are shown in Fig. 6.36. Variation of slip speed ω_{sl} with frequency is also shown in this figure.

As seen in Figs. 6.35 and 6.36, the motor has a constant maximum torque from zero to base speed ω_{mb}, hence the drive operates in constant torque mode. In this frequency range, V is changed with frequency as shown in Fig. 6.33(a) and the slip speed at the maximum permissible current remains constant. From base speed to speed ω_{mc}, the maximum power has a constant value, hence the motor operates in constant power mode. At speed ω_{mc} (Fig. 6.35), the breakdown torque is reached. Any attempt to operate the motor at the maximum permissible current beyond this speed will stall the motor. Hence, beyond the speed ω_{mc}, the machine is operated at a constant slip speed and the maximum permissible current and maximum power are allowed to

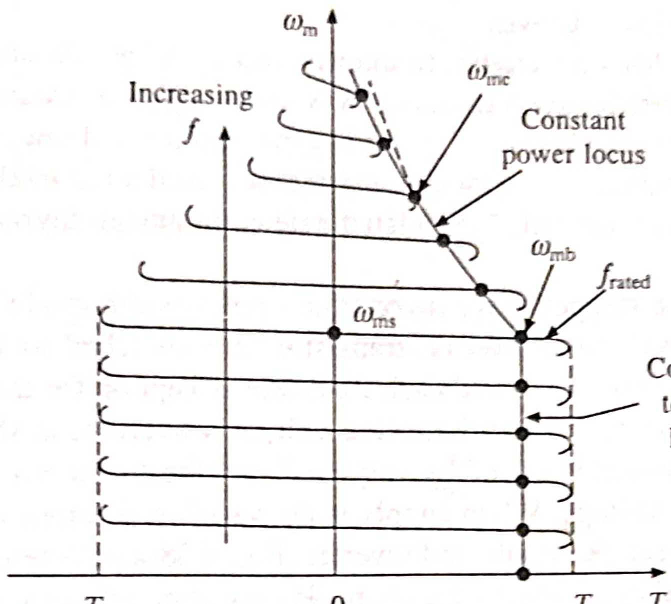


Fig. 6.35 Modes of operation and torque and power limits

decrease (Fig. 6.36). Now the motor current reduces inversely with speed and torque decreases inversely as the speed squared. The operation in this region is required in drives requiring wide speed range but low torque at high speeds. For example in traction applications the drive operates in this region when running at full speed because the torque required in steady state at high speeds is very small compared to its value during acceleration.

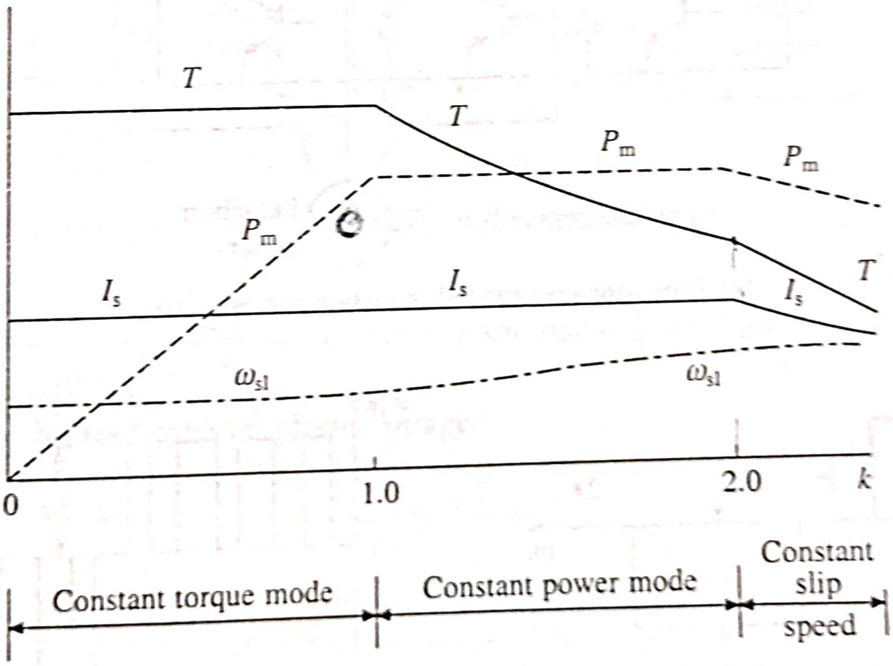


Fig. 6.36 Modes of operation and variations of I_s, ω_{sl}, T and P_m with per unit frequency k

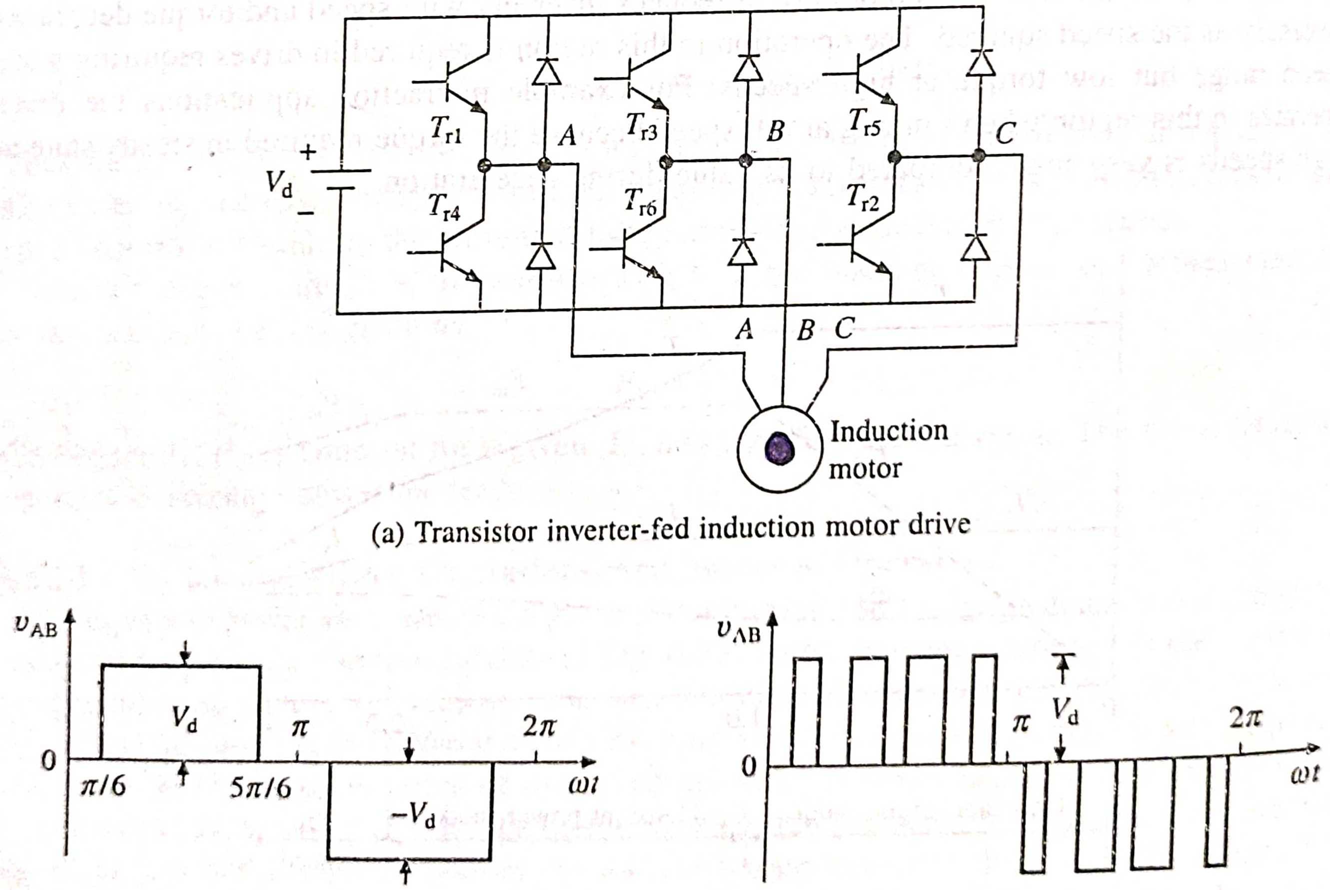
6.13 VOLTAGE SOURCE INVERTER (VSI) CONTROL

Variable frequency and variable voltage supply for induction motor control can be obtained either from a voltage sourve inverter (VSI) or a cycloconverter. VSI fed induction motor drives are described here and cycloconverter fed drives are described in Sec. 6.14.

6.13.1 VSI Induction Motor Drives

Voltage sourve inverter allows a variable frequency supply to be obtained from a dc supply. Fig. 6.37(a) shows a VSI employing transistors. Any other self-commutated device can be used instead of a transistor. Generally MOSFET is used in low voltage and low power inverters, IGBT (insulated gate bipolar transistor) and power transistors are used up to medium power levels and GTO (gate turn off thyristor) and IGCT (insulated gate commutated thyristor) are used for high power levels.

VSI can be operated as a stepped wave inverter or a pulse-width modulated (PWM) inverter. When operated as a stepped wave inverter, transistors are switched in the sequence of their numbers with a time difference of $T/6$ and each transistor is kept on for the duration $T/2$, where T is the time period for one cycle. Resultant line voltage waveform is shown in Fig. 6.37(b). Frequency of inverter operation is varied by varying T and the output voltage of the inverter is varied by varying dc input voltage. When supply is dc, variable dc input voltage is obtained by connecting a chopper between dc supply and inverter (Fig. 6.38(a)). When supply is ac, variable dc input voltage is obtained by connecting a controlled rectifier between ac supply and inverter (Fig. 6.38(b)). A large electrolytic filter capacitor C is connected in dc link to make inverter operation independent of rectifier or chopper and to filter out harmonics in dc link voltage.



(a) Transistor inverter-fed induction motor drive

(b) Stepped wave inverter line voltage waveform

(c) PWM inverter line voltage waveform

Fig. 6.37 VSI fed induction motor drives:

Inverter output line and phase voltages are given by the following Fourier series:

$$V_{AB} = \frac{2\sqrt{3}}{\pi} V_d \left[\sin \omega t - \frac{1}{5} \sin 5\omega t - \frac{1}{7} \sin 7\,\omega t + \frac{1}{11} \sin 11\omega t + \frac{1}{13} \sin 13\,\omega t \ldots \right] \quad (6.77)$$

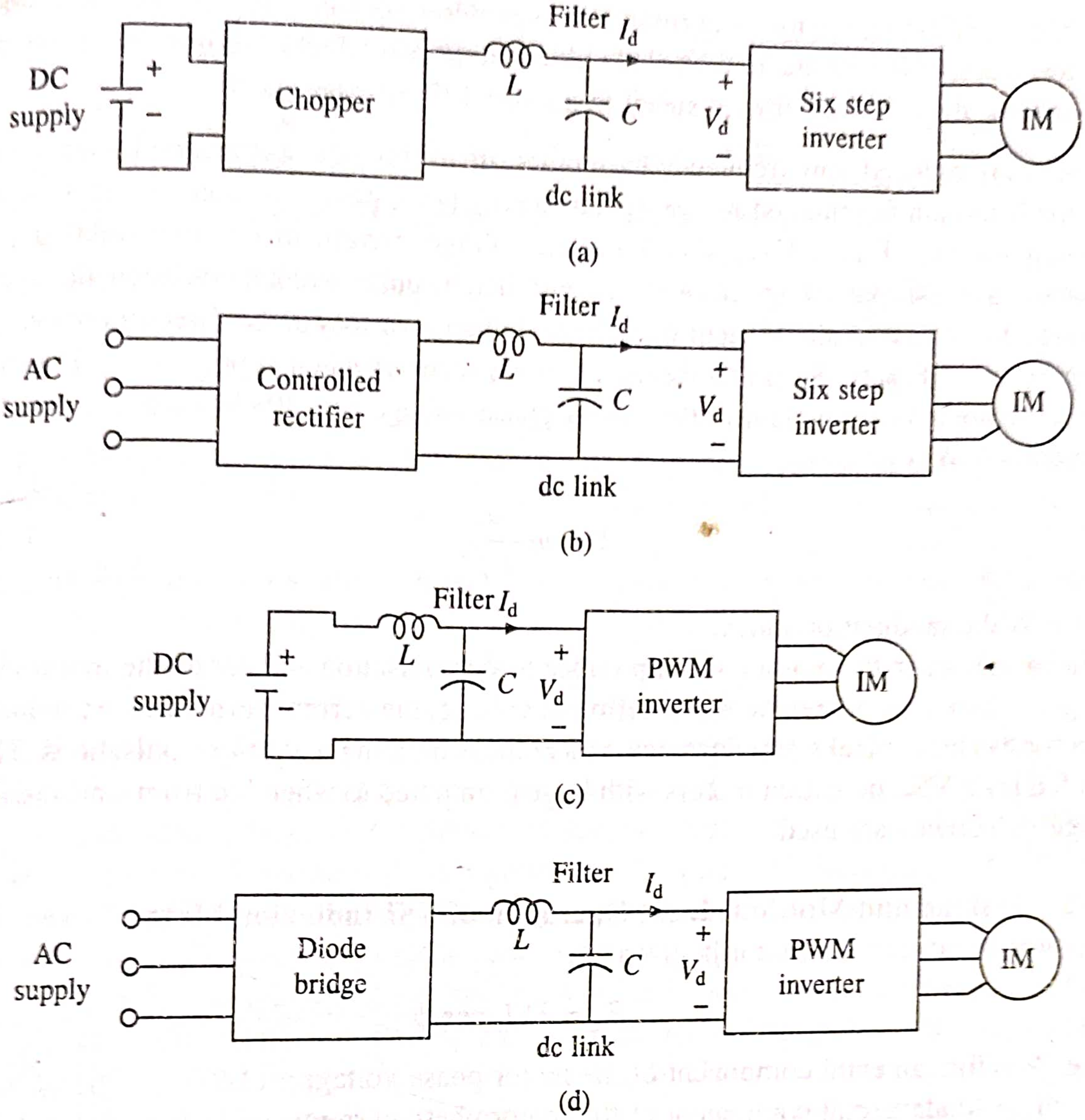


Fig. 6.38 VSI controlled IM drives

$$V_{AN} = \frac{2}{\pi} V_d \left[\sin \omega t + \frac{1}{5} \sin 5\omega t + \frac{1}{7} \sin 7 \omega t \right] \tag{6.78}$$

The rms value of the fundamental phase voltage

$$V = \frac{\sqrt{2}}{\pi} V_d \tag{6.79}$$

The torque for a given speed can be calculated by considering only fundamental component as explained in Sec. 6.4. The main drawback of stepped wave inverter is the large harmonics of low frequency in the output voltage. Consequently, an induction motor drive fed from a stepped wave inverter suffers from the following drawbacks:

(a) Because of low frequency harmonics, the motor losses are increased at all speeds causing derating of the motor.
(b) Motor develops pulsating torques due to fifth, seventh, eleventh and thirteenth harmonics which cause jerky motion of the rotor at low speeds as explained in Sec. 6.4.

(c) Harmonic content in motor current increases at low speeds. The machine saturates at light loads at low speeds due to high (V/f) ratio. These two effects overheat the machine at low speeds, thus limiting lowest speed to around 40% of base speed.

Harmonics are reduced, low frequency harmonics are eliminated, associated losses are reduced and smooth motion is obtained at low speeds also when inverter is operated as a pulse-width modulated inverter. Fig. 6.37(c) shows output voltage waveform for sinusoidal pulse-width modulation. Since output voltage can now be controlled by pulse-width modulation, no arrangement is required for the variation of input dc voltage, hence inverter can be directly connected when the supply is dc [Fig. 6.38(c)] and through a diode rectifier when supply is ac. [Fig. 6.38(d)].

The fundamental component in the output phase voltage of a PWM inverter operating with sinusoidal PWM is given by

$$V = m\frac{V_d}{2\sqrt{2}} \tag{6.80}$$

where m is the modulation index.

The harmonics in the motor current produce torque pulsation and derate the motor (Sec. 6.4). For a given harmonic content in motor terminal voltage, the current harmonics are reduced when the motor has higher leakage inductance, this reduces derating and torque pulsations. Therefore, when fed from VSI, induction motors with large (compared to when fed from sinusoidal supply) leakage inductance are used.

6.13.2 Braking and Multiquadrant Operation of VSI Induction Motor Drives

The power input into the motor is given by

$$P_{in} = 3VI_s \cos \phi$$

where V = fundamental component of the motor phase voltage
I_s = fundamental component of the motor phase current
ϕ = phase angle between V and I_s.

In motoring operation $\phi < 90°$, therefore P_{in} is positive i.e. power flows from the inverter to the machine. A reduction in frequency makes the synchronous speed less than the rotor speed and the relative speed between the rotor conductors and air-gap rotating field reverses. This reverses the rotor induced emf, rotor current and component of stator current which balances the rotor ampere turns. Consequently, angle ϕ becomes greater than 90° and power flow reverses. The machine works as a generator feeding power into the inverter, which in turn feeds power into dc link by reversing the dc link current I_d. Regenerative braking is obtained when the power flowing from the inverter to the dc link is usefully employed and dynamic braking is obtained when it is wasted in a resistance.

Dynamic Braking Let us first consider the dynamic braking of pulse-width modulated inverter drive of Fig. 6.38(d). With dynamic braking the drive will be as shown in Fig. 6.39. For dynamic braking, switch SW and a self-commutated switch (here transistor) in series with braking resistance R_B connected across the dc link are added to the drive of Fig. 6.38(d). When operation of the motor is shifted from motoring to braking switch SW is opened. Generated energy flowing into

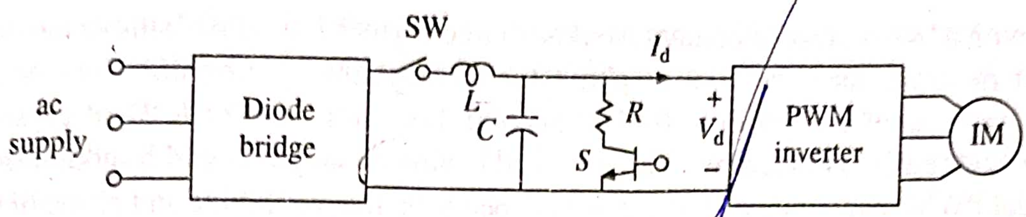


Fig. 6.39 Dynamic braking of VSI controlled IM drives

the dc link charges the capacitor and its voltages rises. When it crosses a set value, switch S is closed, connecting the resistance across the link. The generated power and a part of energy stored in the capacitor flow into the resistance, and dc link voltage reduces. When it falls to its nominal value, S is opened. Thus by closing and opening switch S based on the value of dc link voltage, generated energy is dissipated in the resistance, giving dynamic braking. The dynamic braking operation of the drives of Figs. 6.38(a) to (c) can be obtained similarly.

Regenerative Braking: Let us first consider the regenerative braking of pulse-width modulated (PWM) inverter drives of Figs. 6.38(c) and (d). In the drive of Fig. 6.38(c) when machine operation shifts from motoring to braking, I_d reverses and flows into the dc supply feeding the energy to the source. Thus, the drive of Fig. 6.38(c) already has regenerative braking capability. In the case of the drive of Fig. 6.38(d), for regenerative braking, the power supplied to the dc link must be transferred to the ac supply. When the operation shifts from motoring to braking I_d reverses but V_d remains in the same direction. Thus for regenerative braking capability, a converter capable of dealing with dc voltage of one polarity and dc current of either direction is required. A dual converter has this capability and was employed in the past. The recent drives use synchronous link converter (SLC) because it takes sinusoidal current at unity power factor from the ac source, both during motoring and braking operations. Thus while its performance is superior, it requires less devices than a dual converter. Principle of its operation is explained here. A regenerative drive with a SLC and PWM inverter is shown in Fig. 6.40. The inductors L_s and PWM inverter I constitute a SLC. PWM inverter I is operated to produce voltage V_I of required magnitude and

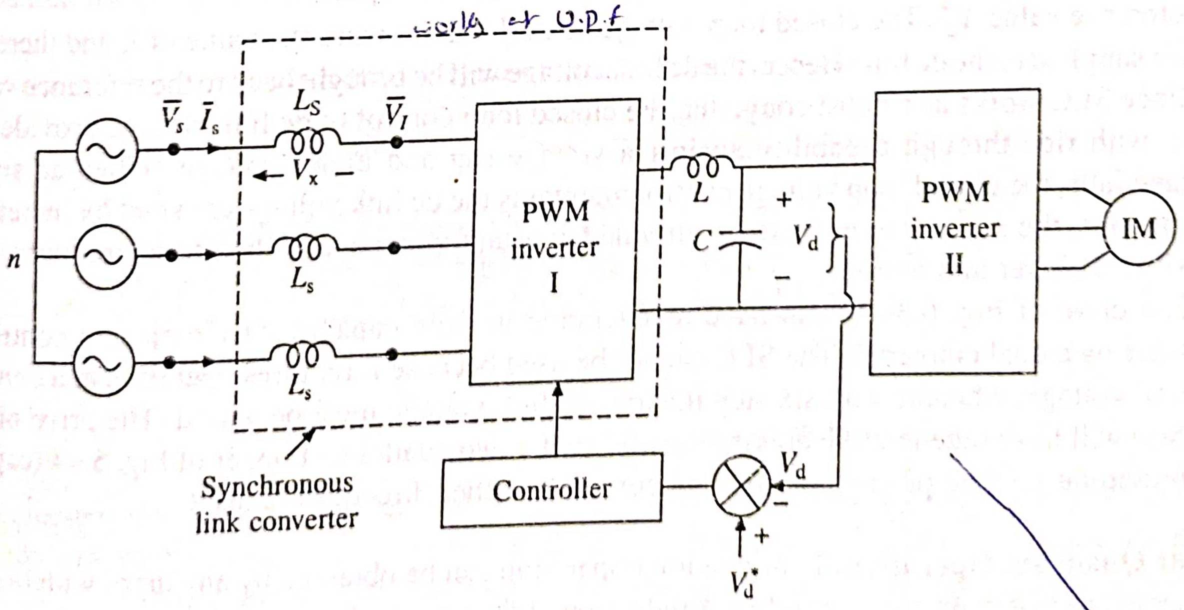
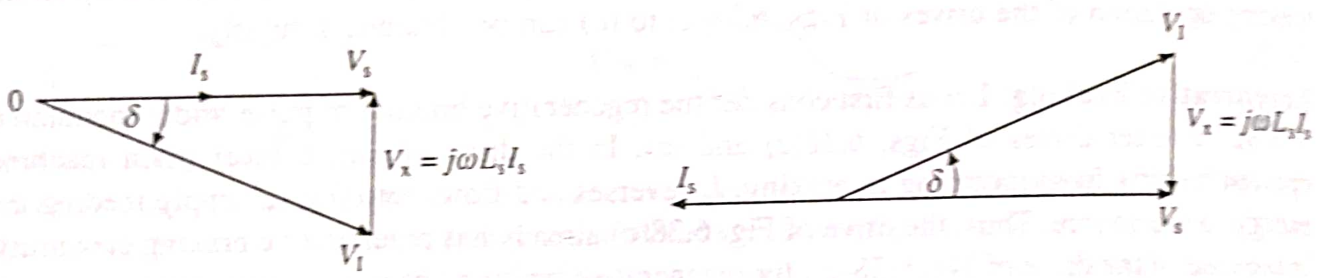


Fig. 6.40 VSI IM drive with regenerative braking capability (SLC fed PWM inverter IM drive)

phase and with a low harmonic content, so that source current I_s is nearly sinusoidal and in phase with V_s for motoring and 180° out of phase for braking, thus giving unity power factor. The phasor diagrams are shown in Figs. 6.41(a) and (b). For each value of I_s, V_I of given phase and magnitude is required. This can be easily realized in sinusoidal pulse-width modulation (PWM). In sinusoidal PWM magnitude and phase of V_I depends on the magnitude and phase of modulation signal [1]. Therefore, V_I of given phase and magnitude can be produced by producing modulating signal of required magnitude and phase. Since V_I is produced by PWM inverter, it does not contain low frequency harmonics. The inductor L_s filters out high frequency harmonics to produce a nearly sinusoidal source current I_s. The phasor diagrams of Fig. 6.41 are similar to that of a synchronous machine. Thus behavior of synchronous link converter is similar to that of a synchronous machine, hence it is called synchronous link converter.



(a) Motoring operation

(b) Braking operation

Fig. 6.41 Phasor diagrams of synchronous link converter

When the drive of Fig. 6.40 is operating in steady state, power supplied (taken) by SLC must be equal to power taken (supplied) by PWM inverter II. Since the two work independent of each other, this is achieved by providing closed loop control of the dc link voltage. When the power supplied by SLC to the dc link equals the power taken by PWM inverter II, no energy will be supplied or taken from the capacitor C and its voltage will be constant and equal to the reference value V_d^*. If now the load on IM is increased, power taken by PWM inverter II from the dc link will be higher than the power supplied by the SLC. Hence, the capacitor voltage V_d will fall below its reference value V_d^*. The closed loop voltage control will increase the value of I_s and therefore power supplied to the dc link. Hence, the dc link voltage will be brought back to the reference value.

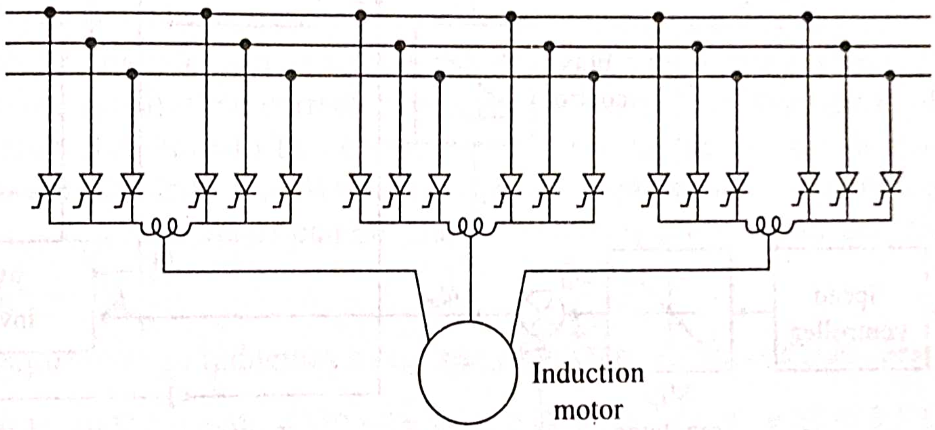
Since SLC works as a boost converter, the closed loop control of dc link voltage provides the drive with ride through capability against a voltage sag and under voltage. When ac source voltage falls, the closed loop voltage control maintains the dc link voltage constant by increasing I_s, and thus, the motor continues to be provided constant voltage, and therefore, produces same maximum power and torque.

The drive of Fig. 6.38(b) can have regenerative braking capability by replacing controlled rectifier by a dual converter. The SLC cannot be used because it requires operation at a constant dc link voltage, whereas with six step inverter dc link voltage must be varied. The drive of Fig. 6.38(a) will have regenerative braking capability if a two quadrant chopper of Fig. 5.44 (capable of providing voltage of one polarity and current in either direction) is used.

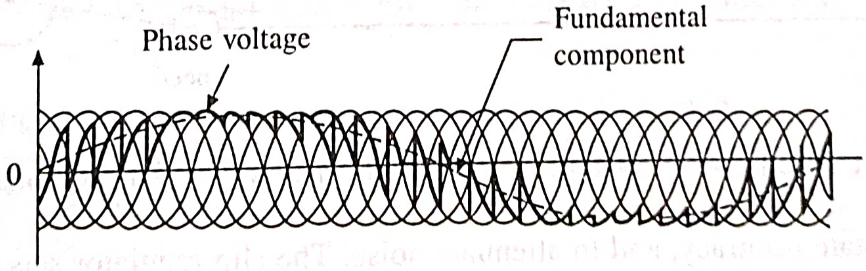
Four Quadrant Operation: Four quadrant operation can be obtained by any drive with braking (regenerative or dynamic) capability. A reduction of the inverter frequency, to make synchronous speed less than the motor speed, transfers the operation from quadrant I (forward motoring) to II (forward braking). The inverter frequency and voltage are progressively reduced as speed falls to brake the machine up to zero speed. Now phase sequence of the inverter output voltage is reversed by interchanging the firing pulses between the switches of any two legs of the inverter, for example, between the pairs (T_{r1}, T_{r4}) and (T_{r3} and T_{r6}) in Fig. 6.37(a). This transfers the operation to quadrant III (reverse motoring). The inverter frequency and voltage are increased to get the required speed in the reverse direction.

6.14 CYCLOCONVERTER CONTROL

Cycloconverter allows variable frequency and variable voltage supply to be obtained from a fixed voltage and frequency ac supply. A half-wave cycloconverter is shown in Fig. 6.42 along with the nature of its output voltage waveform. Because of low harmonic content when operating at low frequencies, smooth motion is obtained at low speeds. Harmonic content increases with frequency, making it necessary to limit the maximum output frequency to 40% of the source frequency. Thus, maximum speed is restricted to 40% of synchronous speed at the mains frequency. A motor with large leakage inductance is used in order to minimize derating and torque pulsations due to harmonics in motor current. The drives has regenerative braking capability. Full four-quadrant operation is obtained by reversing the phase sequence of motor terminal voltage. Since cycloconverter employs large number of thyristors, it becomes economically acceptable only in large power drives.



(a) Half wave cycloconverter-fed induction motor



(b) Phase voltage waveform

Fig. 6.42 Cycloconverter controlled induction motor drive

Cycloconverter drive has applications in high power drives requiring good dynamic response but only low speed operation e.g. in ball mill in a cement plant. The low speed operation is obtained by feeding a motor with large pole numbers from a cycloconverter operating at low frequencies. These drives are called gearless drives because, unlike conventional drives, the low speed operation of load is obtained without a reduction gear, thus eliminating the associated cost, space and maintenance.

6.15 CLOSED-LOOP SPEED CONTROL AND CONVERTER RATING FOR VSI AND CYCLOCONVERTER INDUCTION MOTOR DRIVES

A closed-loop speed controlled drive is shown in Fig. 6.43. It is similar to the drive of Fig. 3.5. It employs inner slip-speed loop with a slip limiter and outer speed loop. Since for a given current, slip speed has a fixed value, the slip speed loop also functions as an inner current loop. Further it also ensures that the motor operation always occurs on the portion of speed-torque curve between synchronous speed and the speed at the maximum torque for all frequencies, thus ensuring high torque to current ratio as explained in Sec. 6.12. The drive uses a PWM inverter fed from a dc source, which has capability for regenerative braking and four-quadrant operation. The drive scheme is however applicable to any VSI or cycloconverter drive having regenerative or dynamic braking capability. The drive operation is explained below.

The speed error is processed through a PI controller and a slip regulator. PI controller is used

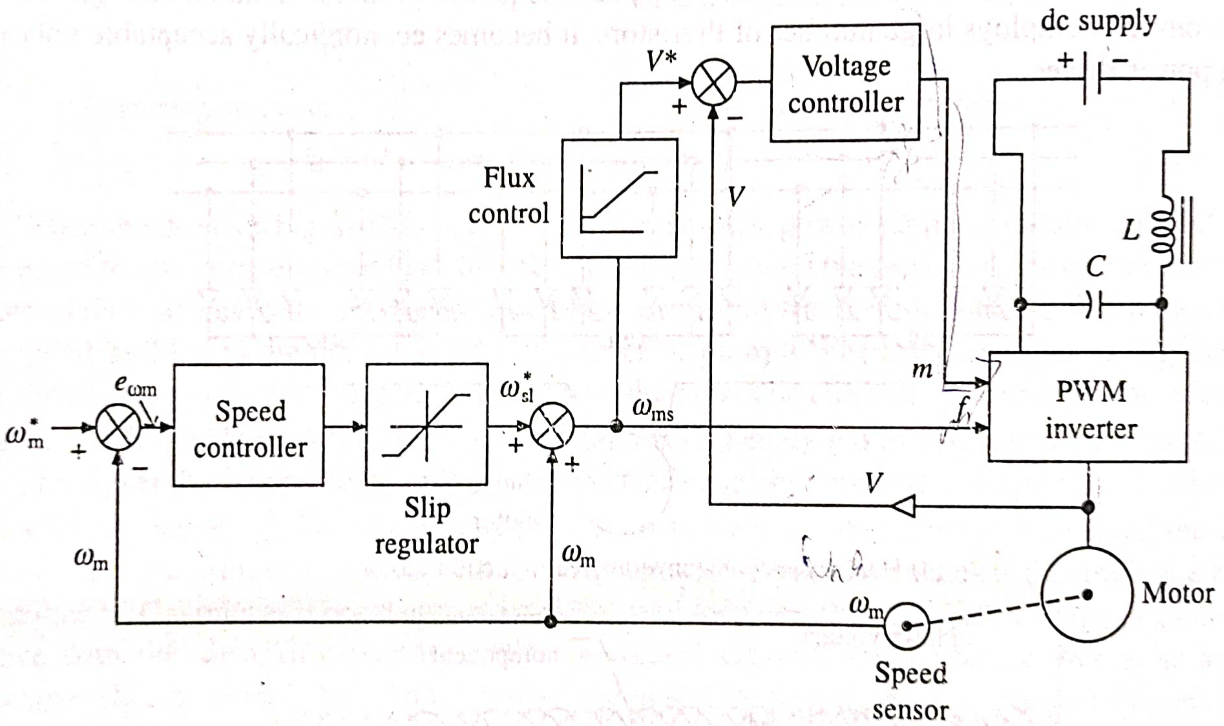


Fig. 6.43 Closed-loop slip controlled PWM inverter drive with regenerative braking

to get good steady-state accuracy, and to attenuate noise. The slip regulator sets the slip speed command ω_{sl}^*, whose maximum value is limited to limit the inverter current to a permissible value. The synchronous speed, obtained by adding actual speed ω_m and slip speed ω_{sl}^*, determines the inverter frequency. The reference signal for the closed-loop control of the machine terminal voltage V^* is generated from frequency f using a function generator. It ensures nearly a constant flux operation up to base speed and the operation at a constant terminal voltage above base speed.

A step increase in speed command ω_m^* produces a positive speed error. The slip speed command ω_{sl}^* is set at the maximum value. The drive accelerates at the maximum permissible inverter current, producing the maximum available torque, until the speed error is reduced to a small value. The drive finally settles at a slip speed for which the motor torque balances the load torque.

A step decrease in speed command produces a negative speed error. The slip speed command is set at the maximum negative value. The drive decelerates under regenerative braking, at the maximum permissible current and the maximum available braking torque, until the speed error is reduced to a small value. Now the operation shifts to motoring and the drive settles at the slip speed for which the motor torque equals the load torque.

The drive has fast response because the speed error is corrected at the maximum available torque. Direct control of slip assures stable operation under all operating conditions.

For operation beyond the base speed, as explained at the beginning of Sec. 6.12, the slip speed limit of the slip regulator must be increased linearly with the frequency until the breakdown value is reached. This is achieved by adding to the slip regulator output an additional slip speed signal, proportional to frequency and of appropriate sign. For frequencies higher than the frequency for which the breakdown torque is reached, the slip speed limit is kept fixed near the breakdown value.

When fast response is required the maximum slip can be allowed to be equal to s_m, because induction motors can be allowed to carry several times the rated current during transient operations of short duration. The inverter and its front end converter are built using semiconductor devices whose transient and steady-state current ratings are the same. Then the ratings of inverter and front end converter will have to be chosen several time the motor current rating. This will substantially increase the drive cost. When fast transient response is not required, current ratings of inverter and front end converter can be chosen to be marginally higher than that of motor.

Example 6.9

A Y-connected squirrel-cage induction motor has following ratings and parameters:

$$400 \text{ V}, 50 \text{ Hz}, 4\text{-pole}, 1370 \text{ rpm}, R_s = 2\,\Omega, R_r' = 3\,\Omega, X_s = X_r' = 3.5\,\Omega$$

Motor is controlled by a voltage source inverter at constant *V/f* ratio. Inverter allows frequency variation from 10 to 50 Hz.

(i) Obtain a plot between the breakdown torque and frequency.

(ii) Calculate starting torque and current of this drive as a ratio of their values when motor is started at rated voltage and frequency.

Solution

$$\omega_{ms} = 50\pi$$

From Eq. (6.13), for a frequency K times the rated frequency and with *V/f* ratio constant

$$T_{max} = \frac{3}{2K\omega_{ms}} \times \left[\frac{K^2V^2}{R_s + \sqrt{R_s^2 + K^2(X_s + X_r')^2}}\right]$$

$$= \frac{3}{2\omega_{ms}} \times \frac{V^2}{(R_s/K) + \sqrt{(R_s/K)^2 + (X_s + X_r')^2}}$$

Substitution of values of parameters gives

$$T_{max} = \frac{509.296}{(2/K) + \sqrt{(2/K)^2 + 49}} \quad (1)$$

From Eq. (1), values of T_{max} can be calculated for various values of frequency. These results are tabulated below:

K	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
f, Hz	50	45	40	35	30	25	20	15	10
T_{max}, N-m	54.88	53.24	51.24	48.89	45.94	42.22	37.44	31.18	22.93

A plot between T_{max} and f is given in Fig. E.6.9 which shows that for a constant (V/f) ratio, breakdown torque decreases with frequency.

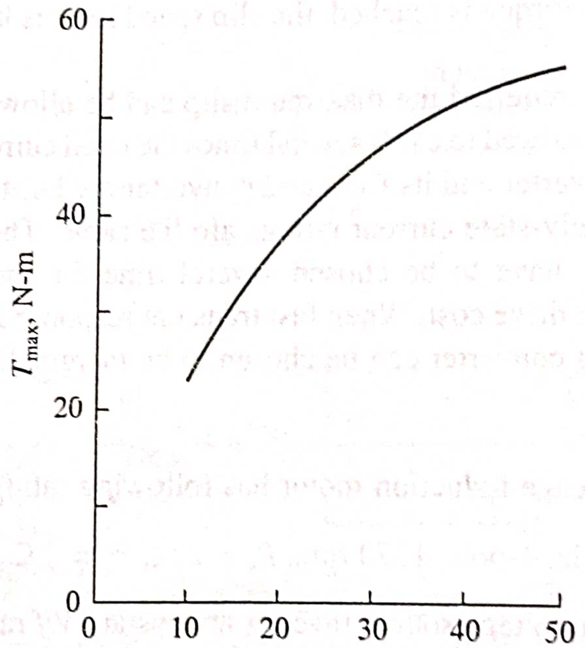


Fig. E.6.9

(ii) Since the minimum frequency available is 10 Hz, motor will have to be started at 10 Hz. From Eq. (6.10) starting torque is given by

$$T_{st} = \frac{3}{\omega_{ms}}\left[\frac{V^2 R_r'}{(R_s + R_r')^2 + (X_s + X_r')^2}\right] \quad (2)$$

At 50 Hz
$$T_{st} = \frac{3}{50\pi}\left[\frac{(400/\sqrt{3})^2 \times 3}{(2+3)^2 + (3.5+3.5)^2}\right] = 41.29 \text{ N-m}$$

Starting current
$$I_{st} = \frac{V}{\sqrt{(R_s + R_r')^2 + (X_s + X_r')^2}} \tag{3}$$

$$= \frac{400/\sqrt{3}}{\sqrt{(5)^2 + (7)^2}} = 26.85 \text{ A}$$

With variable frequency control and constant *V/f* ratio; for frequency *K* times rated, from Eq. (2)

$$T_{st}' = \frac{3}{\omega_{ms}} \times \frac{V^2 R_r'/K}{\left[\left(\frac{R_s + R_r'}{K}\right)^2 + (X_s + X_r')^2\right]} \tag{4}$$

Similarly from (3)
$$I_{st}' = \frac{V}{\sqrt{\left(\frac{R_s + R_r'}{K}\right)^2 + (X_s + X_r')^2}} \tag{5}$$

for 10 Hz, $K = 10/50 = 0.2$.

Substitution in Eqs. (4) and (5) gives

$$T_{st}' = \frac{3}{50\pi} \times \frac{(400/\sqrt{3})^2 \times 3/0.2}{\left[\left(\frac{5}{0.2}\right)^2 + 7^2\right]} = 22.67 \text{ N-m}$$

$$I_{st}' = \frac{400/\sqrt{3}}{\sqrt{\left(\frac{5}{0.2}\right)^2 + 7^2}} = 8.895 \text{ A}$$

Now
$$\frac{T_{st}'}{T_{st}} = \frac{22.67}{41.29} = 0.549$$

$$\frac{I_{st}'}{I_{st}} = \frac{8.895}{26.85} = 0.33$$

Note, as compared to start at rated frequency, the ratio (torque/current) has increased from 1.54 to 2.55.

Example 6.10

V/f ratio of variable frequency drive of Example 6.9 is controlled to get a constant breakdown torque at all speeds. Lowest frequency of inverter is also extended to 5 Hz. Calculate and plot *V* against *f* and compare with that used in Example 6.9.

Solution

From Eq. (6.13) breakdown torque for a frequency *K* times rated is given by

$$T_{max} = \frac{3}{2K\omega_{max}} \times \frac{V^2}{R_s + \sqrt{R_s^2 + K^2(X_s + X_r')^2}}$$

or
$$V^2 = \frac{2K\omega_{ms}T_{max}}{3}[R_s + \sqrt{R_s^2 + K^2(X_s + X_r')^2}] \tag{1}$$

Substitution of parameter values and value of $T_{max} = 54.88$, as obtained in Example 6.9 for rated operation, gives

$$(\sqrt{3}V)^2 = V_L^2 = 2 \times 50\,\pi \times 54.88\,K\,[3 + \sqrt{4 + 49\,K^2}]$$

$$= 17241\,K\,[2 + \sqrt{4 + 49\,K^2}] \tag{2}$$

Line voltage for various frequencies as calculated from Eq. (2) is:

K	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
f	50	45	40	35	30	25	20	15	10	5
V_L	400	365.5	331	296.7	262.3	228	193.7	159.2	123.7	84.3

These results are plotted in Fig. E.6.10. For constant breakdown torque at all frequencies V/f ratio is to be progressively increased with the decrease in frequency.

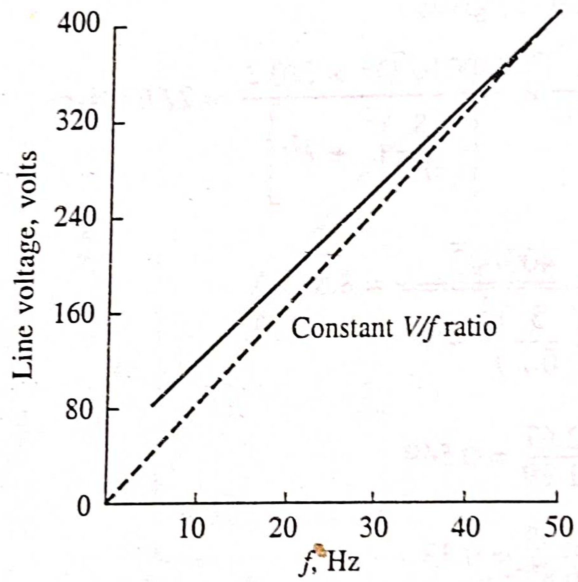


Fig. E.6.10

EXAMPLE 6.11

Calculate approximate values of the following for inverter-fed induction motor drive of Example 6.9:

(i) Speed for a frequency of 30 Hz and 80% of full-load torque.
(ii) Frequency for a speed of 1000 rpm and full-load torque.
(iii) Torque for a frequency of 40 Hz and speed of 1100 rpm.

Solution

Motor speed-torque curves for various frequencies from full-load motoring to full-load braking can be assumed to be parallel straight lines, each passing through corresponding synchronous speed without significant error, as shown in Fig. E.6.11.

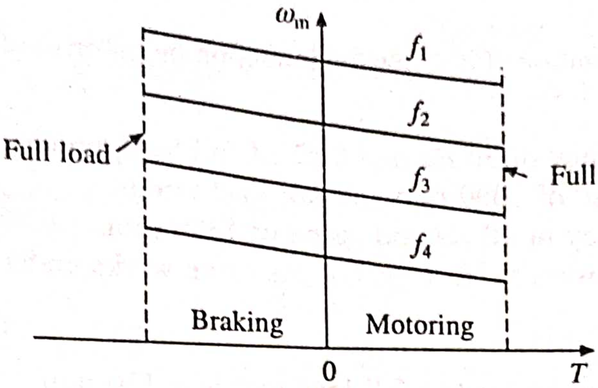


Fig. E6.11

(i) At 50 Hz, drop in speed from no load to full-load torque = 1500 – 1370 = 130 rpm

Drop in speed from no load to 80% of full-load = 130 × 0.8 = 104 rpm

$$\text{Synchronous speed at 30 Hz} = \frac{120f}{p} = \frac{120 \times 30}{40} = 900 \text{ rpm}$$

Therefore, motor speed = 900 – 104 = 796 rpm.

(ii) Drop in speed from no load to full load toruqe = 130 rpm.

Synchronous speed N_s = 1000 + 130 = 1130 rpm

$$f = \frac{pN_s}{120} = \frac{4 \times 1130}{120} = 37.67 \text{ Hz}$$

(iii) At 40 Hz synchronous speed $N_s = \dfrac{120f}{p} = \dfrac{120 \times 40}{4} = 1200$ rpm

Drop in speed from no load to 1100 rpm = 1200 – 1100 = 100 rpm

$$\text{Torque} = \frac{100}{130} T_F = 0.769\, T_F$$

where T_F is the full load torque.

At full load $s = \dfrac{1500 - 1370}{1500} = 0.08667$

$$T_F = \frac{3}{\omega_{ms}} \times \frac{V^2 R_r'/s}{\left(R_s + \dfrac{R_r'}{s}\right)^2 + (X_s + X_r')^2}$$

$$= \frac{3}{50\,\pi} \times \frac{(400/\sqrt{3})^2 \times 3/0.08667}{\left(2 + \dfrac{3}{0.08667}\right)^2 + 7^2} = 25.37 \text{ N-m}$$

Hence torque = $0.769T_F$ = 0.769 × 25.37 = 19.51 N-m

EXAMPLE 6.12

For regenerative braking operation of inverter-fed induction motor drive of Example 6.9, determine approximate values of:

(i) Speed for the frequency of 30 Hz and 80% of full load torque.
(ii) Frequency for a speed of 1000 rpm and full load torque.
(iii) Torque for a frequency of 40 Hz and speed of 1300 rpm.
(iv) What will be the answers to (i) to (iii), if the drive works under dynamic braking?

Solution

(i) Increase in speed from no-load to full load torque = 130 rpm

Increase in speed from no load to 0.8 of full load-torque = 0.8 × 130 = 104 rpm

$$\text{Synchronous speed at } 30 \text{ Hz} = \frac{30}{50} \times 1500 = 900 \text{ rpm}$$

Machine speed = 900 + 104 = 1004 rpm

(ii) Synchronous speed = 1000 – 130 = 870 rpm

$$f = \frac{pN_s}{120} = \frac{4 \times 870}{120} = 29 \text{ Hz}$$

(iii) At 40 Hz synchronous speed

$$N_s = \frac{120f}{p} = \frac{120 \times 40}{120} = 1200 \text{ rpm}$$

Increase in speed from no load speed = 1300 – 1200 = 100 rpm

$$\text{Motor torque} = -\frac{100}{130}T_f = -\frac{100}{130} \times 25.37 = -19.51 \text{ N-m}$$

(iv) In both regenerative and dynamic braking motor works as a generator. The two braking methods of inverter-fed induction motor differ only in the way braking energy is disposed off, in former it is transferred to the source and in latter it is dissipated in a resistor. Hence answers to (i)-(iii) will be the same.

EXAMPLE 6.13

Calculate motor breakdown torque for inverter-fed induction motor drive of Example 6.9 for a frequency of 60 Hz as a ratio of its value at 50 Hz.

Solution

Up to 50 Hz motor operates with a constant V/f ratio and above 50 Hz with constant terminal voltage. Hence at 60 Hz, motor will be operated at a voltage of 400 V. From Eq. (6.13), for a frequency K times the rated and constant terminal voltage.

$$T'_{max} = \frac{3}{2K\omega_{ms}} \times \left[\frac{V^2}{R_s + \sqrt{R_s^2 + K^2(X_s + X'_r)^2}}\right]$$

At 60 Hz, $K = \dfrac{60}{50} = 1.2$

$$T'_{max} = \frac{3}{2 \times 1.2 \times 157.08} \times \left[\frac{(400/\sqrt{3})^2}{2 + \sqrt{4 + (1.2 \times 7)^2}}\right] = 39.9 \text{ N-m}$$

At 50 Hz
$$T_{max} = \frac{3}{2\omega_{ms}} \times \left[\frac{V^2}{R_s + \sqrt{R_s^2 + (X_s + X'_r)^2}}\right]$$

$$T_{max} = \frac{3}{2 \times 157.08} \times \left[\frac{(400/\sqrt{3})^2}{2 + \sqrt{4 + 49}}\right] = 54.88 \text{ N-m}$$

$$\frac{T'_{max}}{T_{max}} = \frac{39.9}{54.88} = 0.727$$

6.16 VARIABLE FREQUENCY CONTROL FROM A CURRENT SOURCE

Control of induction motor employing variable frequency voltage sources was considered in previous section. This section considers motor control by variable frequency current source (VFCS). An equivalent circuit for motor fed from a current source is obtained when voltage source V is replaced by a current source I_s in Fig. 6.1(a). Now

$$I'_r = \frac{X_m I_s}{\sqrt{(R'_r/s)^2 + (X_m + X'_r)^2}} \tag{6.81}$$

$$T = \frac{3}{\omega_{ms}} I'^2_r \frac{R'_r}{s} = \frac{3}{\omega_{ms}} \left[\frac{I_s^2 X_m^2 R'_r/s}{(R'_r/s)^2 + (X_m + X'_r)^2}\right] \tag{6.82}$$

and
$$I_m^2 = \left[\frac{(R'_r/s)^2 + X'^2_r}{(R'_r/s)^2 + (X_m + X'_r)^2}\right] I_s^2$$

$$= \left[\frac{(R'_r/sf)^2 + (2\pi L'_r)^2}{(R'_r/sf)^2 + (2\pi L_m + 2\pi L'_r)^2}\right] I_s^2 \tag{6.83}$$

Motor speed-torque curves for various values of I_s and natural speed-torque curve, which corresponds to the operation at rated constant flux, are shown in Fig. 6.44(a). For a given I_s, operation of motor above the natural characteristic takes place for a flux higher than rated and below it at lower than rated. Since rated flux operation is preferred due to reasons explained in Sec 6.12, the natural characteristic is locus of preferred operating points. From Eq. (6.83), one can obtain a relationship between I_s and rotor frequency (sf) for rated I_m (or rated flux). This relationship, which is independent of frequency, is shown in Fig. 6.44(b). Drive is operated such that relationship of Fig. 6.44(b) is maintained between stator current I_s and rotor frequency (sf), when frequency is changed to control the speed.

When operating at a constant flux, the operating points are located mostly on the part of speed torque curve, which gives unstable operation with most loads (Fig. 6.44(a)). Hence, closed loop control is mandatory. Since motor is constraint to operate at constatn flux, its steady-state behavior is identical to that with VFVS. Thus at a given slip speed (or rotor frequency), the motor draws a constant current and develops a constant torque at all frequency, as explained in Sec. 6.12. This behavior is explained specifically for a motor fed from VFCS in example 6.14.

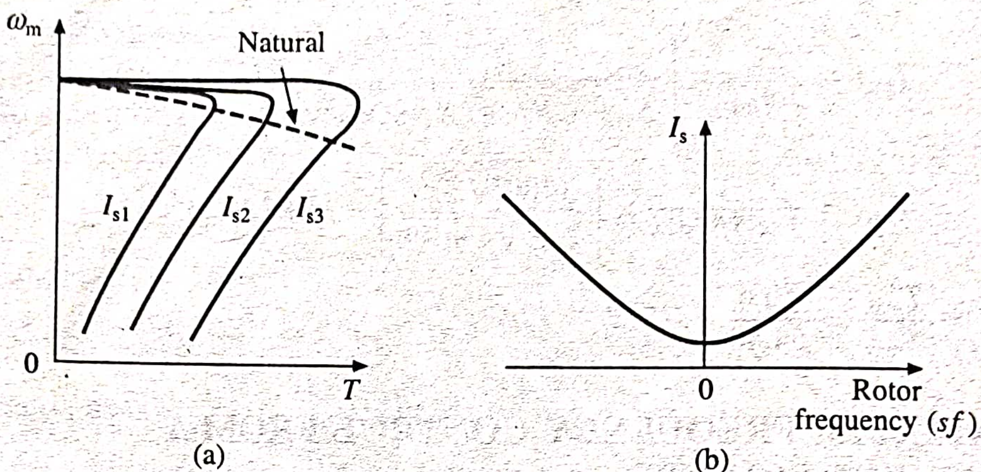


Fig. 6.44 Operation of induction motor from a current source: (a) speed torque curves; (b) I_s vs sf curves

The motor, therefore, operates in constant torque mode from zero to base speed. At base speed, either rated machine voltage is reached or VFCS voltage saturates. In either case machine operates at a constant terminal voltage above base speed, providing constant power mode. Variable frequency current supply is provided by a current source inverter.

6.17 CURRENT SOURCE INVERTER CONTROL

A thyristor current source inverter (CSI) is shown in Fig. 6.45. Diodes D_1-D_6 and capacitors C_1-C_6 provide commutation of thyristors T_1-T_6, which are fired with a phase difference of 60° in sequence of their numbers. It also shows the nature of output current waveforms. Inverter behaves as a current source due to the presence of large inductance L_d in dc link. The fundamental component of motor phase current from Fig. 6.45(b) is

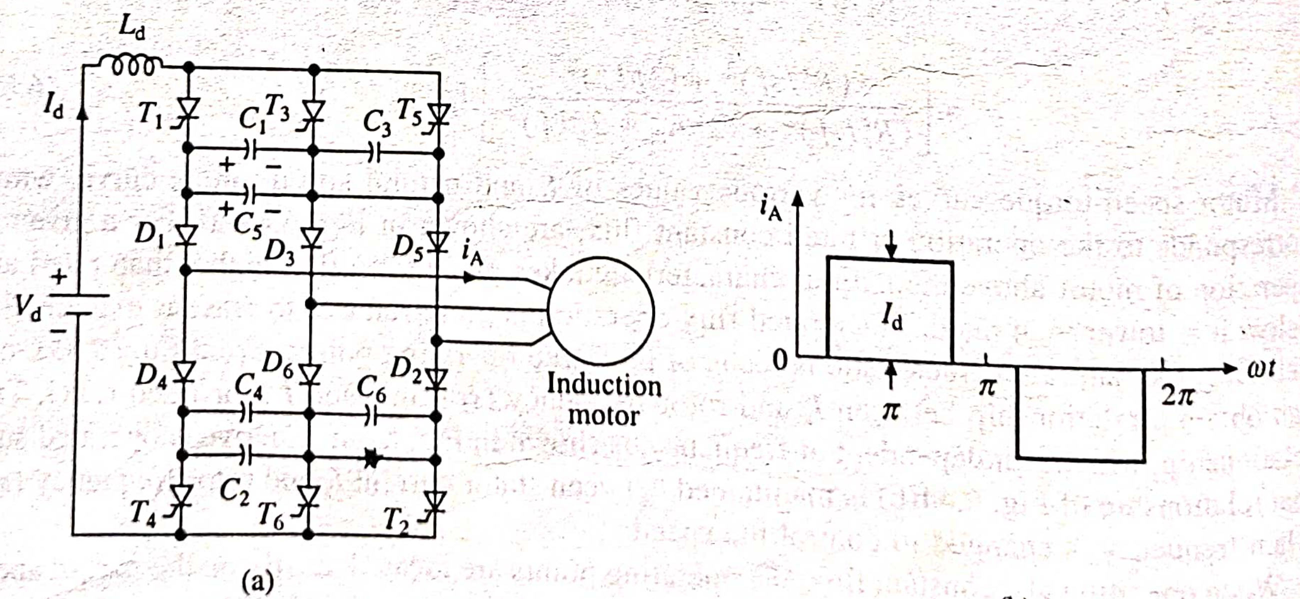
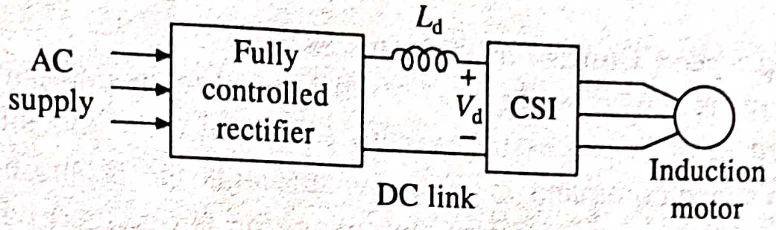


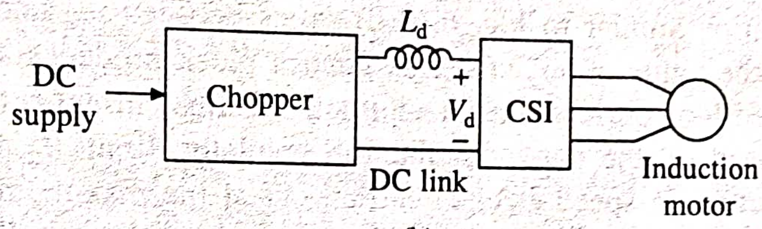
Fig. 6.45 Current source inverter fed induction motor drive

$$I_s = \frac{\sqrt{6}}{\pi} I_d \tag{6.84}$$

For a given speed, toruqe is controlled by varying dc link current I_d by changing the value of V_d. Therefore, when supply is ac, a controlled rectifier is connected between the supply and inverter and when supply is dc, a chopper is interposed between the supply and inverter (Fig. 6.46). The maximum value of dc output voltage of fully-controlled rectifier and chopper are chosen so that the motor terminal voltage saturates at rated value.



(a)



(b)

Fig. 6.46 Current source inverter (CSI) induction motor drives

The major advantage of CSI is its reliability. In case of VSI (Fig. 6.37(a)), a commutation failure will cause two devices in the same leg (e.g. T_{r1} and T_{r4}) to conduct. This connects conducting devices directly across the source. Consequently, current through devices suddenly rises to dangerous values. Expensive high speed semiconductor fuses are required to protect the devices. In case of CSI, condution of two devices in the same leg does not lead to sudden rise of current through them due to the presence of a large inductance L_d. This allows time for commutation to take place and normal operation to get restored in subsequent cycles. Further, less expensive HRC fuses are good enough for protection of thyristors.

As seen in Fig. 6.45, motor current rise and fall are very fast. Such a fast rise and fall of current through the leakage inductance of the motor produces large voltage spikes. Therefore, a motor with low leakage inductance is used. Even then voltage spikes have large value. The commutation capacitors C_1-C_6 reduce the voltage spikes by reducing the rate of rise and fall of current. Large value of capacitors is required to sufficiently reduce the voltage spikes. Large commutation capacitors have the advantages that cheap converter grade thyristors can be used but then they reduce the frequency range of the inverter, and therefore, speed range of the drive. Further, due to large values of inductor L_d and capacitors, the CSI drive is expensive and has more weight and volume.

6.17.1 Regenerative Braking and Multiquadrant Operation

When inverter frequency is reduced to make synchronous speed less than motor speed, machine works as a generator. Power flows from machine to dc link and dc link voltage V_d (Fig. 6.46) reverses. If fully-controlled converter of Fig. 6.46(a) is made to work as an inverter, the power supplied to dc link will be transferred to ac supply and regenerative braking will take place. Thus, no additional equipment is required for regenerative braking of CSI drive of Fig. 6.46(a). Change of phase sequence of CSI will provide motoring and braking operations in the reverse direction.

The drive of Fig. 6.46(b) can have regenerative braking capability and four-quadrant operation if a two quadrant chopper providing current in one direction but voltage in either direction is used [1].

6.17.2 Closed-Loop Speed Control of CSI Drives

A closed loop CSI drive is shown in Fig. 6.47. Actual speed ω_m is compared with the reference speed ω_m^*. The speed error is processed through a PI controller and slip regulator. The slip regulator sets the slip speed command ω_{sl}^*. The synchronous speed obtained by adding ω_m ω_{sl}^*, determines the inverter frequency. Constant flux operation is obtained when slip speed ω_{sl} (or rotor frequency) and I_s have relationship of Fig. 6.44(b). Since I_d is proportional to I_s, according to Eqn. (6.84), a relation similar to Fig. 6.44(b) exists between ω_{sl} and I_d for constant flux operation. Based on the value of ω_{sl}^*, the flux control block produces a referenc current I_d^*, which through a closed-loop current control adjusts the dc link current I_d to maintain a constant flux. The limit imposed on the output of the slip regulator, limits I_d at the inverter rating. Therefore, any correction in speed error is carried out at the maximum permissible inverter curent and maximum available torque, giving fast transient response and current protection.

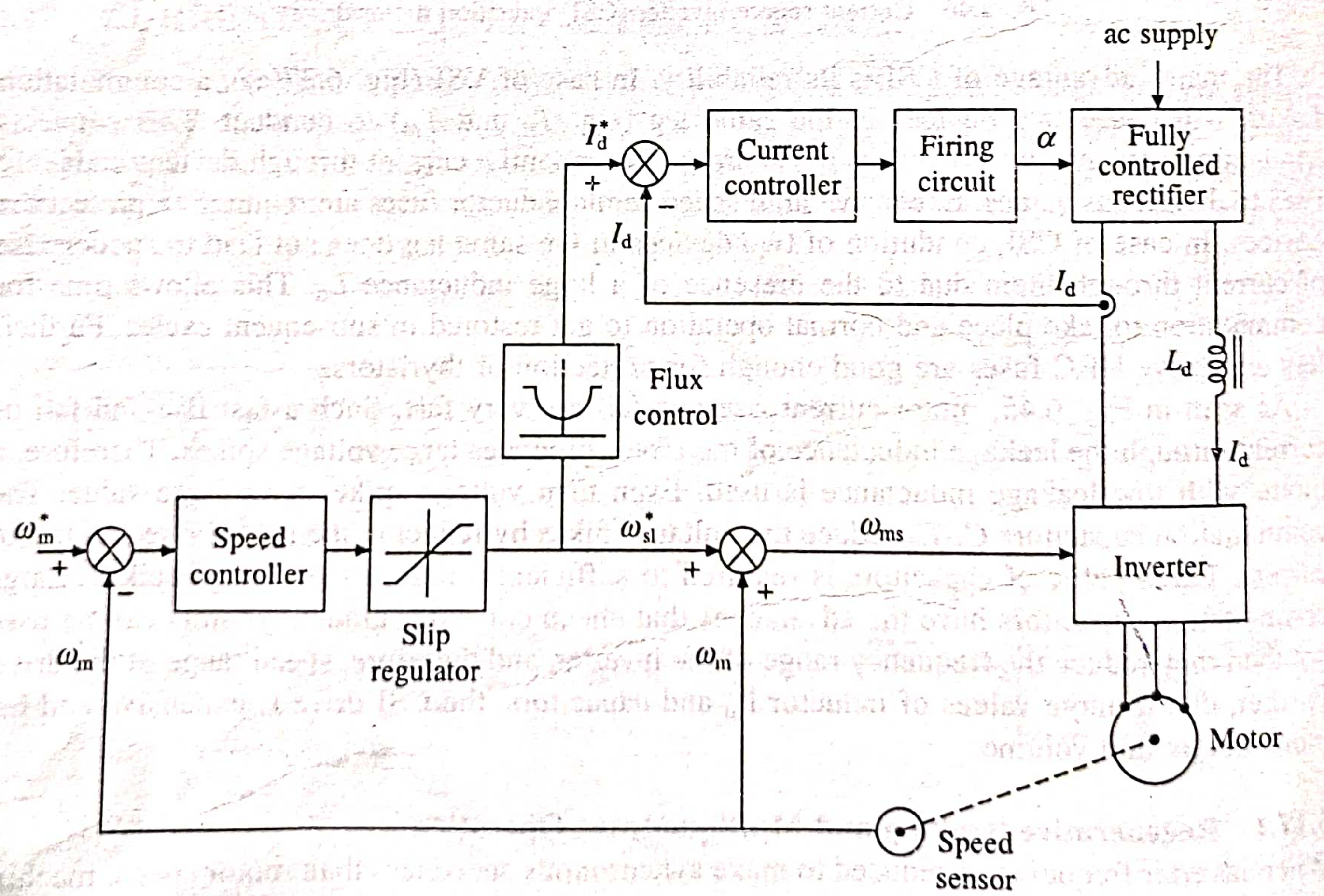


Fig. 6.47 Closed-loop slip controlled CSI drive with regenerative braking

Beyond base speed, machine terminal voltage saturates as explained at the beginning of Sec. 6.13. Flux control and closed-loop control of I_d are made ineffective. To operate the drive up to rated inverter current, the slip speed limit of the slip regulator must increase linearly with frequency. This is realized by adding to the slip regulator output a signal proportional to frequency.

6.17.3 Comparison of Current Source Inverter (CSI) and Voltage Source Inverter (VSI) Drives

The relative advantages and disadvantages of CSI and VSI drives are

(a) CSI is more reliable than VSI because (i) conduction of two devices in the same leg due to commutation failure does not lead to sharp rise of current through them and (ii) it has inherent protection against a short circuit across motor terminals.

(b) Because of large inductance in the dc link and large inverter capacitors, CSI drive has higher cost, weight and volume, lower speed range and slower dynamic response.

(c) The CSI drive is not suitable for multimotor drives. Hence, each motor is fed from its own inverter and rectifier. A single converter can be used to feed a number of VSI-motor systems connected in parallel. A single VSI can similarly feed a number of motors connected in parallel.

EXAMPLE 6.14

Show that a variable frequency induction motor drive, develops at all frequencies the same toruqe for a given slip-speed when operating at constant flux.

Solution

When operating at a frequency K times rated frequency f, Eq. (6.83) becomes

$$I_m^2 = \left[\frac{(R_r'/Ksf)^2 + (2\pi L_r')^2}{(R_r'/Ksf)^2 + (2\pi L_m + 2\pi L_r')^2}\right] I_s^2 \qquad (1)$$

For constant flux operation I_m must be constant. Therefore, for a given I_s, Ksf must be maintained constant as frequency is changed, thus

$$Ksf = \text{constant} \qquad (2)$$

or

$$K\omega_{ms}s = \text{constant} \qquad (3)$$

and

$$sK = \text{constant} \qquad (4)$$

$K\omega_{ms}$ is the synchronous speed for frequency Kf and therfore $K\omega_{ms}s$ is the slip speed.

From Eq. (6.82) for a frequency Kf

$$T = \frac{3}{K\omega_{ms}}\left[\frac{I_s^2 K^2 X_m^2 R_r'/s}{(R_r'/s)^2 + K^2(X_m + X_r')^2}\right]$$

$$= \frac{3}{K\omega_{ms}s}\left[\frac{I_s^2 X_m^2 R_r'}{\left(\dfrac{R_r'}{sK}\right)^2 + (X_m + X_r')^2}\right] \qquad (5)$$

For a given slip speed ($K\omega_{ms}s$), Ks is constant. From Eq. (1), for a given Ksf and constant flux operation I_s is fixed. Now from Eq. (5) T is also fixed. Thus, motor develops a constant torque and draws a constant current from the inverter at all frequencies for a given slip speed.

EXAMPLE 6.15

A Y-connected squirrel-cage induction motor has following ratings and parameters:

$$400 \text{ V}, 50 \text{ Hz}, 4\text{-pole}, 1370 \text{ rpm}, R_s = 2\ \Omega, R_r' = 3\ \Omega, X_s = X_r' = 3.5\ \Omega, X_m = 55\ \Omega$$

It is controlled by a current source inverter at a constant flux. Calculate

(i) Motor torque, speed and stator current when operating at 30 Hz and rated slip speed.
(ii) Inverter frequency and stator current for rated motor torque and motor speed of 1200 rpm.

Assuming motor speed torque curves to be parallel straight lines in the region of interest, calculate motor speed when operating at

(iii) 30 Hz and half the rated motor torque.
(iv) 45 Hz and braking torque equal to rated motor torque.

Solution

$$\text{Synchronous speed} = 1500 \text{ rpm or } 50\pi \text{ rad/sec}$$

$$\text{Full load slip } s_f = \frac{1500 - 1370}{1500} = 0.0867$$

$$\text{Full load slip speed} = 1500 - 1370 = 130 \text{ rpm}$$

From Fig. E.6.15 motor impedance

$$Z = 2 + j3.5 + \frac{j55\left(\dfrac{3}{0.0867} + j3.5\right)}{\dfrac{3}{0.0867} + j(55 + 3.5)}$$

$$= 24.65 + j20.19 = 31.86 < 39.3° \ \Omega$$

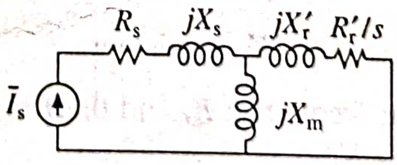


Fig. E.6.15

Full load stator current

$$I_{sf} = \frac{400/\sqrt{3}}{31.86} = 7.2486 \text{ A}$$

Full load rotor current

$$I_{rf}' = I_{sf}\left[\frac{jX_m}{(R_r'/s_f) + j(X_r' + X_m)}\right] = 7.2486\left[\frac{j55}{\dfrac{3}{0.0867} + j(58.5)}\right] = 5.865 \text{ A}$$

Full load torque

$$T_F = \frac{3}{\omega_{ms}}[I_{rf}'^2 R_r'/s_f] = \frac{3}{50\pi} \times (5.865)^2 \times \frac{3}{0.0867} = 22.73 \text{ N-m}$$

(i) According to Example 6.14 at rated slip speed, torque and I_s will have same values as at 50 Hz operation. Thus

$$T = 22.73,\ I_s = 7.2486 \text{ A}$$

Now at 30 Hz synchronous speed $= \frac{30}{50} \times 1500 = 900$ rpm

Full load slip speed = 130 rpm

Motor speed = 900 – 130 = 770 rpm

(ii) At rated motor torque, slip speed and I_s will be same as at 50 Hz operation. Therefore

$$I_s = 7.2486, \text{ slip speed} = 130 \text{ rpm}$$

Synchronous speed = 1200 + 130 = 1330 rpm

$$\text{Frequency} = \frac{1330}{1500} \times 50 = 44.33 \text{ Hz}$$

(iii) When speed-torque curves are assumed to be straight lines,

Slip speed at half the rated torque $= \frac{130}{2} = 65$ rpm

At 30 Hz, synchronous speed = 900 rpm

Motor speed = 900 – 65 = 835 rpm

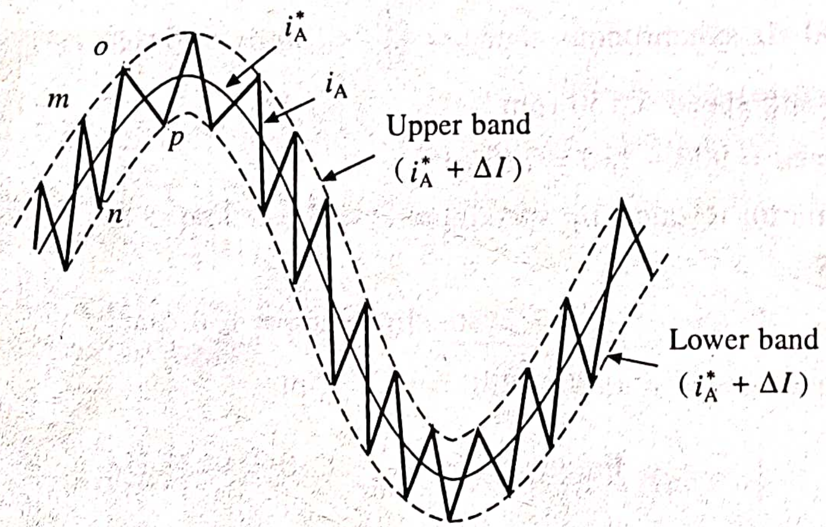
(iv) At rated braking torque, slip speed = – 130 rpm

Synchronous speed at 45 Hz $= \frac{45}{50} \times 1500 = 1350$ rpm

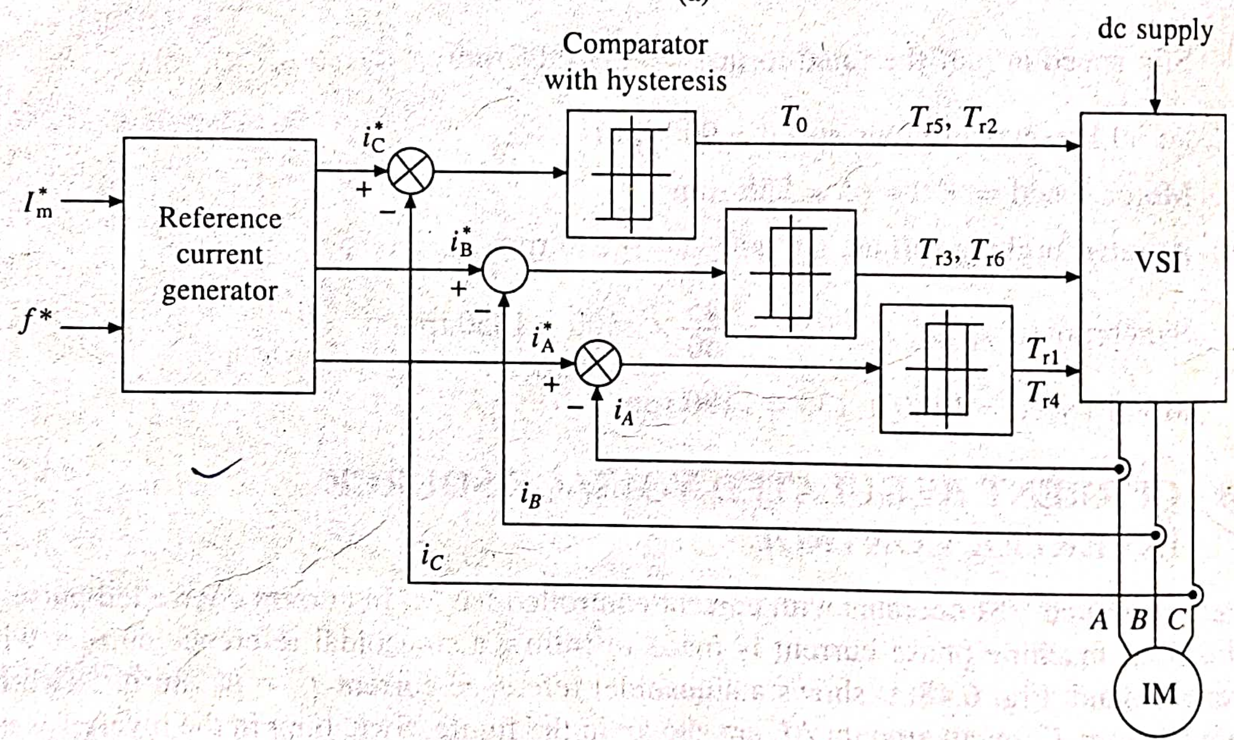
Motor speed = 1350 + 130 = 1480 rpm

6.18 CURRENT REGULATED VOLTAGE SOURCE INVERTER CONTROL

Current regulated VSI operates with current controlled PWM. In current controlled pulse-width modulation, machine phase current is made to follow a sinusoidal reference current within a hysteresis band. Fig. 6.48(a) shows a sinusoidal reference current $i_A^* = I_m \sin \omega t$. Two bands, separated from i_A^* by an amount ΔI, are shown in the figure. Switching in the inverter is carried out such that the actual motor current i_A remains within these two bands. For this voltage source inverter of Fig. 6.37(a) is employed. In this inverter phase A current i_A is shaped by transistors T_{r1} and T_{r4}. When T_{r1} is on (T_{r4} is off), phase A is connected to the positive terminal of dc source, hence the rate of change of current i_A will be positive and when T_{r4} is on (T_{r1} is off), phase A is connected to negative terminal of the dc source, hence rate of change of current i_A will be negative. In Fig. 6.48(a) current i_A is falling along the path *mn* when T_{r4} is on. When i_A reaches the lower band at *n*, T_{r4} is turned off and T_{r1} is turned on. This makes rate of change of i_A to be positive and it rises along the path *no*. When i_A reaches the upper band at *o*, T_{r1} is turned off and T_{r4} is turned on. This makes rate of change of i_A to be negative and it falls along *op*. This way actual current i_A is constraint to remain within two hysteresis bands. Reference current for phases B and C are chosen to be $i_B^* = I_m \sin(\omega t - 120°)$ and $i_C^* = I_m \sin(\omega t - 240°)$ and by controlling respective transistors i_B and i_C are made to follow i_B^* and i_C^* within hysteresis bands.



(a)



(b)

Fig.6.48 Current regulated voltage source inverter

When the band is small, motor currents will be nearly sinusoidal. As the band reduces, harmonic content in phase currents reduces but then switching frequency increases. Thus, inverter with fast switching devices will have lower harmonic content.

Fig. 6.48(b) gives block diagram of current regulated VSI. Based on current amplitude command I_m^* and frequency command f^*, reference current generator generates sinusoidal reference currents i_A^*, i_B^* and i_C^*. These reference currents are compared with respective motor currents, i_A, i_B and i_C in comparators with hysteresis to generate base drives for switches.

Since the magnitude and waveforms of motor currents are independent of changes in motor impedance and source voltage, the inverter essentially operates as a current source inverter. The closed-loop speed control scheme of CSI drive (Fig. 6.47) is therefore used for current regulated VSI drive also and is shown in Fig. 6.49. A servo drive for closed-loop position control is obtained by adding a position loop around the speed loop in Fig. 6.49.

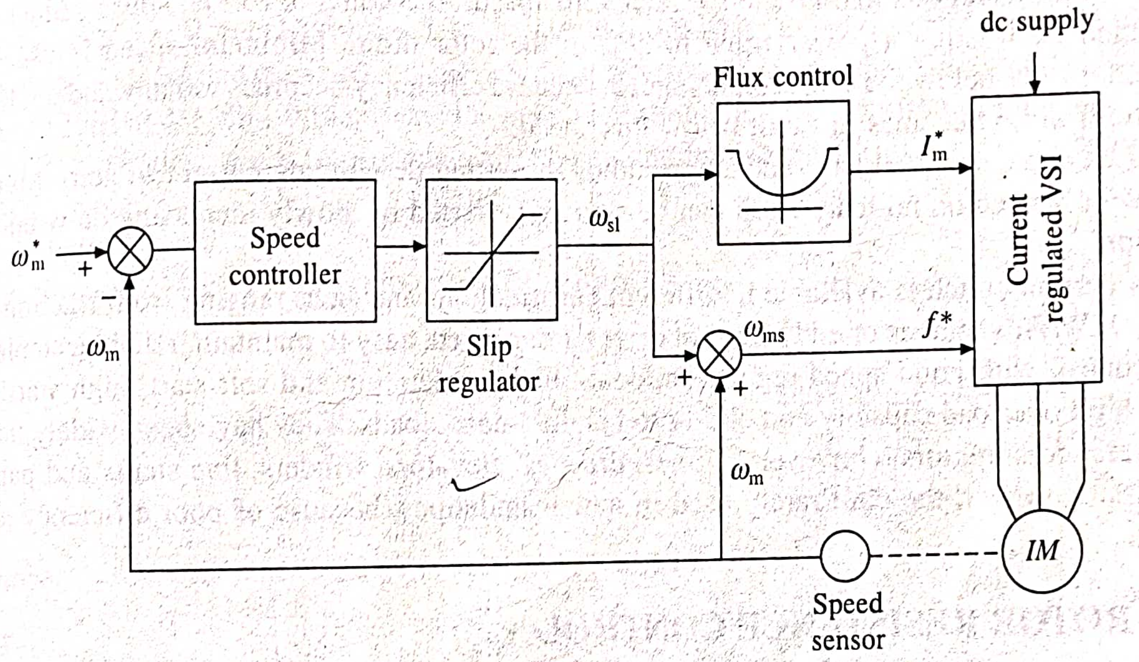


Fig. 6.49 Closed-loop control of current regulated voltage source inverter fed induction motor drive

Although current regulated VSI operates as a CSI, it does not use large dc inductor and filter capacitors, hence it has lower weight, volume and cost and faster dynamic response. This drive has applications in servo control systems.

6.19 EDDY CURRENT DRIVES

Drive consists of an eddy current clutch placed between an induction motor running at a fixed speed and the variable speed load. Speed is controlled by controlling dc excitation to magnetic circuit of the clutch. Since motor itself runs at a fixed speed it can be fed directly from ac mains.

An eddy-current clutch is identical in principle to an induction motor in which both stator and rotor are allowed to rotate. Stator, which is coupled to driving induction motor, has dc winding which produces magnetic field rotating at the speed of stator. Rotor has a metal drum coupled to the load. Eddy currents are induced in rotor drum by stator magnetic field. Interaction between the stator field and eddy currents produces a torque which causes rotor to move with stator with a slip. Slip, and therefore, the load speed, can be controlled by controlling dc current through stator winding. Speed-torque characteristics are identical to an induction motor. Slip is given by