7

Synchronous Motor and Brushless dc Motor Drives

The speed of a synchronous motor can be controlled by varying frequency of its source. Due to non-availability of economical variable frequency sources, this method of speed control was not used in the past. Synchronous motors were mainly used in constant speed applications. The development of semiconductor variable frequency sources, such as inverters and cycloconverters, has allowed their use in variable speed applications such as high power and high speed compressors, blowers, induced and forced draft fans, main line traction, servo drives, etc.

This chapter first reviews their conventional fixed frequency (constant speed) operation and then describes variable speed synchronous motor drives.

7.1 SYNCHRONOUS MOTORS

Commonly used synchronous motors are: wound field, permanent magnet, synchronous reluctance and hysteresis motors. All these motors have a stator with a 3-phase winding, which is connected to an ac source. Fractional horse power synchronous reluctance and hysteresis motors employ a 1-phase stator.

Wound field synchronous motor rotor has a dc field winding, which is supplied from a dc source through slip-rings and brushes. The rotor can have cylindrical or salient pole construction. Cylindrical rotor motors have higher mechanical strength and are employed in high power and high speed applications; for other applications salient pole motors are preferred due to lower cost.

In medium and small size motors, dc field can be produced by permanent magnets. Thus, dispensing with dc source, slip-rings, brushes and field winding losses. Such motors are known as *permanent magnet (PM) synchronous motors*. Usually ferrite magnets are employed. Rare earth (cobalt-samarium) magnets, although very expensive, are some times used to reduce the volume and weight of the motor. PM synchronous motors are classified as: (i) surface mounted and (ii) interior (or buried). Surface mounted PM motors are of two types: (1) projecting type, in which magnets project from the surface of rotor (Fig. 7.1(a)), and (2) inset type, in which magnets are inserted into the rotor, providing a smooth rotor surface (Fig. 7.1(b)). Epoxy glue is used to fix the magnets to the rotor surface in both. While these motors are easy to construct and are less expensive, they are less robust compared to interior type (Fig. 7.1(c)) rotors and are not suitable for high speed applications. In interior type PM motors, magnets are imbedded in the interior of the rotor.

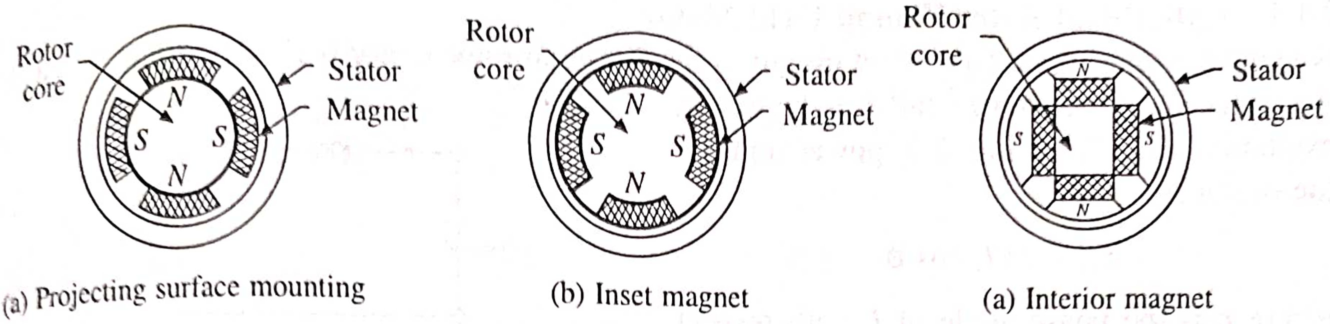


Fig. 7.1 Different types of PM synchronous motors

The wound field and permanent magnet synchronous motors have a higher full load efficiency and power factor than an induction motor. Wound field motors can be designed for a higher power rating than induction motors. Since the air-gap flux is not produced solely by the magnetizing current drawn from the armature, a larger air-gap suiting the mechanical design can be chosen. The ability to control power factor is an important advantage at higher power levels. Operating at unity power factor minimizes the inverter rating. Apart from the robust construction, permanent magnet synchronous motor has low losses and high efficiency. Because of low losses, it is possible to make motors with very high power density and torque to inertia ratios. These make them suitable for servo drives requiring fastest possible dynamic response.

The rotor of a synchronous reluctance motor has salient poles but neither have field winding nor permanent magnets. Motor is driven by reluctance torque which is produced due to tendency of the salient rotor poles to align themselves with synchronously rotating field produced by the stator.

All the abovementioned synchronous motors, when designed to operate with a source of fixed frequency, are provided with damper winding, which is similar to squirrel-cage winding of an induction motor. It is used to start the machine as induction motor and to damp the hunting oscillations which occur during the transient operations. When fed from a variable frequency source, capable of smooth freqency variation from zero to rated, the damper winding is not required for starting. It may, however, be required for damping hunting oscillations or for some other purposes explained later.

One important difference between the wound field and permanent magnet motors, which are designed to operate with a source of fixed frequency, must be noted. When a wound field motor is started as an induction motor, dc field is kept off. In case of a permanent magnet motor, the field cannot be 'turned off'. When at a speed below synchronous speed, the rotor field induces a voltage in the stator, which has a frequency different than the frequency of stator supply. The current produced by induced voltage interacts with the rotor field to produce a braking torque, which opposes induction motor torque due to damper winding. The permanent magnet synchronous motor (PMSM) is designed so that the braking torque is very small compared to induction motor torque. Because of the capability to start direct on line these motors are called line start PMSM. They are available in 3-phase and 1-phase construction. Although expensive compared to induction motors, they have advantages of high efficiency, high power factor and low sensitivity to supply voltage variations. Therefore, they are preferred for industrial applications with large duty cycles such as pumps, fans and compressors.

The hysteresis synchronous motors are employed in low power applications requiring smooth start and quiet operation.

7.1.1 Cylindrical Rotor Wound Field Motor

A simplified per phase equivalent circuit of a cylindrical rotor motor is shown in Fig. 7.2. X_s is the synchronous reactance and E is known as excitation emf. From Fig. 7.2, power input to the motor is

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

where ϕ is the phase angle of I_s with respect to V.

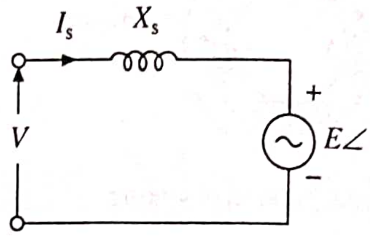


Fig. 7.2 Equivalent circuit of a cylindrical rotor motor

Since stator loss has been neglected, the power developed is

$$P_m = 3VI_s \cos \phi \tag{7.1}$$

From Fig. 7.2,

$$I_s = \frac{V\angle 0 - E\angle -\delta}{jX_s} = \frac{V}{X_s}\angle -\pi/2 - \frac{E}{X_s}\angle -(\pi/2 + \delta)$$

Now $$I_s \cos \phi = \frac{V}{X_s}\cos(\pi/2) - \frac{E}{X_s}\cos(\pi/2 + \delta) = \frac{E}{X_s}\sin\delta$$

Substitution in Eq. (7.1) gives

$$P_m = \frac{3VE}{X_s}\sin\delta \tag{7.2}$$

The rotating field produced by stator moves at a synchronous speed which is given by

$$\omega_{ms} = \frac{4\pi f}{p} \text{ rad/sec} \tag{7.3}$$

where f is the supply frequency and p the number of poles.

For a steady torque to be produced, rotor field must move at the same speed as stator field. Since rotor field has same speed as that of rotor, the rotor also runs at synchronous speed. Therefore, torque is

$$T = \frac{P_m}{\omega_m} = \frac{3VE}{X_s\omega_{ms}}\sin\delta \tag{7.4}$$

For a given field excitation, E is constant. Therefore, P_m and T are proportional to sin δ. The angle δ is called power (or torque) angle.

The speed torque curve is shown in Fig. 7.3. The motoring operation is obtained when δ is positive and E lags being V, whereas regenerative braking is obtained when δ is negative or E leads V. The maximum torque T_{max} (also known as pull-out torque), is reached at $\delta = \pm 90°$. If the load torque exceeds T_{max}, the machine pulls out of synchronism. In order to prevent damage due to excessive current, automatic circuit breakers are provided to disconnect the machine when it comes out of synchronism.

The important feature of wound field motor is that its power factor can be controlled by varying field current (or E). The machine phasor diagrams for a given developed power are

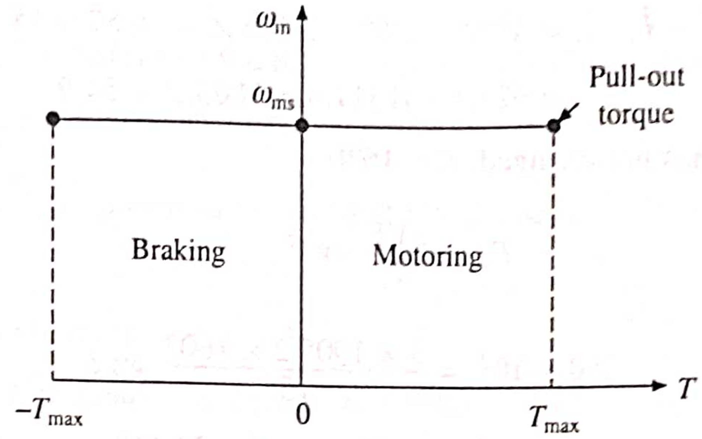
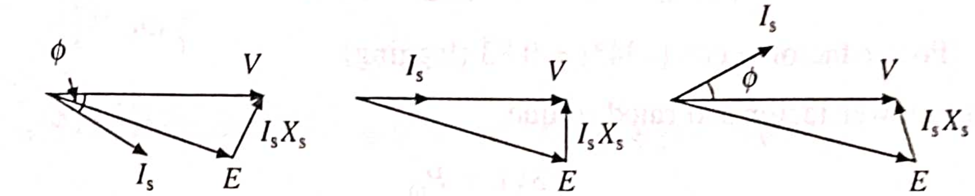


Fig. 7.3 Speed torque characteristic with a fixed frequency supply

shown in Fig. 7.4. When field excitation is small, the machine operates with a lagging power factor. The power factor can be made unity or leading by increasing the field excitation.



(a) Lagging power factor (b) Unity power factor (c) Leading power factor

Fig. 7.4 Variation of power factor with field excitation

EXAMPLE 7.1

A 500 kW, 3-phase, 3.3 kV, 50 Hz, 0.8 (lagging) power factor, 4 pole, star-connected synchronous motor has following parameters: $X_s = 15\ \Omega, R_s = 0$. Rated field current is 10 A. Calculate

(i) Armature current and power factor at half the rated torque and rated field current.
(ii) Field current to get unity power factor at the rated torque.
(iii) Torque for unity power factor operation at field current of 12.5 A.

Solution

$$\sqrt{3}\, V_L I_s \cos\phi = P_m$$

When losses are neglected, rated power output = 500 kW
Synchronous speed = 50π rad/sec
Power at half the rated torque = 250 kW

$$V = \frac{3.3 \times 10^3}{\sqrt{3}} = 1905.2 \text{ V}$$

Also $$\sqrt{3}\, V_L I_s \cos\phi = P_m$$

or $$\sqrt{3} \times 3.3 \times 10^3\, I_s \times 0.8 = 500 \times 10^3$$

or $$I_s = 109.3 \text{ A and } \bar{I}_s = 109.3 \angle -36.86°$$

$$\bar{E} = \bar{V} - \bar{I}_s j X_s = 1905.2 \angle 0° - 109.3 \angle -36.87 \times 15 \angle 90°$$

$$= 921.5 - j1311.6 = 1603 \angle -54.9$$

(i) As field current has not changed, $E = 1630$ 03

$$P_m = \frac{3VE}{X_s} \sin \delta$$

$$250 \times 10^3 = \frac{3 \times 1905.2 \times 1603}{15} \sin \delta$$

or

$$\sin \delta = 0.409 \quad \text{or} \quad \delta = 24.16°$$

$$\bar{I}_s = \frac{V - E\angle -\delta}{jX_s} = \frac{1905.2 - 1603\angle -24.16°}{15\angle 90°}$$

$$= 127 \angle -90° - 106.9 \angle -114.16 = 52.75 \angle -34°$$

Power factor = cos (–34°) = 0.83 (lagging)

(ii) At unity power factor and rated torque

$$3VI_s = P_m$$

or

$$3 \times 1905.2 I_s = 500 \times 10^3$$

or

$$I_s = 87.48 \text{ A}$$

$$\bar{E} = 1905.2\angle 0° - 87.48\angle 0° \times 15 \angle 90° = 1905.2 - j1312.2$$

$$E = 2313.4 \text{ V}$$

$$\text{Field current} = \frac{2313.4}{1603} \times 10 = 14.43 \text{ A}$$

(iii) At the field current of 12.5 A

$$E = \frac{12.5}{10} \times 1603 = 2003.75 \text{ V}$$

$$|\bar{V} - \bar{I}_s(jX_s)| = E$$

or

$$|1905.2\angle 0° - I_s\angle 0° \times 15\angle 90°| = 2003.75$$

or

$$|1905.2 - j15\, I_s| = 2003.75$$

or

$$I_s = \frac{\sqrt{2003.75^2 - 1905.2^2}}{15} = 41.38 \text{ A}$$

$$P_m = 3VI_s \cos\phi = 3 \times 1905.2 \times 41.38 = 236.51 \text{ kW}$$

$$\text{Torque} = \frac{236510}{50\pi} = 1505.7 \text{ N-m}$$

EXAMPLE 7.2

For motor of Example 7.1 determine the following for regenerative braking operation:

(i) Braking torque and field current for machine operation at the rated current and unity power factor.

(ii) Armature current and power factor for 500 kW output at 15 A field current.

Solution

From Example 7.1, rated current = 109.3 A

$$V = 1905.2, \text{ at rated field current } E = 1603 \text{ V}$$

(i)
$$\bar{E} = 1905.2\angle 0° + 109.3\angle 0° \times 15\angle 90°$$

$$= 1905.2 + j1639.5 = 2513.5\angle 40.71°$$

Thus
$$E = 2513.5 \text{ V}, \quad \delta = -40.71°$$

$$P_m = \frac{3VE}{X_s}\sin\delta$$

$$= \frac{3 \times 1905.2 \times 2513.5}{15} \times \sin(-40.71) = -624.67 \text{ kW}$$

$$T = \frac{P_m}{\omega_{ms}} = \frac{-624.67 \times 10^3}{\cancel{1603}) \ 187} = -3976.8 \text{ N-m}$$

$$\text{Field current} = \frac{2513.5}{1603} \times 10 = 15.68 \text{ A}$$

(ii) At the field current of 15 A, $E = \frac{15}{10} \times 1603 = 2404.5$ V

$$P_m = \frac{3VE}{X_s}\sin\delta$$

$$-500 \times 10^3 = \frac{3 \times 1905.2 \times 2404.5}{15}\sin\delta$$

or
$$\sin\delta = -0.546 \quad \text{or} \quad \delta = -33.07°$$

$$\bar{I}_s = \frac{\bar{E} - \bar{V}}{jX_s} = \frac{2404.5\angle 33.07° - 1905.2\angle 0°}{15\angle 90°}$$

$$= 87.81 - j7.33 = 88.11\angle -4.77°$$

$$I_s = 88.11, \text{ power factor} = \cos 4.77° = 0.996 \text{ (lagging)}$$

7.1.2 Salient Pole Wound Field Motor

Because of different synchronous reactances in direct and quadrature axes, the machine cannot be described by a simple equivalent circuit. From the phasor diagram (Fig. 7.5):

$$I_{sd} = \frac{V\cos\delta - E}{X_{sd}} \tag{7.5}$$

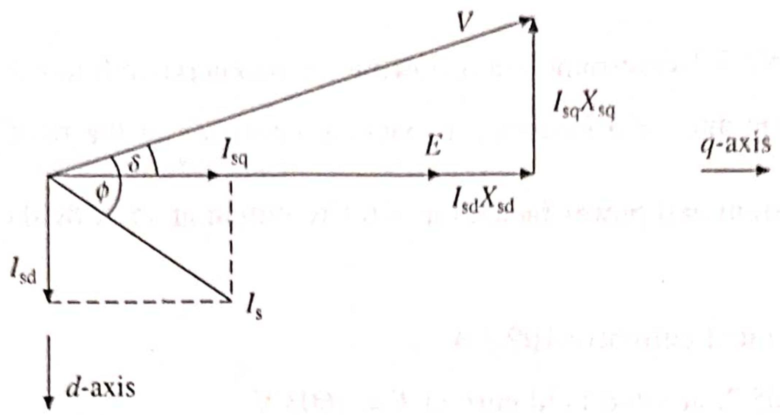


Fig. 7.5 Phasor diagram of a salient pole motor

$$I_{sq} = \frac{V \sin \delta}{X_{sq}} \tag{7.6}$$

$$I_s \cos \phi = I_{sq} \cos \delta - I_{sd} \sin \delta \tag{7.7}$$

where X_{sd} and X_{sq} are respectively synchronous reactances of direct and quadrature axes; and I_{sd} and I_{sq} are respectively direct and quadrature components of I_s.

Substituting from Eqs. (7.5) and (7.6) into (7.7), yields

$$I_s \cos \phi = \frac{E \sin \delta}{X_{sd}} + \frac{V(X_{sd} - X_{sq})}{2X_{sd}X_{sq}} \sin 2\delta \tag{7.8}$$

Substituting in Eq. (7.1) gives

$$P_m = 3\left[\frac{VE}{X_{sd}} \sin \delta + \frac{V^2(X_{sd} - X_{sq})}{2X_{sd}X_{sq}} \sin 2\delta\right] \tag{7.9}$$

$$T = \frac{P_m}{\omega_{ms}} = \frac{3}{\omega_{ms}}\left[\frac{VE}{X_{sd}} \sin \delta + \frac{V^2(X_{sd} - X_{sq})}{2X_{sd}X_{sq}} \sin 2\delta\right] \tag{7.10}$$

The torque expression has two components. First component (synchronous torque) is proportional to $\sin \delta$, and the second component (reluctance torque) is proportional to $\sin 2\delta$. The speed-torque characteristic is similar to that shown in Fig. 7.3.

7.1.3 Permanent Magnet Motor

In this motor, field excitation is obtained by mounting permanent magnets on the rotor. This eliminates dc source, losses associated with the field winding and frequent maintenance associated with slip rings and brushes in a wound field motor. But then the power factor cannot be controlled because the field excitation cannot be changed. These motors are usually designed to operate at unity power factor at full load. While projecting type machine has an uniform air-gap, the inset and interior types have essentially salient-pole construction. Therefore, power and torque expressions of Eqs. (7.2) and (7.4) are applicable to projecting type surface magnet machines and those of (7.9) and (7.10) are applicable to buried (or interior) and inset type surface magnet machines.

variation of current and torque is not large. Therefore, a single section of resistance is enough. At zero speed, the induced voltage, and therefore, armature current and torque are zero. As the torque is available in whole speed range and it is zero at zero speed, dynamic braking is suitable for stopping motor.

Theoretically, plugging can also be employed. However, it is not used in practice. Plugging torque is produced by damper winding. Because of its low resistance, while current drawn from the supply is very large, the braking torque produced is much smaller compared to that produced by dynamic braking. In case of large motors, high plugging current can create a severe disturbance in supply lines.

7.3 SYNCHRONOUS MOTOR VARIABLE SPEED DRIVES

7.3.1 Variable Frequency Control

Synchronous speed (Eq. (7.3)) is directly proportional to frequency. Motor speed can be controlled by varying the frequency. As in case of an induction motor, constant flux operation below base speed is achieved by operating the motor with a constant (V/f) ratio; which is increased at low speeds to compensate for the stator resistance drop. According to Eqs. (7.4), (7.10) and (7.11), for all types of synchronous motors this gives operation with a constant pull-out torque. Rated voltage is reached at the base speed. For higher speeds, the machine is operated at a rated terminal voltage and variable frequency, and the pull-out torque decreases with an increase in frequency.

7.3.2 Modes of Variable Frequency Control

Variable frequency control may employ any of the two modes: (i) true synchronous mode or (ii) self-controlled mode, also known as self-synchronous mode.

In true synchronous mode, the stator supply frequency is controlled from an independent oscillator. Frequency from its initial to the desired value is changed gradually so that the difference between synchronous speed and rotor speed is always small. This allows rotor speed to track the changes in synchronous speed. When the desired synchronous speed (or frequency) is reached, the rotor pulls into step, after hunting oscillations. Variable frequency control not only allows the speed control, it can also be used for smooth starting and regenerative braking, as long as it is ensured that the changes in frequency are slow enough for rotor to track changes in synchronous speed. A motor with damper winding is used for pull-in to synchronism.

In self-control mode, the stator supply frequency is changed so that synchronous speed is the same as rotor speed. This ensures that rotor runs at synchronous speed for all operating points. Consequently, rotor cannot pull-out of step and hunting oscillations are eliminated. For such applications, the motor may not require a damper winding.

In self-control mode, the stator supply frequency is changed in proportion to the rotor speed so that the rotating field produced by the stator always moves at the same speed as the rotor (or rotor field). Since, the voltage induced in the stator phase has a frequency proportional to rotor speed, self-control can be realized by making the stator supply frequency to track the frequency of induced voltage. Alternatively sensors can be mounted on the stator to track the rotor position. These sensors are called rotor position sensors. The frequency of signals generated by these sensors is proportional to rotor speed. Hence, the stator supply frequency can be made to track the frequency of these signals.

7.4 VARIABLE FREQUENCY CONTROL OF MULTIPLE SYNCHRONOUS MOTORS

A drive operating in true synchronous mode is shown in Fig. 7.9. Frequency command f^* is applied to a voltage source inverter through a delay circuit so that rotor speed is able to track the changes in frequency. A flux control block changes stator voltage with frequency to maintain a constant flux below rated speed and a constant terminal voltage above rated speed. This scheme is commonly used for the control of multiple synchronous reluctance or permanent magnet motors in fiber spinning, textile and paper mills where accurate speed tracking between the motors is required.

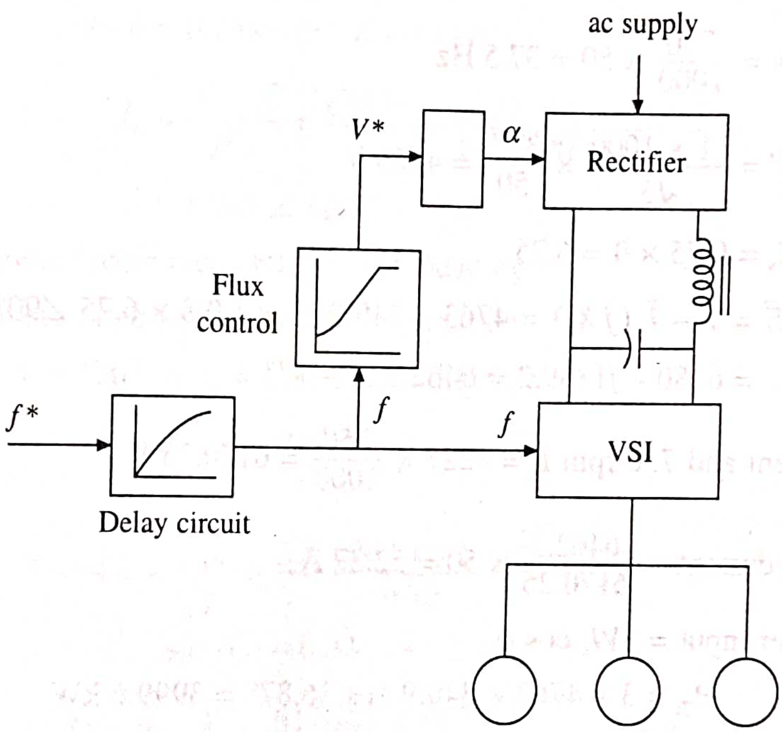


Fig. 7.9 Variable frequency control of multiple synchronous motors

EXAMPLE 7.3

A 6 MW, 3-Phase, 11 kV, Y-connected, 6-pole, 50 Hz, 0.9 (leading) power factor synchronous motor has $X_s = 9\ \Omega$ and and $R_s = 0$. Rated field current is 50 A.

Machine is controlled by variable frequency control at constant (V/f) ratio up to the base speed and at constant V above base speed. Determine

(i) Torque and field current for the rated armature current, 750 rpm and 0.8 leading power factor.

(ii) Armature current and power factor for half the rated motor torque, 1500 rpm and rated field current.

(iii) Armature current and power factor for regenerative braking power output of 4.2 MW at 750 rpm and rated field current.

(iv) Torque and field current for regenerative braking operation at rated armature current, 1500 rpm and unity power factor.

Solution

At rated operation

$$3VI_s \cos\phi = P_m$$

or $$3 \times \frac{11000}{\sqrt{3}} I_s \times 0.9 = 6 \times 10^6 \quad \text{or} \quad I_s = 349.9 \text{ A}$$

$$\bar{E} = \bar{V} - \bar{I}_s (jX_s) = 6350.85 - 9\angle 90° \times 349.9 \angle \cos^{-1} 0.9$$

$$= 7723.4 - j2834.2 = 8227 \angle -20.15°$$

For operation at 750 rpm

$$\text{Frequency} = \frac{750}{1000} \times 50 = 37.5 \text{ Hz}$$

$$V = \frac{11 \times 1000}{\sqrt{3}} \times \frac{37.5}{50} = 4763 \text{ V}$$

$$X_s = 0.75 \times 9 = 6.75$$

$$\bar{E} = \bar{V} - \bar{I}_s (jX_s) = 4763 - 349.9\angle \cos^{-1} 0.8 \times 6.75 \angle 90°$$

$$= 6180 - j1889.2 = 6462.3 \angle -17°$$

At rated field current and 750 rpm $E = 8227 \times \dfrac{750}{1000} = 6170.25$ V

$$\text{Field current} = \frac{6462.3}{6170.25} \times 50 = 52.37 \text{ A}$$

$$\text{Power input} = 3VI_s \cos\phi$$

or $$P_m = 3 \times 4763 \times 349.9 \cos 36.87° = 3999.6 \text{ kW}$$

$$\text{Motor speed} = \frac{750}{60} \times 2\pi = 78.54 \text{ rad/sec}$$

$$\text{Torque} = \frac{3999.6 \times 10^3}{78.54} = 50924.4 \text{ N-m}$$

(ii) At 1500 rpm

$$\text{Frequency} = \frac{1500}{1000} \times 50 = 75 \text{ Hz}$$

$$X_s = \frac{75}{50} \times 9 = 13.5\ \Omega$$

$$E \text{ at rated field current} = 8227 \times \frac{75}{60} = 12340.5 \text{ V}$$

$$V = \text{rated voltage} = 6350.85 \text{ V}$$

If ω_{ms} and ω'_{ms} denote synchronous speeds at 1000 rpm and 1500 rpm, respectively, the power developed at 1500 rpm will be

$$P'_m = 0.5\ T_{rated} \times \omega'_{ms}$$

$$= 0.5\ T_{rated} \times 1.5\ \omega_{ms} = 0.5 \times 1.5\ P_m$$

where P_m is the rated power of the machine. Substituting its value

$$P'_m = 0.5 \times 1.5 \times 6 = 4.5 \text{ MW}$$

Since $$P_m = \frac{3VE}{X} \sin\delta$$

$$4.5 \times 10^6 = \frac{3 \times 6350.85 \times 12340.5}{13.5} \sin\delta$$

or $$\sin\delta = 0.258 \quad \text{or} \quad \delta = 14.98°$$

$$\bar{I}_s = \frac{\bar{V} - \bar{E}}{jX_s} = \frac{6350.85 - 12340.5\angle -14.98}{13.5\angle 90°}$$

$$= 475.5\angle 60.2°$$

$I_s = 475.5$ A, Power factor = cos 60.2° = 0.5 (leading)

(iii) At 750 rpm and rated field current (from part (i))

$$V = 4763 \text{ V},\ X_s = 6.75\ \Omega,\ E = 6170.25 \text{ V}$$

$$P_m = \frac{3VE}{X_s} \sin\delta$$

or $$-4.2 \times 10^6 = \frac{3 \times 4763 \times 6170.25}{6.75} \sin\delta$$

or $$\sin\delta = -0.32 \quad \text{or} \quad \delta = 18.757°$$

Now $$\bar{I}_s = \frac{\bar{E} - \bar{V}}{jX_s} = \frac{6170.25\angle 18.757° - 4763\angle 0°}{6.75\angle 90°}$$

$$= 293.98 - j159.92 = 334.66\angle -28.55°$$

Thus $$I_s = 334.66 \text{ A}$$

Power factor = cos (– 28.55°) = 0.878 (lagging)

(iv) From part (ii) at 1500 rpm

$$X_s = 13.5\ \Omega,\ V = 6350.85$$

$$E \text{ at rated field current} = 12340.85 \text{ V}$$

From part (i) rated armature current = 349.9 A

$$\bar{E} = \bar{V} + jX_s\bar{I}_s = 6350.85\angle 0° + j13.5 \times 349.9\angle 0°$$

$$= 6350.85 + j4723.65 = 7915\angle 36.64°$$

Field current $$= \frac{7915}{12340.85} \times 50 = 32.07 \text{ A}$$

$$P_m = \frac{3VE}{X_s}\sin\delta = \frac{3 \times 6350.85 \times 7915}{13.5}\sin 36.64° = 6666353 \text{ Watts}$$

Motor speed = 1500 rpm = 50π rad/sec

$$T = \frac{6666353}{50\pi} = 42439 \text{ N-m}$$

7.5 SELF-CONTROLLED SYNCHRONOUS MOTOR DRIVE EMPLOYING LOAD COMMUTATED THYRISTOR INVERTER

A self-controlled synchronous motor drive employing a load commutated thyristor inverter is shown in Fig. 7.10. In large power drives wound field synchronous motor is used. Medium power drives also employ permanent magnet syrschronous motor. The drive employs two converters, which are termed here as source side converter and load side converter. The source side converter is a 6-pulse line-commutated thyristor converter described in Sec. 5.12. For a firing angle range $0 \le \alpha_s \le 90°$, it works as a line-commutated fully controlled rectifier delivering positive V_{ds} and positive I_d, and for the range of firing angle $90° \le \alpha_s \le 180°$ it works as a line-commutated inverter delivering negative V_{ds} and positive I_d.

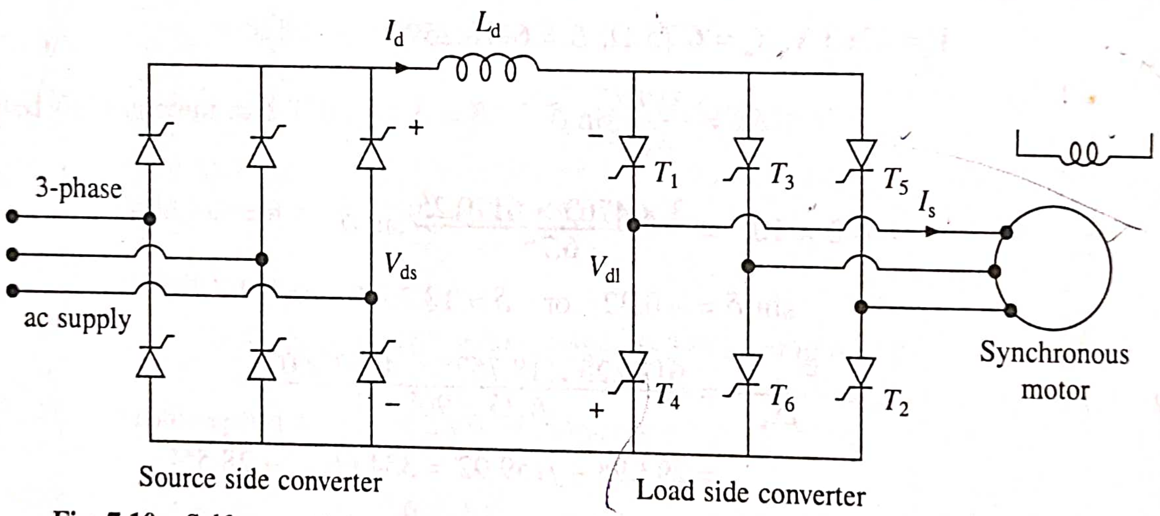


Fig. 7.10 Self-controlled synchronous motor drive employing load commutated inverter

When synchronous motor operates at a leading power factor, thyristors of the load side converter can be commutated by the motor induced voltages in the same way, as thyristors of a line-commutated converter are commutated by line voltages. Commutation of thyristors by induced voltages of load (here load is a motor) is known as load commutation. Firing angle is measured by comparison of induced voltages in the same way as by the comparison of line voltages in a line commutated converter. Converter operates as an inverter producing negative V_{dl} and carrying positive I_d for $90° \le \alpha_l < 180°$. For $0 \le \alpha_l \le 90°$ it works as a rectifier giving positive V_{dl}. For $0 \le \alpha_s \le 90°$, $90° \le \alpha_l \le 180°$ and with $V_{ds} > V_{dl}$, the source side converter works as a rectifier and load side converter as an inverter, causing power to flow from ac source to the motor, thus giving motoring operation. When firing angles are changed such that $90° \le \alpha_s < 180°$ and $0° \le \alpha_l \le 90°$, the load side converter operates as a rectifier and the source side as an inverter. Consequently, the power flow reverses and machine operates in regenerative braking. The magnitude of torque depends on ($V_{ds} - V_{dl}$). Speed can be changed by control of line side converter firing angles.

When working as an inverter, the firing angle has to be less than 180° to take care of commutation overlap and turn-off of thyristors. It is common to define a commutation lead angle for load side converter as

$$\beta_l = 180^\circ - \alpha_l$$

If commutation overlap is ignored, the input ac current of the converter will lag behind input ac voltage by angle α_l. Since motor input current has an opposite phase to converter input current, the motor current will lead its terminal voltage by an angle β_l. Therefore, the motor operates at a leading power factor.

Lower the value of β_l, higher the motor power factor and lower the inverter rating. The commutation overlap for the load side converter depends on the subtransient inductance of the motor. The motor is provided with a damper winding in order to reduce subtransient inductance. This allows operation with a substantially lower value of β_l. The damper winding does not play its conventional roles of starting the machine as an induction motor and to damp oscillations, because rotor and rotating field speeds are always the same as explained later. In a simple control scheme, the drive is operated at a fixed value of commutation lead angle β_{lc} for the load side converter working as an inverter and at $\beta_l = 180^\circ$ (or $\alpha_l = 0^\circ$) when working as a rectifier. When good power factor is required to minimize converter rating, the load side converter when working as an inverter is operated with *constant margin angle control*. If commutation overlap of the thyristor under commutation is denoted by u, then the duration for which the thyristor under commutation is subjected to reverse bias after current through it has fallen to zero is given by

$$\gamma = \beta_l - u$$

For successful commutation of thyristor

$$\gamma > \omega t_q$$

where t_q is the turn-off time of thyristors and ω the frequency of motor voltage in radians/sec. Since u is proportional to I_d, for a given I_d, β_l can be calculated such that the thyristor under commutation is reverse biased for a duration γ_{min} which is just enough for its commutation. This in turn minimizes β_l and maximizes motor power factor. Since γ is kept constant at its minimum value γ_{min}, the control scheme is called *constant margin angle control*.

The dc link inductor L_d reduces the ripple in the dc link current I_d and prevents the two converters from interfering with each other's operation. Because of the presence of inductor in the dc link, the load side converter when working as an inverter, behaves essentially as a current source inverter of Fig. 6.45, except that thyristor commutation is now performed by motor induced voltages. Consequently, the motor phase current has six step waveform of Fig. 6.45(b). Because of the dc current through L_d, the ac input current of source side converter also has a six step current waveform.

The dc line current I_d flows through the machine phase for 120° in each half cycle. Fundamental component of motor phase current I_s has following relationship with I_d

$$I_s = \frac{\sqrt{6}}{\pi} I_d \tag{7.24}$$

For machine operation in the self-controlled mode, rotating field speed should be the same as rotor speed. This condition is realised by making frequency of the load side converter output voltage equal to the frequency of voltage induced in the armature. Firing pulses are therefore generated either by comparison of motor terminal voltages (as induced voltages are not directly accessible) or by the rotor position sensors. Self control is ensured when firing pulses are generated by the comparison of motor terminal voltages (as induced voltages are not directly accessible). Alternatively firing pulses are generated by rotor position sensors, which are stationary and suitably aligned with the armature winding. The frequency of induced voltages depends on the speed of rotor (or rotor field) and their phase depends on the location of rotor poles with respect to the armature winding. Hence, signals generated by rotor position sensors have the same frequency as that of the induced voltages and they have a definite phase with respect to induced voltages. Load side converter thyristors are fired in the sequence of their numbers with 60° interval. Therefore, for the control of load side converter thyristors, in all six rotor angular positions are required to be detected per cycle of the induced voltage. The Hall-effect sensors can detect the magnitude and direction of a magnetic field. Hence, three Hall-effect sensors can detect the six rotor positions. The sensors are mounted at 60° electrical intervals and aligned suitably with armature winding.

As stated earlier the load side converter and the current source inverter of Fig. 6.45 perform essentially the same function. The only difference between the two is that while the former uses the load commutation, the later uses forced commutation. Load commutation has a number of advantages over forced commutation: (i) it does not require commutation circuits, (ii) frequency of operation can be higher, and (iii) it can operate at power levels beyond the capability of forced commutation [1].

Load side converter performs somewhat similar function as commutator in a dc machine. The load side converter and synchronous motor combination functions similar to a dc machine. First, it is fed from a dc supply and secondly like a dc machine the stator and rotor fields remain stationary with respect to each other at all speeds. Consequently, the drive consisting of load side converter and synchronous motor is known as *commutator less dc motor*.

At low speeds, motor induced emf will be insufficient to commutate the thyristors of load side converter, therefore, at start and for speeds below 10% of base speed, the commutation of load side converter thyristors is done by forcing the current through conducting thyristors to zero. This is realised by making source side converter to work as inverter each time load side converter thyristors are to be turned off.

For example thyristors T_1 and T_2 are to conduct together for 60° electrical. After 60°, source side converter will be made to work as an inverter, which will reverse V_{ds}, and turn-off thyristors T_1 and T_2. Now the source side converter operation is brought back to rectification and gate pulses are released to T_2 and T_3 to turn them on and make them conduct together for next 60° electrical. Since frequency of operation of load side converter at low motor speeds is very low compared to source frequency, such an operation can be realized. This operation of the inverter can be termed as *pulsed mode*. This mode of operation requires rotor position sensors. Therefore, even when the normal operation above 10% of base speed is implemented by sensing motor terminal voltages, rotor position sensors will be needed to realize pulsed mode.

The dc supply to the field can be provided from a controlled rectifier through slip-rings and brushes. Alternatively, brushless excitation system consisting of diode bridge mounted on the rotor and therefore rotating with the rotor and supplied by a rotating transformer can be used. The field current is controlled by controlling the input voltage of the transformer by feeding it from an ac voltage regulator. The brushless excitation eliminates slip-rings and brushes and associated maintenance.

A closed-loop speed control scheme is shown in Fig. 7.11. It employs outer speed control loop and inner current control loop with a limiter, like a dc motor (Fig. 5.47). The terminal voltage sensor generates reference pulses of the same frequency as the machine-induced voltages. The phase delay circuit shifts the reference pulses suitably to obtain control at a constant commutation lead angle β_{lc}. Depending on the sine of speed error, β_{lc} is set to provide motoring or braking operation. Speed ω_m can be sensed either from the terminal voltage sensor or from a separate tachometer. An increase in reference speed ω_m produces a positive speed error. β_{lc}

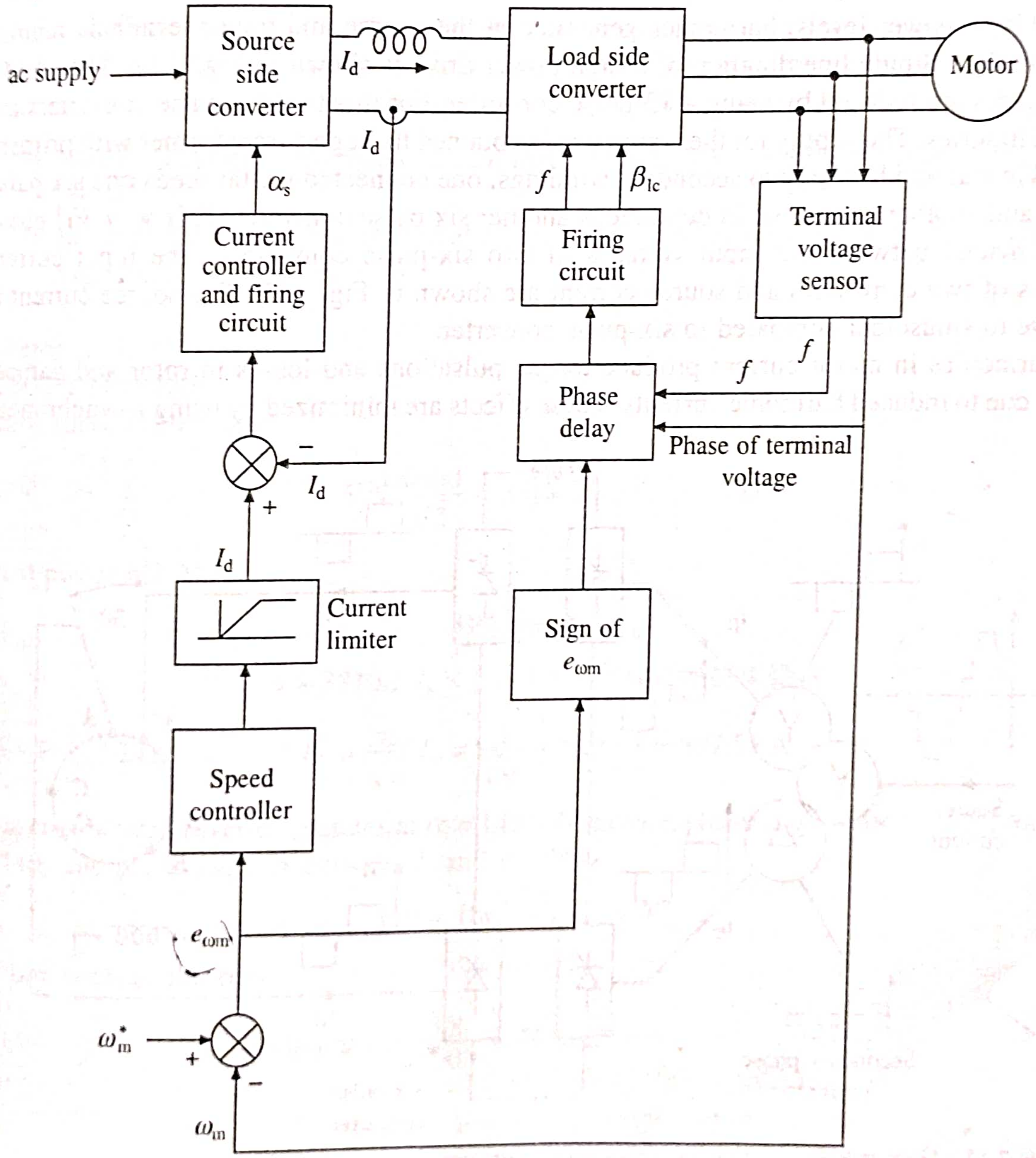


Fig. 7.11 Closed-loop speed control of load commutated inverter synchronous motor drive

value is set for motoring operation. The speed controller and current limiter set the dc link current reference at the maximum permissible value. The machine accelerates fast. When close to the desired speed, the current limiter desaturates and the drive settles at the desired speed and at the dc link current which balances motor and load torques. Similarly a reduction in reference speed produces a negative speed error. This sets β_{lc} for regenerative braking operation (i.e. 180°) and the motor decelerates. When speed error changes sign β_{lc} value is set for motoring operation and the drive settles at the desired speed.

High efficiency, four-quadrant operation with regenerative braking, high power ratings (up to 100 MW) and ability to run at high speeds (6000 rpm) are some important advantages of this drive. Some prominent applications are high speed and high power drives for compressors, blowers, fans, pumps, conveyers, steel rolling mills, main line traction, ship propulsion and aircraft test facilities.

At very high power levels, harmonics generated at the source and motor terminals require special attention. Single line diagram of a high power drive is shown in Fig. 7.12. The source side harmonics are reduced by using a 12-pulse converter. For this two six-pulse converters are connected in series. The supply for the converters is obtained through a transformer with primary connected in star and having two secondary windings, one connected in star feeds one six pulse converter and another connected in delta feeds another six pulse converter. This way 30° phase shift is provided between the input voltages of two six-pulse converters. The input current waveforms of two converters and source current are shown in Fig. 7.12. The source current is more close to sinusoidal compared to six-pulse converter.

The harmonics in motor current produce torque pulsations and losses in rotor and damper windings due to induced harmonic currents. These effects are minimized by using a synchronous

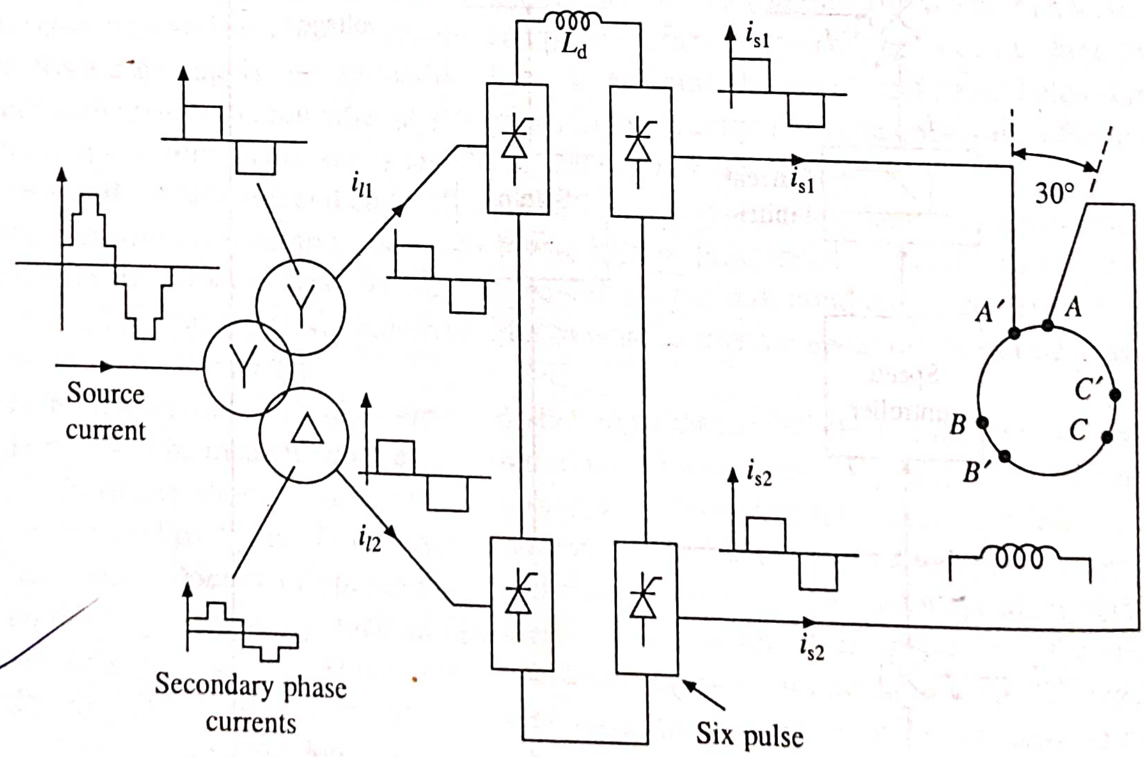


Fig. 7.12 High power synchronous motor drive with series connections of 6-pulse converters to obtain 12-pulse configurations

motor equipped with two three phase windings on stator with a phase shift of 30° between their axes and feeding them from two series connected six-pulse load commutated converters with their output current phase shifted by 30° (Fig. 7.12). The resultant stator mmf has twelve pulse waveform. Therefore, torque pulsations and rotor and damper winding losses are reduced. When the motor has only single winding, it can be supplied with 12-pulse current by connecting the series connected six-pulse converters with the motor via transformers in the same way as mentioned above for source side converters.

EXAMPLE 7.4

A synchronous motor is controlled by a load commutated inverter, which in turn is fed from a line commutated converter. Source voltage is 6.6 kV, 50 Hz. Load commutated inverter operates at a constant firing angle α_l of 140° and when rectifying $\alpha_l = 0°$. dc link inductor resistance $R_d = 0.1\ \Omega$. Drive operates in self-control mode with a constant (V/f) ratio. Motor has the details: 8 MW, 3-phase, 6600 V, 6 pole, 50 Hz, unity power factor, star connected, $X_s = 2.8\ \Omega$, $R_s = 0$. Determine source side converter firing angles for the following:

(i) Motor operation at the rated current and 500 rpm. What will be the power developed by motor?

(ii) Regenerative braking operation at 500 rpm and rated motor current. Also calculate power supplied to the source.

Solution

At 50 Hz operation

Motor speed = 1000 rpm

$$V = \frac{6600}{\sqrt{3}} = 3810.5\ \text{V},\ X_s = 2.8\ \Omega$$

Rated power = 8 MW

$$3VI_s \cos\phi = P_m$$

$$3 \times 3810.5\ I_s \times 1 = 8 \times 10^6 \text{ or } I_s = 699.82\ \text{A}$$

From Eq. (7.24)

$$I_d = \frac{\pi}{\sqrt{6}} I_s = \frac{\pi}{\sqrt{6}} \times 699.82 = 897.55\ \text{A}$$

Load commutated inverter operates at $\alpha_l = 140°$. Therefore, phase angle between $(-I_s)$ and V will be 140° and phase angle ϕ, between I_s and V will be

$$\phi = 180° - 140° = 40°$$

For operation at 500 rpm

$$\text{Frequency} = \frac{500}{1000} \times 50 = 25\ \text{Hz}$$

$$V = \frac{25}{50} \times 3810.5 = 1905.25\ \text{V}$$

Now

$$P_m = 3VI_s \cos\phi = 3 \times 1905.25 \times 699.82 \cos 40° = 3.064\ \text{MW}$$

Now for three-phase load commutated inverter

$$V_{dl} = \frac{3\sqrt{6}}{\pi} V \cos \alpha_l = \frac{3\sqrt{6}}{\pi} \times 1905.25 \cos 140° = -3413.9 \text{ V}$$

$$V_{ds} = -V_{dl} + I_d R_d = 3413.9 + 897.55 \times 0.1 = 3503.67 \text{ V}$$

Also $$V_{ds} = \frac{3\sqrt{6}}{\pi} V_s \cos \alpha_s$$

Thus $$3503.67 = \frac{3\sqrt{6}}{\pi} \times \frac{6600}{\sqrt{3}} \cos \alpha_s \quad \text{or} \quad \cos \alpha_s = 0.393 \text{ and } \alpha_s = 66.85°$$

(ii) From part (i) rated $I_s = 699.82$ A, $I_d = 897.55$ A

At 500 rpm, $V = 1905.25$
When rectifying $\alpha_l = 0$, the machine operates at $\phi = 0$, or unity power factor

$$P_m = 3VI_s \cos \phi = 3 \times 1905.25 \times 699.82 \times 1 = 3999996 \text{ Watts}$$

Assuming negligible loss in both converters,

$$\text{Power supplied to the source} = P_m - I_d^2 R_d$$

$$= 3999996 - 897.55^2 \times 0.1 = 3.919 \text{ MW}$$

For load commutated converter

$$V_{dl} = \frac{3\sqrt{6}}{\pi} V \cos \alpha_l = \frac{3\sqrt{6}}{\pi} \times 1905.25 \cos 0° = 4456.6 \text{ V}$$

$$V_{ds} = I_d R_d - V_{dl} = 897.55 \times 0.1 - 2333.4 = -4366.8 \text{ V}$$

$$V_{ds} = \frac{3\sqrt{6}}{\pi} V_s \cos \alpha_s \text{ or } -2243.6 = \frac{3\sqrt{6}}{\pi} \times \frac{6600}{\sqrt{3}} \cos \alpha_s$$

or $$\cos \alpha_s = -0.49 \text{ or } \alpha_s = 113.9°$$

7.6 STARTING LARGE SYNCHRONOUS MACHINES

When operating with self-control, the starting current is low and starting torque is high, compared to direct on-line starting as an induction motor. Hence, self control is employed for starting large synchronous machines in gas turbine and pumped-storage power plants. Load-commutated inverter drive of Fig. 7.10 is employed. From stand-still to 10% of base speed, the inverter is operated in pulsed mode as motor induced voltages are not sufficient to commutate thyristors. Above 10% of base speed to synchronous speed, the inverter operates with load commutation. When conditions become favourable for synchronization, the machine is switched into mains and inverter is disconnected. Though expensive, such a starting method becomes economical when a number of synchronous machines time share a common inverter.

7.7 SELF-CONTROLLED SYNCHRONOUS MOTOR DRIVE EMPLOYING A CYCLOCONVERTER

Self-controlled drive of Fig. 7.13 consists of a synchronous motor fed by a cycloconverter. Firing pulses are generated either by comparison of the motor terminal voltages or by rotor position senors as in the case of drive of Fig. 7.10.

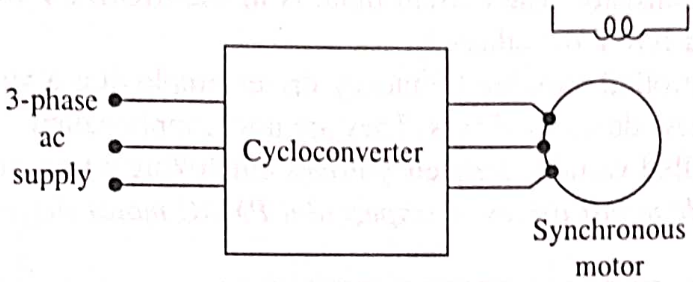


Fig. 7.13 Self-controlled synchronous motor drive employing a cycloconverter

Cycloconverter control has the advantages of smooth low speed operation, four-quadrant operation with regenerative braking and good dynamic response. But it has low speed range and because it uses large number of thyristors it becomes economically acceptable only when the drive rating is high. A synchronous motor without the damper winding is used, because the damper winding reduces the inductance of the machine, and therefore, its ability to filter out harmonics in the output voltage of cycloconverter. Since the drive operates in self-controlled mode, the damper winding is not needed for its conventional roles.

The drive is employed in low speed gearless drives for ball mills in cement plants, mine hoists, reversing rolling mills requiring fast dynamic response and in ships equipped with diesel generator fed cycloconverter controlled synchronous motor drives. These drives have power ratings in the megawatt range. At such high power levels, considerable saving in cycloconverter cost is obtained by operating the motor at unity power factor by adjusting the field current.

A typical rating of a synchronous motor for a ball mill in a cement plant is: 8750 hp, unity power factor, 14.5 rpm, 4.84 Hz, 1900 V and 40 poles. A cycloconverter is ideally suitable for such a low frequency supply. Earlier gears were employed to get low speed operation. Absence of gears in this drive reduces the cost and maintenance requirements. Because of similarity with an ac commutator motor, the drive is also known as ac commutatorless motor.

7.8 PERMANENT MAGNET ac MOTOR DRIVES

Permanent magnet synchronous motors are now commonly known as permanent magnet ac (PMAC) motors. They are classified based on the nature of voltage induced in the stator as *sinusoidally excited* and *trapezoidally excited*; in the former induced voltage has a sinusoidal waveform and in the later induced voltage has trapezoidal waveform. These PMAC motors are commonly known as *sinusoidal PMAC* and *trapezoidal PMAC* motors. A sinusoidal PMAC motor has distributed winding (similar to wound field synchronous motor) in the stator. It employs rotor geometries such as inset or interior shown in Fig. 7.1. Rotor poles are so shaped that the voltage induced in a stator phase has a sinusoidal waveform. The stator of a trapezoidal PMAC motor has concentrated windings and a rotor with a wide pole arc. The voltage induced in the stator phase has a trapezoidal waveform. It employs rotor geometries such as surface magnets shown in Fig. 7.1.

The speed of PMAC motors is controlled by feeding them from variable frequency voltage/currents. They are operated in self-controlled mode. Rotor position sensors are employed for operation in self-control mode. Alternatively induced voltage can be used to achieve self-control.

Different inverter/converter circuits for PMAC motors described in Secs. 7.8 to 7.10 are drawn using a power transistor. The current trend is to use MOSFET for low voltage and low power applications and IGBT for others.

In the past self-controlled variable frequency drives employing a sinusoidal PMAC motor were also called brushless dc motor drives. They are now simply called *sinusoidal PMAC motor drives*. The self-controlled variable frequency drives employing a trapezoidal PMAC motor are now called *brushless dc motor drives* or *trapezoidal PMAC motor drives*.

7.9 SINUSOIDAL PMAC MOTOR DRIVES

Since the voltages induced in the stator phases of a sinusoidal PMAC motor are sinusoidal, ideally, the three stator phases must be supplied with variable frequency sinusoidal voltages or currents with a phase difference of 120° between them. Behavior of such a motor from a variable frequency voltage source is already described in earlier sections. Let us now examine its behavior from a variable frequency current source.

Fig. 7.13(a) is the Norton's equivalent of the synchronous motor equivalent circuit of Fig. 7.2. Where

$$\bar{I}_f = \frac{\bar{E}}{jX_s} = \frac{E}{X_s} \angle -(\delta + \pi/2) \tag{7.25}$$

$$\bar{I}_m = \bar{I}_s + \bar{I}_f \tag{7.26}$$

The phasor diagram of the motor with I_s as a reference phasor is shown in Fig. 7.13(b). The mechanical power developed is

$$P_m = 3EI_s \cos(\delta' - \pi/2)$$

Substituting for E from Eq. (7.25) gives

$$P_m = 3X_s I_s I_f \sin \delta' \tag{7.27}$$

Now

$$T = \frac{P_m}{\omega_{ms}} = KI_s I_f \sin \delta' \tag{7.28}$$

where $K = \dfrac{3X_s}{\omega_{ms}}$ = constant.

For

$$\delta' = \pm 90°$$

$$T = \pm KI_f I_s = \pm K_T I_s \tag{7.29}$$

Hence torque is proportional to I_s.

For a given value of I_s, maximum torque is obtained when $\delta' = \pi/2$. Phasor diagram for $\delta' = \pi/2$ is shown in Fig. 7.13(c). In this condition, the motor is said to operate with unity internal

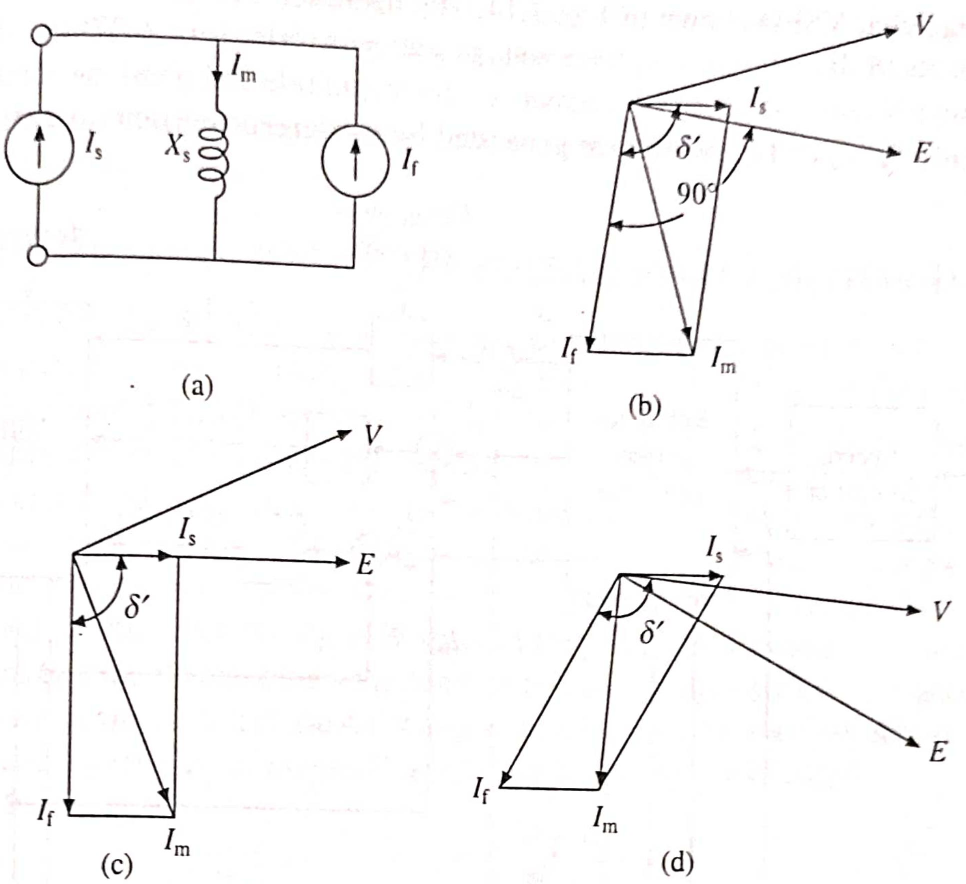


Fig. 7.13 Equivalent circuits and phasor diagrams

power factor because I_s is in phase with E. The motor itself has a lagging power factor. It is desirable to obtain maximum torque per unit of stator current, therefore, this is the preferred operating condition. Similarly in braking operation, maximum torque per unity of stator current is obtained when $\delta' = -\pi/2$, hence this is the preferred operating condition for braking operation. The condition $\delta = -\pi/2$ is obtained by reversing stator current I_s. It should be noted that δ' is the angle between the rotating fields produced by the stator and rotor and the maximum torque is obtained when the axis of two fields make an angle of $\pm \pi/2$.

Flux Weakening: There are applications which require speed control in wide range. In wound field motors, the operation up to the base speed is obtained by varying both voltage and frequency. The speed control above the base speed is obtained by reducing the air-gap flux so that motor terminal voltage remains at the rated value as frequency is increased. In Fig. 7.13(c), air-gap flux can be reduced by reducing I_m. In a would field machine this can be achieved by reducing I_f by reducing field current. This cannot be done in a permanent magnet machine. However, I_m for a given I_s can be progressively reduced by increasing δ' with speed, as shown in the phasor diagram of Fig. 7.13(d). At $\delta = 90°$, I_s is in quadrature with I_f For $\delta' > 90°$, I_s can be resolved into two components, one in quadrature with I_f and another in phase opposition to I_f, which causes reduction in I_m and air-gap flux.

7.9.1 Servo Drive Employing Sinusoidal PMAC Motor Fed from a Current Regulated Voltage Source Inverter

The block diagram of a closed loop variable speed drive employing sinusoidal PMAC motor fed from current regulated VSI is shown in Fig. 7.14. The operation of a current regulated VSI is described in Sec. 6.18. It employs a 3-phase voltage source inverter [Fig. 6.37(a)]. The inverter is operated to supply motor three phase currents of the magnitude and phase as commanded by reference currents i_A^*, i_B^* and i_C^*, which are generated by a reference current generator.

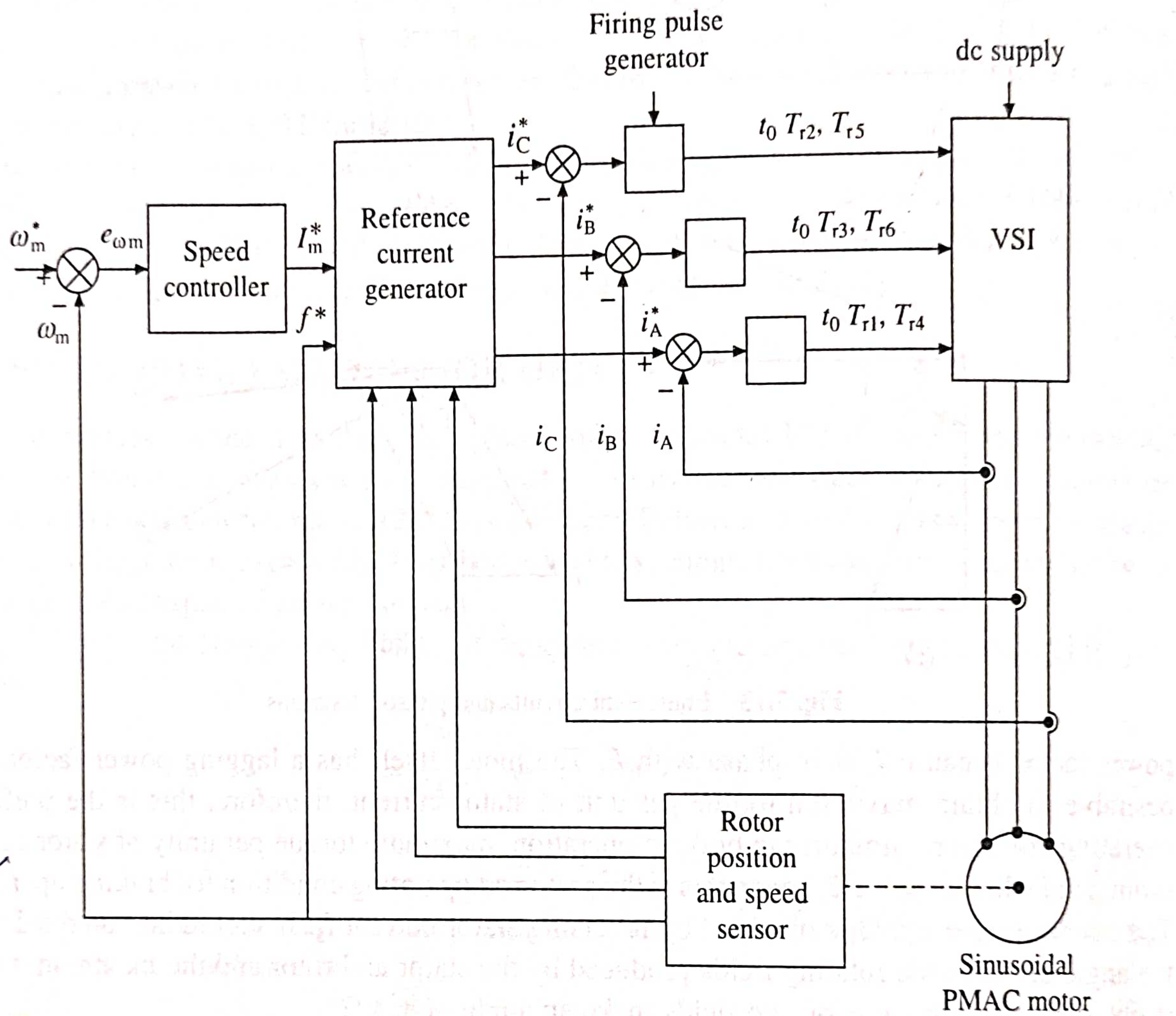


Fig. 7.14 Current regulated VSI fed sinusoidal PMAC motor drive for servo application

The actual speed ω_m is compared with reference speed ω_m^*. The speed error is processed through the speed controller. The output of the speed controller sets a reference for the amplitude and polarity of the stator current I_s^*. The stator current templates for the three phases are generated by the rotor position sensors in such a way that $\delta' = \pi/2$. When speed error is positive the machine will work as a motor and the drive will accelerate to reference speed ω_m^*. If speed error is negative, braking will decelerate the motor to reference speed ω_m^*.

Since sinusoidal current template is to be generated based on the rotor position, an absolute rotor position sensor or resolver is required, which is expensive. Because of features like excellent dynamic performance, and low torque ripple, the drive is widely used in high performance servo drives inspite of its high cost.

For the production of maximum torque for a given stator current, the rotating fields produced by the stator and rotor should have an angle of 90°. The stator field will be along phase A axis when the current in phase A reaches its positive peak. The rotor South Pole axis, at this instant must be 90° electrical behind. Therefore, rotor South Pole axis must be 180° electrical behind phase A axis at the positive zero crossing of phase A current. This information is utilized to locate the rotor position sensor.

A servo drive for closed-loop position control is obtained by adding a position loop around the speed loop in Fig. 7.14.

7.10 BRUSHLESS dc (OR TRAPEZOIDAL PMAC) MOTOR DRIVES

The cross section of a 3-phase 2 pole trapezoidal PMAC motor is shown in Fig. 7.15. It has permanent magnet rotor with wide pole arc. The stator has three concentrated phase windings, which are displaced by 120° and each phase winding spans 60° on each side. The voltages induced in three phases are shown in Fig. 7.17(a). The reason for getting the trapezoidal waveforms can now be explained. When revolving in the counter-clockwise direction, up to 120° rotation from the position shown in Fig. 7.15, all top conductors of phase A will be linking the south pole and all bottom conductors of phase A will be linking the north pole. Hence the voltage induced in phase A will be the same during 120° rotation (Fig. 7.17(a). Beyond 120°, some conductors in the top link north pole and others the south pole. Same happens with the bottom conductors. Hence, the voltage induced in phase A linearly reverses in next 60° rotation. Rest of the waveform of phase A and waveforms of phases B and C can be similarly explained.

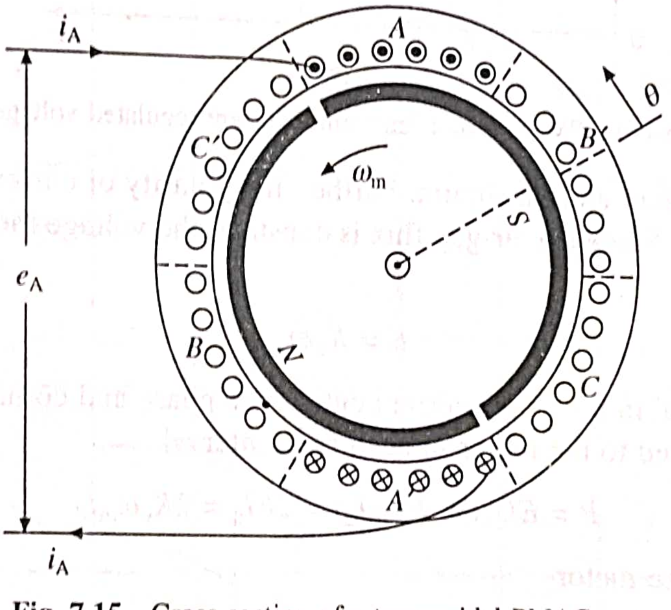


Fig. 7.15 Cross section of a trapezoidal PMAC motor

An inverter fed trapezoidal PMAC motor drive operating in self-controlled mode is called a brushless dc motor.

7.10.1 Brushless dc Motor Drive for Servo Applications

A brushless dc motor employing a voltage source inverter (VSI) and a trapezoidal PMAC motor is shown in Fig. 7.16(a). The stator windings are star connected. It will have rotor position sensors, which are not shown in the figure. The phase voltage waveforms for a trapezoidal PMAC motor are shown in Fig. 7.17(a). Let the stator windings be fed with current pulses shown in Fig. 7.17(b). The current pulses are each of 120° duration and are located in the region where

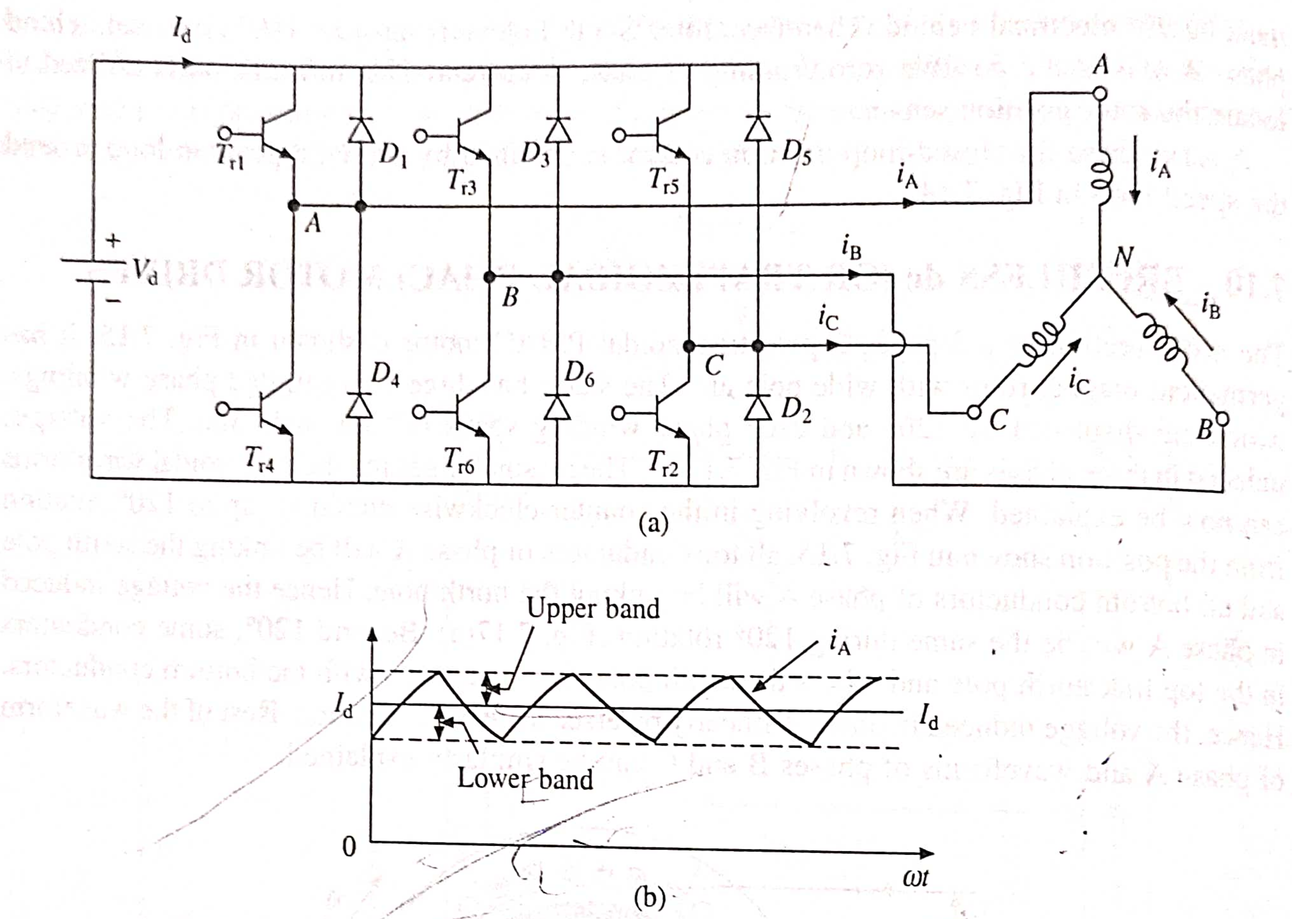


Fig. 7.16 Trapezoidal PMAC motor fed from a current regulated voltage source inverter

induced voltage is constant and maximum. Further, the polarity of current pulses is the same as that of induced voltage. Since the air-gap flux is constant, the voltage induced is proportional to speed of rotor.

$$E = K_e \omega_m \tag{7.30}$$

During each 60° interval in Fig. 7.17, current enters one phase and comes out of another phase, therefore, power supplied to the motor in each such interval

$$P = EI_d + (-E)(-I_d) = 2EI_d = 2K_e\omega_m I_d$$

Torque developed by the motor

$$T = \frac{P}{\omega_m} = 2K_e I_d = K_T I_d \tag{7.31}$$

The waveform of torque is given in Fig. 7.17(c). According to Eq. (7.31) torque is proportional to current I_d. It can be shown that a dc current I_d flows in the dc link. Regenerative braking operation is obtained by reversing phase currents. This will also reverse the source current I_d. Now power flows from the machine to inverter and from inverter to dc source. When speed is reversed, the polarity of induced voltages reverse. With current polarity shown in Fig. 7.17, the drive gives regenerative braking operation, and when current direction is reversed motoring operation is obtained. The current waveforms shown in Fig. 7.17(b) are produced as follows.

During the period 0° to 60°, $i_A = I_d$ and $i_B = -I_d$. The current i_A enters through the phase A and

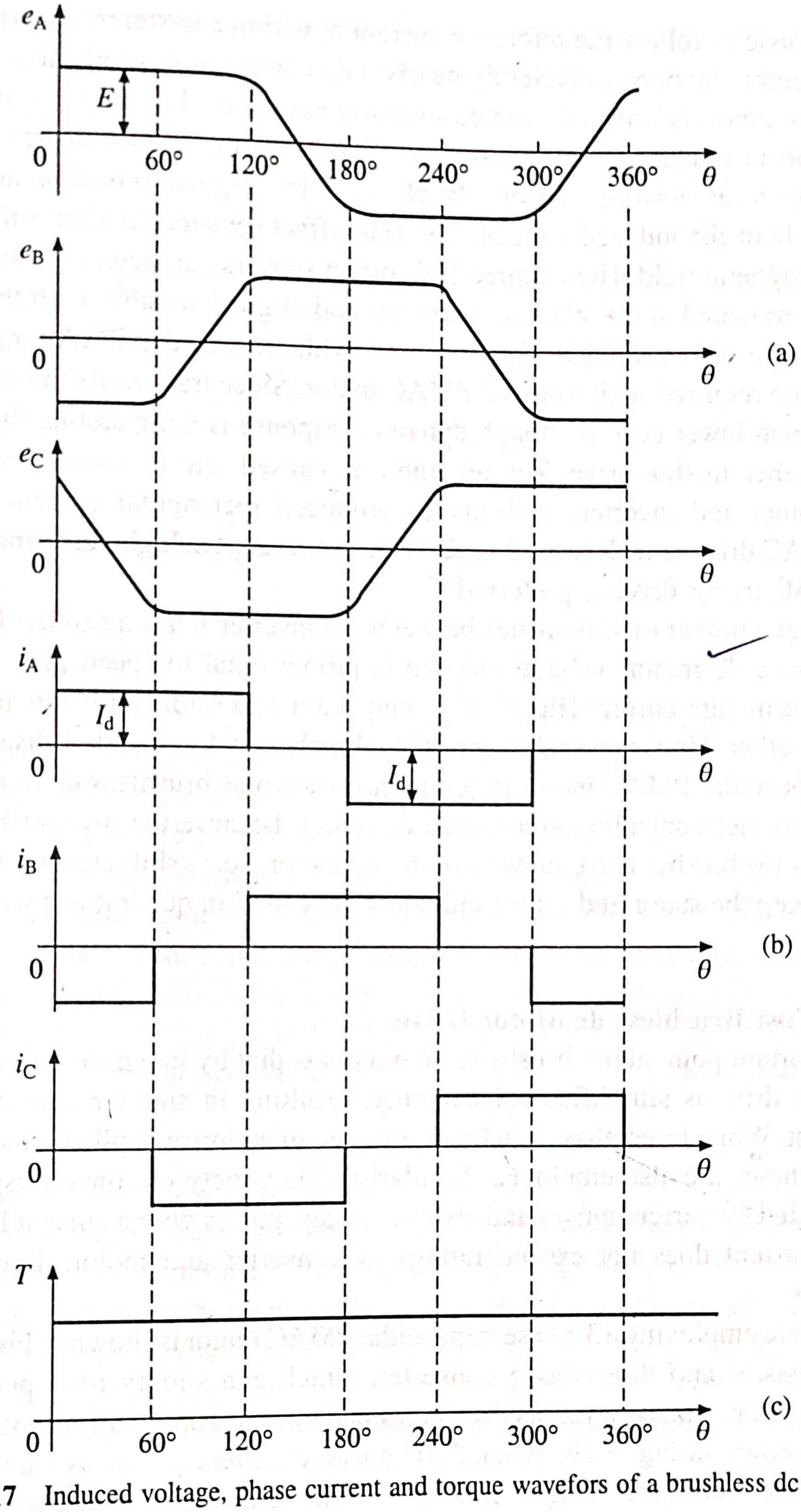


Fig. 7.17 Induced voltage, phase current and torque wavefors of a brushless dc motor

leaves through the phase B. When transistors T_{r1} and T_{r6} are on, terminals A and B are respectively connected to positive and negative terminals of the dc source V_d. A current will flow through the path consisting of V_d, T_{r1}, phase A, phase B and T_{r6} and rate of change of current i_A will be positive. When T_{r1} and Tr_6 are turned off this current will flow through a path consisting of phase A, phase B, diode D_3, V_d and diode D_4. Since the current has to flow against voltage V_d, the rate of change of i_A will be negative. Thus, by alternately turning on and off T_{r1} and T_{r6}, phase A

current can be made to follow the reference current I_d within a hysteresis band as shown in Fig. 7.16(b). By reducing the band sufficiently nearly a dc current of desired value can be produced. The operation for other 60° intervals can be similarly explained. For properly placing the current pulses with respect to induced voltages, or identification of these sixty-degree intervals, signals are generated by rotor position sensors. In all six rotor angular positions are required to be detected per cycle of the induced voltage. The Hall effect sensors can detect the magnitude and direction of a magnetic field. Hence three Hall-effect sensors can detect the six rotor positions. The sensors are mounted at 60° electrical interval and aligned suitably with the stator winding. Optical sensors are also available. Sensors used with trapezoidal PMAC motor are cheaper compared to those required with sinusoid PMAC motor. Since trapezoidal motor is also cheaper, the drive has much lower cost. Although dynamic response is comparable, the torque ripple is considerably higher in this drive. Torque ripple is caused due to induced voltage not being exactly trapezoidal and inverters inability to produced rectangular current waveforms. The trapezoidal PMAC drive is widely used in servo drives, except in high performance drives where sinusoidal PMAC motor drive is preferred.

There are large number of similarities between the inverter fed trapezoidal PMAC motor and a dc motor. Like a dc motor, voltage induced is proportional to speed [Eq. (7.30)], torque is proportional to armature current [Eq. (7.31)], and stator and rotor fields remain stationary with respect to each other. However, it does not have brushes and associated disadvantages, hence inverter-fed trapezoidal PMAC motor is commonly known as brushless dc motor. This motor is also conceived as electronically commutated dc motor, because the inverter here performs the same function as the brushes and commutator in a dc motor, i.e. to shift currents between armature conductors to keep the stator and rotor fields stationary (and in quadrature) with respect to each other.

7.10.2 Low Cost Brushless dc Motor Drives

One of the important point about brushless dc motors is that by integration of converter/inverter with motor, the drive is simplified substantially, resulting in simpler control and substantial reduction in cost. While three phase machines are used in majority applications, single phase and four phase machines are also employed. Similarly wide variety of converters/inverters is used. The motors are fed by current pulses and also by voltage pulses with a current limit only to make sure that the current does not exceed ratings of converter and motor. Two such drives are described below.

A low cost drive employing a 3-phase trapezoidal PMAC motor is shown in Fig. 7.18. It employs only three transistor and three diode converter, which can supply only positive currents or voltages to three motor phases. Induced voltages and current supplied for motoring and braking operations are shown in Fig. 7.19. When 120° positive current pulses as shown in Fig. 7.19(b) are supplied to the motor, motoring operation is obtained in counter clockwise direction. When these pulses are shifted by 180°, as shown in Fig. 7.19(c), braking operation is obtained. Motoring and braking operations for clockwise rotation is obtained by timing the pulses as shown in Fig. 7.19(c) and (b), respectively. Each phase is essentially supplied by a chopper. The phase NA current is controlled by T_{r1} and D_1. When T_{r1} is on source V_d is connected across winding NA and rate of change of i_A is positive. When T_{r1} is turned off, current i_A freewheels through diode D_1 and rate of change of i_A is negative. Thus during the period for 0° to 120°, T_{r1} can be alternately turned on and off so that current i_A is made to follow a rectangular reference current i_A^* within a hysteresis band.

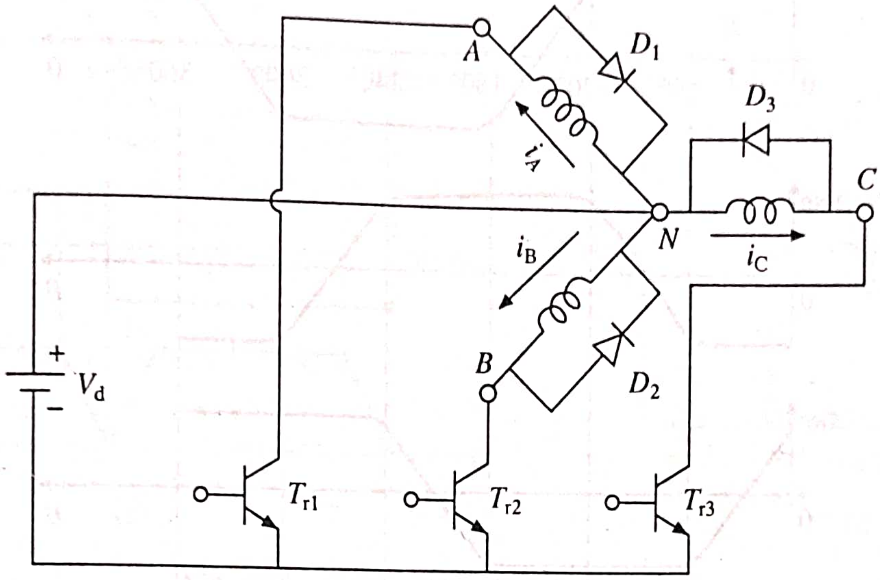


Fig. 7.18 A low cost-three phase brushless dc motor drive

As compared to the drive of Fig. 7.16, the torque produced by this drive for a given value of I_d will be half, giving slower dynamic response. The drive also has higher torque ripple.

Let us also examine a single phase brushless dc motor. Let the motor has wide pole arc as shown in Fig. 7.15 and a single concentrated phase winding with a spread of 60° on either side. Let θ be measured from the instant when the axis of phase coincides with the axis of the rotor pole, then the voltage induced in the phase winding will have waveform as shown in Fig. 7.20. Let the motor be supplied from a half bridge single phase converter shown in Fig. 7.20(d) with a rectangular current waveforms shown in Fig. 7.20(b). Then the torque produced by the motor will have waveform shown in Fig. 7.20(c). Although the torque has a large ripple, when running at high speeds the torque ripple will be filtered out by the inertia of motor load system, giving a uniform speed.

7.10.3 Important Features and Applications

Due to the absence of brushes and commutator, brushless dc motors have a number of advantages compared to conventional dc motors. They require practically no maintenance, have long life, high reliability, low inertia and friction, and low radio frequency interference and noise. Due to low inertia and friction, they have a faster acceleration and can be run at much higher speeds - up to 100,000 rpm and higher are common. Because armature windings are on the stator, cooling is much better, i.e. higher specific outputs can be obtained. These motors have high efficiency, exceeding 75% whereas wound field motors of low power ratings have much lower efficiency. The disadvantages compared to conventional dc motors are high cost and low starting torque. The size of a brushless dc motor is nearly the same as of conventional dc motor.

The brushless dc motor finds applications in turn table drives in record players, tape drive for video recorders, spindle drives in hard disk drives for computers, and low cost and low power drives in computer peripherals, instruments and control systems. They also have applications in the fields of aerospace, e.g. gyroscope motors, and biomedical like cryogenic coolers and artificial heart pumps. They are also used for driving cooling fans for electronic circuits and heat sinks.

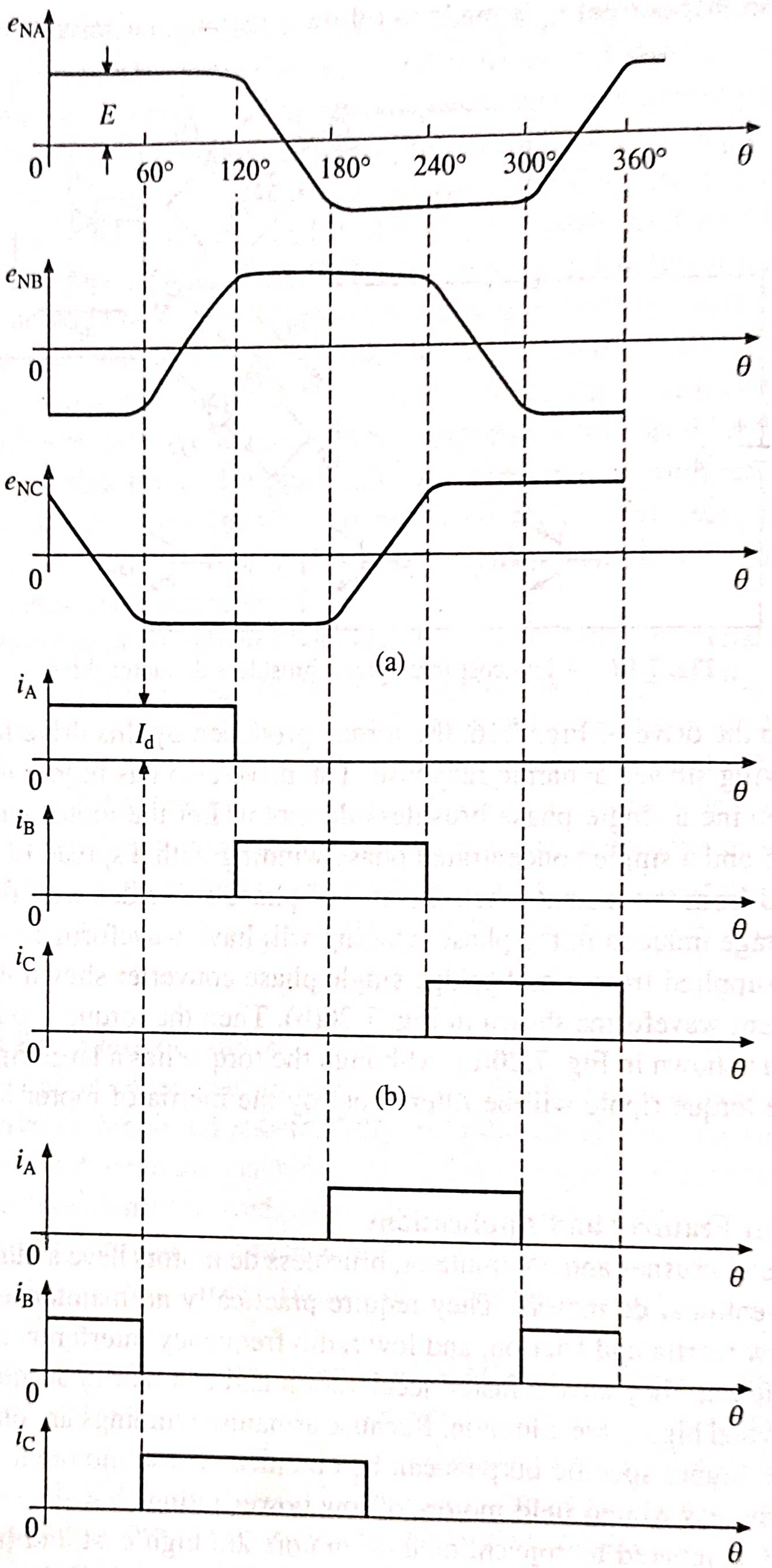


Fig. 7.19 A low cost three-phase brushless dc motor drive

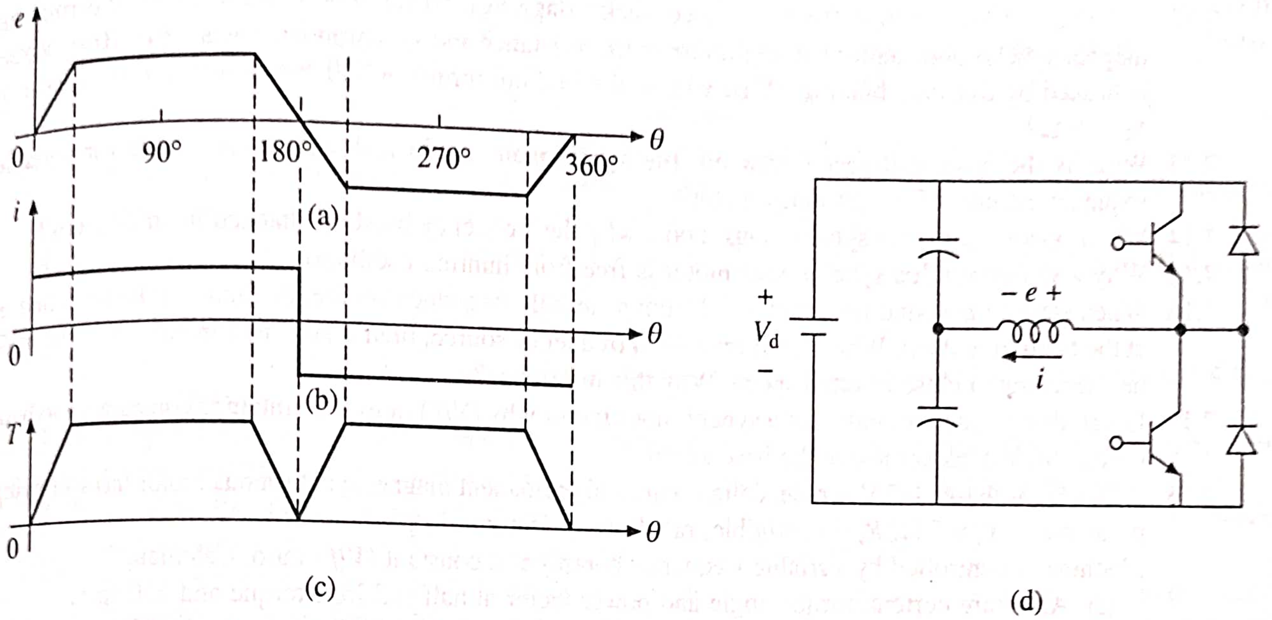


Fig. 7.20 Single-phase brushless dc motor

PROBLEMS

7.1 Why a synchronous motor does not have starting torque?

7.2 How do you start a synchronous motor?

7.3 State and explain the roles of a damper winding in a synchronous motor.

7.4 When started on no load, a salient pole synchronous motor pulls into synchronism even before dc excitation is applied, why?

7.5 When rotor speed is close to synchronous speed, application of dc field leads to pull-in of the rotor into synchronism. However, application of dc field at a speed considerably lower than synchronous speed does not lead to pull-in of the rotor into synchronism, why?

7.6 What are the important features of a hysteresis synchronous motor? What are its applications?

7.7 How the operation of a synchronous motor shifts from motoring to regenerative braking?

7.8 A 3-phase, 5 kW, 440 V, 50 Hz, 4 pole, Y-connected synchronous motor has stator winding resistance of 0.2Ω, synchronous reactance of 8 Ω and a rated field current of 1 A. When operating at full load the power factor is unity.

(i) Calculate the torque angle when operating at full load.
(ii) Pull-out torque and power.
(iii) Power factor, armature current and efficiency at half the rated torque.
(iv) Field current to get unity power factor at half the rated torque.

7.9 A 3-phase, 5 KW, 440 V, 0.8 rated power factor (lagging), 50 Hz, 6 pole, star-connected synchronous motor has negligible stator winding resistance and synchronous reactance of 6 Ω. Calculate

(i) Torque angle at full load
(ii) Pull out torque
(iii) Armature current and power factor at half the rated torque
(iv) Torque when operating at unity power factor and 150% of rated field current.

7.10 Motor of Problem 7.8 is now operated under regenerative braking with its terminals connected to a bus having rated motor voltage.

(i) Field current is adjusted so that motor operates at rated current and unity power factor. Calculate braking torque, torque angle and field current.
(ii) Calculate power factor and armature current when the machine develops braking torque equal to rated torque. Field current is 1.2 A.

7.11 Permanent magnet motor of Problem 7.9 is operating in regenerative braking at braking torque equal to 1.2 times the rated motor torque. Calculate stator current and power factor.