Industrial Drives and Applications (18EE741)

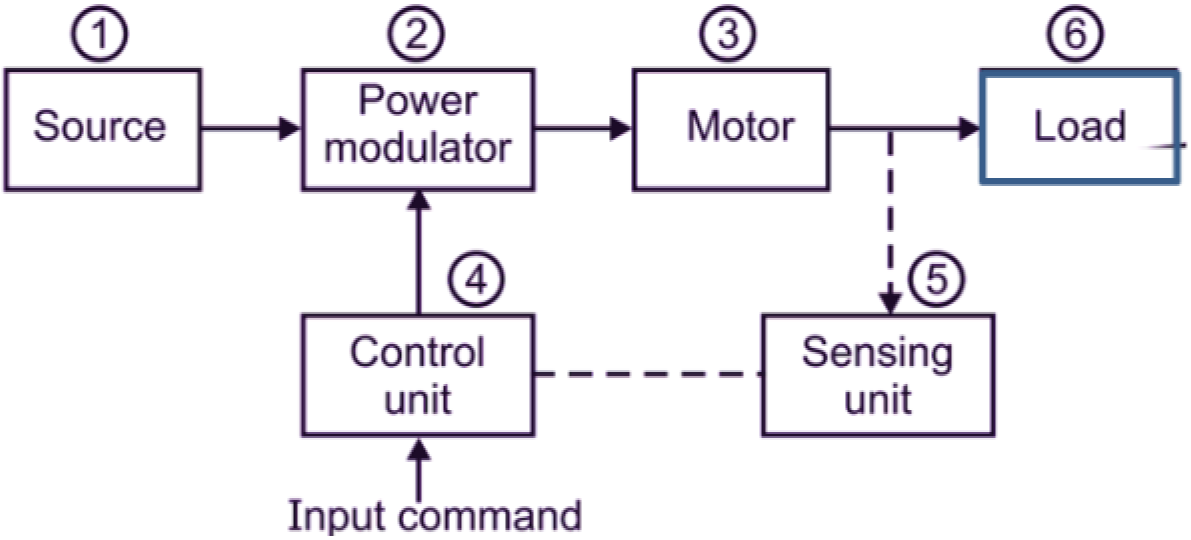
VTU Solution

1.a. With neat block diagram explain various components of an Electric drive.

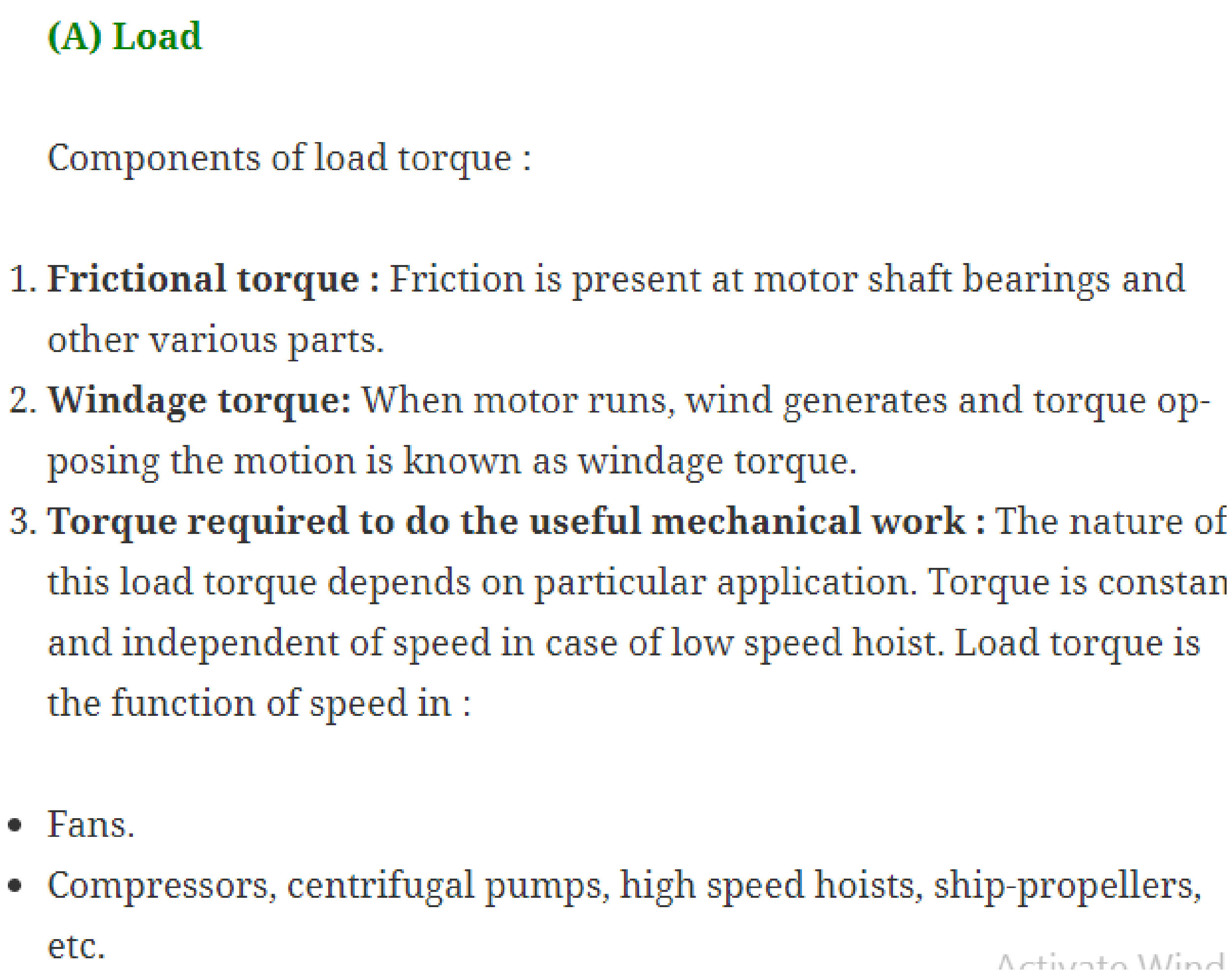
Block Diagram of Electric Drive and Main Components (i.e. Parts)

Components are electric drive are :

1. Source.
2. Power modulator.
3. Motor.
4. Control unit.
5. Sensing unit.
6. Load.



Block diagram of an electric drive



(A) Load

Components of load torque :

1. **Frictional torque :** Friction is present at motor shaft bearings and other various parts.
2. **Windage torque:** When motor runs, wind generates and torque opposing the motion is known as windage torque.
3. **Torque required to do the useful mechanical work :** The nature of this load torque depends on particular application. Torque is constan and independent of speed in case of low speed hoist. Load torque is the function of speed in :

- Fans.
- Compressors, centrifugal pumps, high speed hoists, ship-propellers, etc.

(B) Types of Motors

Commonly used motors as drives are already discussed earlier such as :

1. D.C. motors – Shunt, series, compound, P.M. motor.
2. A.C. motors – Squirrel cage, slip-ring, linear.
3. Synchronous motors – Wound field, permanent/magnet.
4. Brushless D.C. motors.
5. Stepper motors.
6. Switched reluctance motors.

Power Modulators

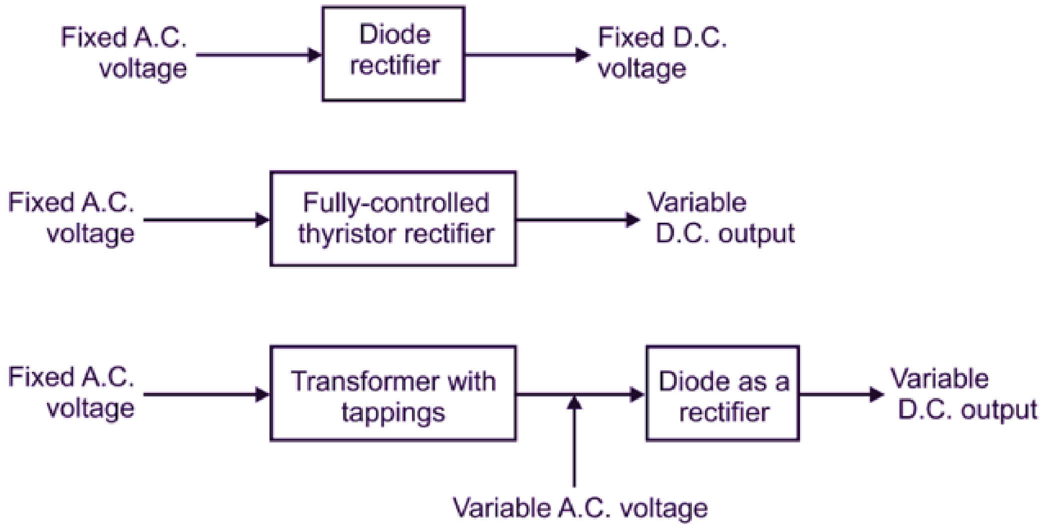
These can be grouped into three parts :

1. Converters.
2. Variable impedances.
3. Switching circuits.

Power modulator and its functions

1. Power modulator modulates the flow of power from the source to the motor. See the block diagram. It is connecting source and motor.
2. It acts as a rectifier or inverter i.e. if source is A.C. and motor is D.C., it converts A.C. into D.C. acting as a rectifier. If source is D.C. and to be connected to induction motor operating on A.C., it acts as an inverter to change D.C. into A.C. of variable frequency.
3. In operation such as starting, braking, speed reversals, it restricts source and motor currents with the permissible range (margins).
4. It helps in selecting the mode of operation of motor i.e. motoring or braking.

Converter: A. C. to D.C. converters



Variable impedance

Resistors, inductors, their combination with steps or continuous variations for lining the currents in the circuits are used

Switching circuits

These are used for :

1. Changing the motor connections to change quadrant operations.
2. For auto-starting / braking.
3. Operation as per pre-determined sequence.
4. Maloperation preventions (to provide interlocking).
5. Disconnection in abnormal happenings.

High power electromagnetic relays are used in the functioning of switching operations.

Sources

1. For small drives – 230 V, A.C„ single phase.
2. For moderate and high power – 440 volts, 50 Hz, 3-phase A-C.
3. For bulk capacity motors – 3.3 kV, 6.6 kV, 11 kV. Some drives are power from batteries, 6 V, 12 V, 24 V, 48 V and 11 V D.C.

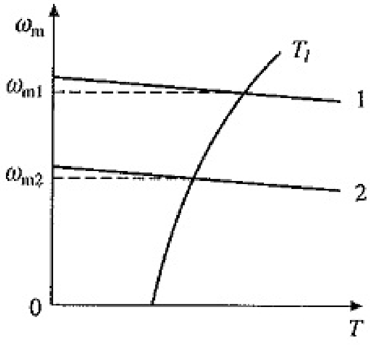
Control unit

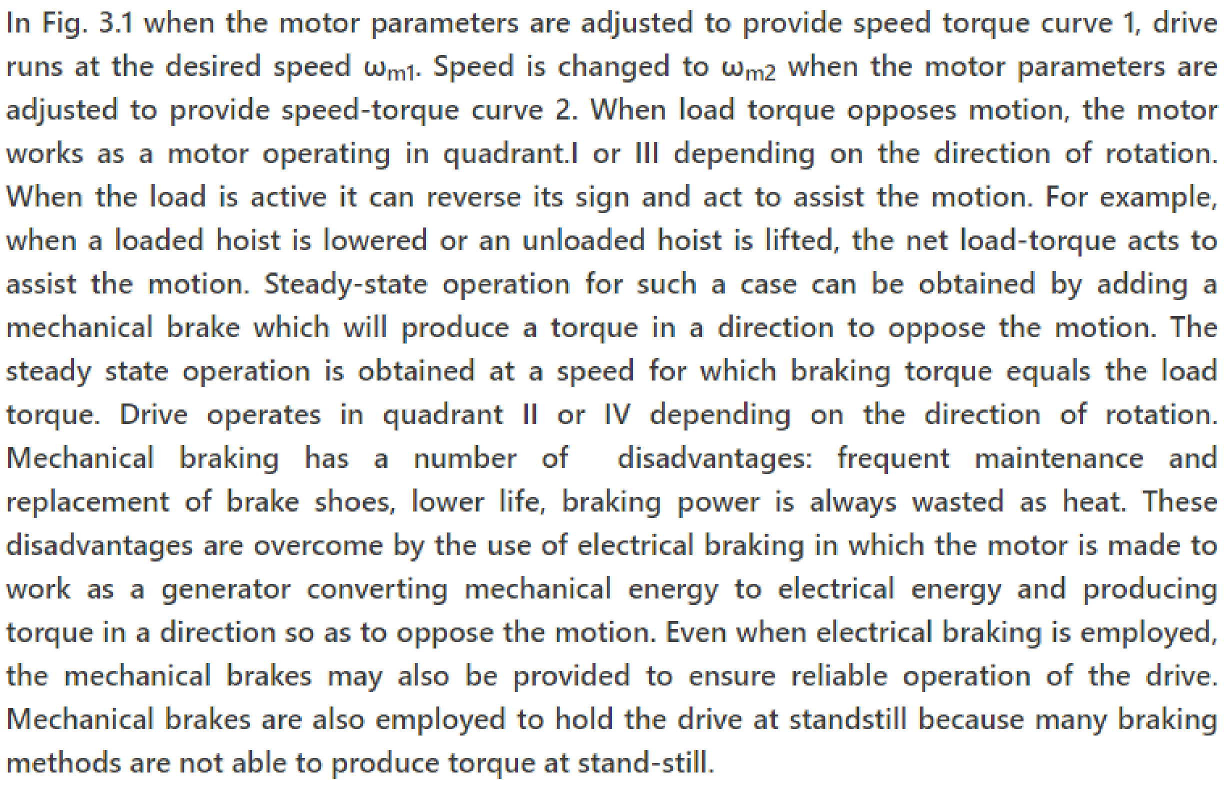
Control unit depends upon power modulator used. For semiconductor converters, control unit consists of firing circuit, employlng digital linear circuit and transistors, microprocessor.

1. B. Explain the modes of operation of an Electric Drive.

- **Steady-State**
- **Acceleration including starting**
- **Deceleration including stopping**

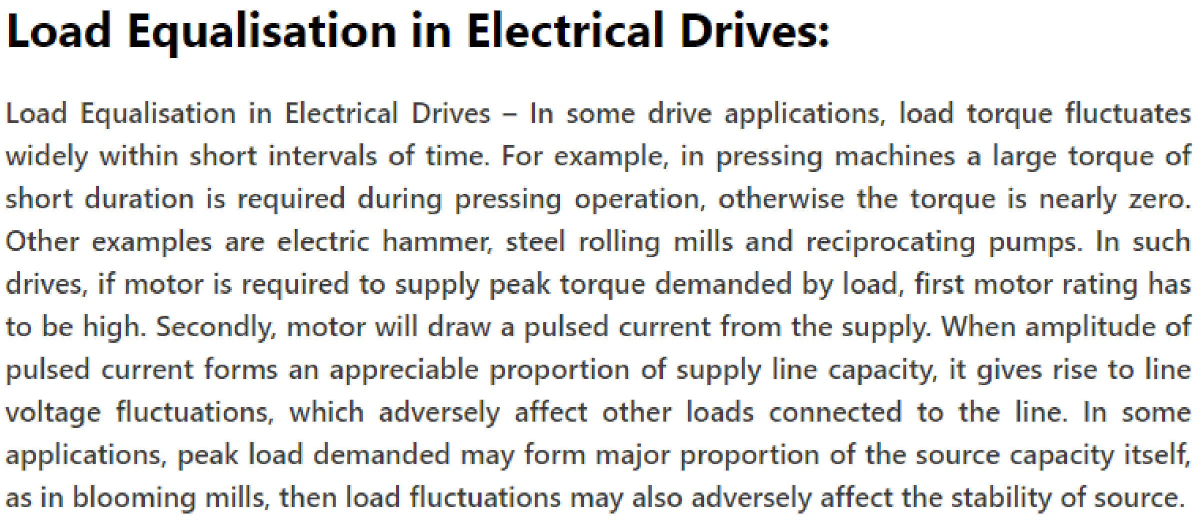
As we know already, steady-state operation takes place when motor torque equals the load torque. The steady-state operation for a given speed is realized by the adjustment of steady-state motor speed-torque curve such that the motor and load torques are equal at this speed. Change in speed is achieved by varying the steady-state motor speed torque curve so that motor torque equals the load torque at the new desired speed.





In Fig. 3.1 when the motor parameters are adjusted to provide speed torque curve 1, drive runs at the desired speed ω_{m1}. Speed is changed to ω_{m2} when the motor parameters are adjusted to provide speed-torque curve 2. When load torque opposes motion, the motor works as a motor operating in quadrant.I or III depending on the direction of rotation. When the load is active it can reverse its sign and act to assist the motion. For example, when a loaded hoist is lowered or an unloaded hoist is lifted, the net load-torque acts to assist the motion. Steady-state operation for such a case can be obtained by adding a mechanical brake which will produce a torque in a direction to oppose the motion. The steady state operation is obtained at a speed for which braking torque equals the load torque. Drive operates in quadrant II or IV depending on the direction of rotation. Mechanical braking has a number of disadvantages: frequent maintenance and replacement of brake shoes, lower life, braking power is always wasted as heat. These disadvantages are overcome by the use of electrical braking in which the motor is made to work as a generator converting mechanical energy to electrical energy and producing torque in a direction so as to oppose the motion. Even when electrical braking is employed, the mechanical brakes may also be provided to ensure reliable operation of the drive. Mechanical brakes are also employed to hold the drive at standstill because many braking methods are not able to produce torque at stand-still.

2.a. Explain the necessity of mounting the flywheel in on the motor shaft in non-reversible drives. Obtain the equation to calculate the moment of Inertia of the Flywheel.



Load Equalisation in Electrical Drives:

Load Equalisation in Electrical Drives – In some drive applications, load torque fluctuates widely within short intervals of time. For example, in pressing machines a large torque of short duration is required during pressing operation, otherwise the torque is nearly zero. Other examples are electric hammer, steel rolling mills and reciprocating pumps. In such drives, if motor is required to supply peak torque demanded by load, first motor rating has to be high. Secondly, motor will draw a pulsed current from the supply. When amplitude of pulsed current forms an appreciable proportion of supply line capacity, it gives rise to line voltage fluctuations, which adversely affect other loads connected to the line. In some applications, peak load demanded may form major proportion of the source capacity itself, as in blooming mills, then load fluctuations may also adversely affect the stability of source.

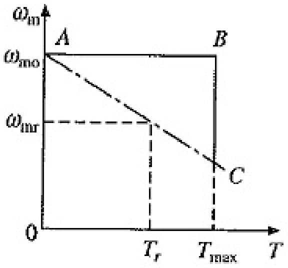


Fig. 2.10 Shapes of motor speed torque curves for fluctuating roads

Above mentioned problems of fluctuating loads are overcome by mounting a flywheel on the motor shaft in non-reversible drives. Motor speed-torque characteristic is made drooping. Alternatively, by closed loop current control torque is prevented from exceeding a permissible value. During high load period, load torque will be much larger compared to the motor torque. Deceleration occurs producing a large dynamic torque component (J $d\omega_m/dt$). Dynamic torque and motor torque together are able to produce torque required by the load (Eq. (2.2)). Because of Fig. 2.10 Shapes of motor speed torque curves for deceleration, the motor speed falls. During light load period, the motor torque exceeds the load torque causing acceleration Speed is brought back to original value before the next high load period.

Variation of motor and load torques, and speed for a periodic load and for a drooping motor speed-torque curve are shown in Fig. 2.11. It shows that peack torque required from the motor has much smaller value than the peak load torque. Hence, a motor with much smaller rating than peak load can be used and peak current drawn by motor from the source is reduced by a large amount. Fluctuations in motor torque and speed are also reduced. Since power drawn from the source fluctuates very little, this is called load equalisation.

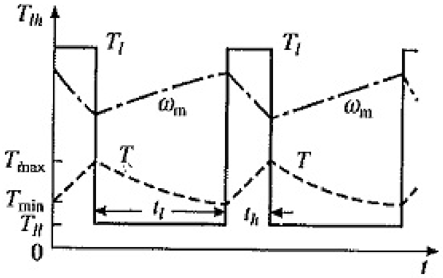


Fig. 2.11

Moment of inertia of the flywheel required for Load Equalisation in Electrical Drives is calculated as follows: Assuming a linear motor-speed-torque curve in the region of interest

$$\omega_m = \omega_{m0} - \frac{\omega_{m0} - \omega_{mr}}{T_r} \cdot T \tag{2.31}$$

where ω_{m0},ω_{mr} and and T_r are no-load speed, rated speed and rated torque, respectively.

Because of slow response due to large inertia, motor can be assumed to be in electrical equilibrium during transient operation of the motor-load system. In that case Eq. (2.31) will be applicable for the transient operation also. Differentiating (2.31) and multiplying both sides by J gives

$$J\frac{d\omega_m}{dt} = -\frac{J(\omega_{m0} - \omega_{mr})}{T_r}\frac{dT}{dt} \tag{2.32}$$

$$= -\tau_m \frac{dT}{dt} \tag{2.33}$$

where

$$\tau_m = \frac{J(\omega_{m0} - \omega_{mr})}{T_r} \tag{2.34}$$

Term τ_m is defined as the mechanical time constant of the motor. It is the time required for the motor speed to change by $(\omega_{m0} - \omega_{mr})$ when motor torque is maintained constant at rated value T_r.

From Eqs. (2.2) and (2.33)

$$\tau_m \frac{dT}{dt} + T = T_l \tag{2.35}$$

Consider now a periodic load torque, a cycle of which consists of one high load period with torque T_{lh} and duration t_h, and one light load period with torque T_{ll} and duration t_t (Fig. 2.11). For high load period ($0 \leq t \leq t_h$) solution of Eq. (2.35) is

$$T = T_{lh}\,(1 - e^{-t/\tau_m}) + T_{\min}e^{-t/\tau_m}$$

$$0 \leq t \leq t_h \qquad (2.36)$$

where $T_{\min}$ is the motor torque at $t = 0$, which is also the instant when heavy load T_{lh} is applied. If motor torque at the end of heavy load period is $T_{\max}$, then from Eq. (2.36)

$$T_{\max} = T_{lh}\,(1 - e^{-t_h/\tau_m}) + T_{\min}e^{-t_h/\tau_m} \qquad (2.37)$$

Solution of Eq. (2.35) for the light load period ($t_h \leq t \leq t_h + t_l$) with the initial motor torque equal to $T_{\max}$ is

$$T = T_{ll}\,(1 - e^{-t'/\tau_m}) + T_{\max}e^{-t'/\tau_m}$$

$$0 \leq t' \leq t_l \qquad (2.38)$$

$$t' = t - t_h \qquad (2.39)$$

$$\tau_{\mathrm{m}} = \frac{t_{\mathrm{h}}}{\log_{\mathrm{e}}\left(\frac{T_{l\mathrm{h}} - T_{\min}}{T_{l\mathrm{h}} - T_{\max}}\right)} \tag{2.41}$$

From (2.34) and (2.41)

$$J = \frac{T_{\mathrm{r}}}{(\omega_{\mathrm{m}0} - \omega_{\mathrm{mr}})}\left[\frac{t_{\mathrm{h}}}{\log_{\mathrm{e}}\left(\frac{T_{l\mathrm{h}} - T_{\min}}{T_{l\mathrm{h}} - T_{\max}}\right)}\right] \tag{2.42}$$

Also from Eq.(2.40)

$$\tau_{\mathrm{m}} = \frac{t_l}{\log_{\mathrm{e}}\left(\frac{T_{\max} - T_{ll}}{T_{\min} - T_{ll}}\right)} \tag{2.43}$$

From Eqs. (2.34) and (2.43)

$$J = \frac{T_{\mathrm{r}}}{(\omega_{\mathrm{m}0} - \omega_{\mathrm{mr}})}\left[\frac{t_l}{\log_{\mathrm{e}}\left(\frac{T_{\max} - T_{ll}}{T_{\min} - T_{ll}}\right)}\right] \tag{2.44}$$

2.b. Explain the speed-Torque convention and Multi-quadrant operation of a Motor driving a Hoist Load.

A motor operates in two modes motoring and braking. In motoring, it converts electrical energy to mechanical energy, which supports its motion. In braking, it works as a generator converting mechanical energy to electrical energy, and thus, opposes the motion. Motor can provide motoring and braking operations for both forward and reverse directions.

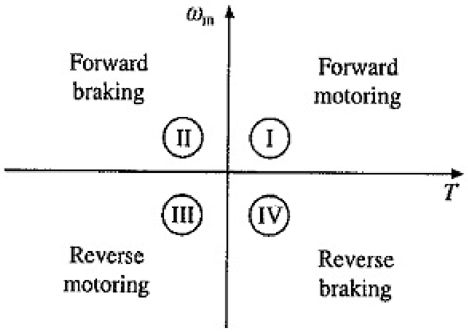


Fig. 2.2 Multiquadrant-operation of drives

Figure 2.2 shows the torque and speed coordinates for both forward (positive) and reverse (negative) motions of Four Quadrant Operation of Motor Drive. Power developed by a motor is given by the product of speed and torque. In quadrant I, developed power is positive. Hence, machine works as a motor supplying mechanical energy. Operation in quadrant I is, therefore, called **forward motoring**. In quadrant II, power is negative. Hence, machine works under braking opposing the motion. Therefore, operation in quadrant II is known as **forward braking**. Similarly, operations in quadrant III and IV can be identified as reverse motoring and braking respectively.

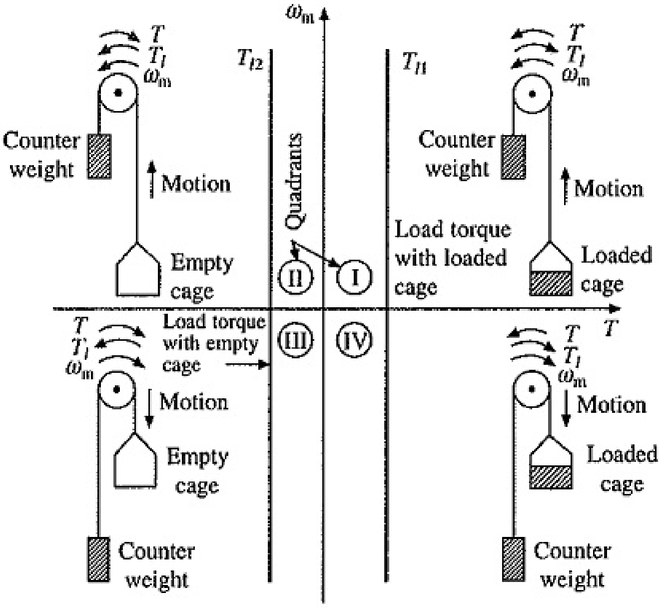


Fig. 2.3 Four quadrant operation of a motor driving a hoist load

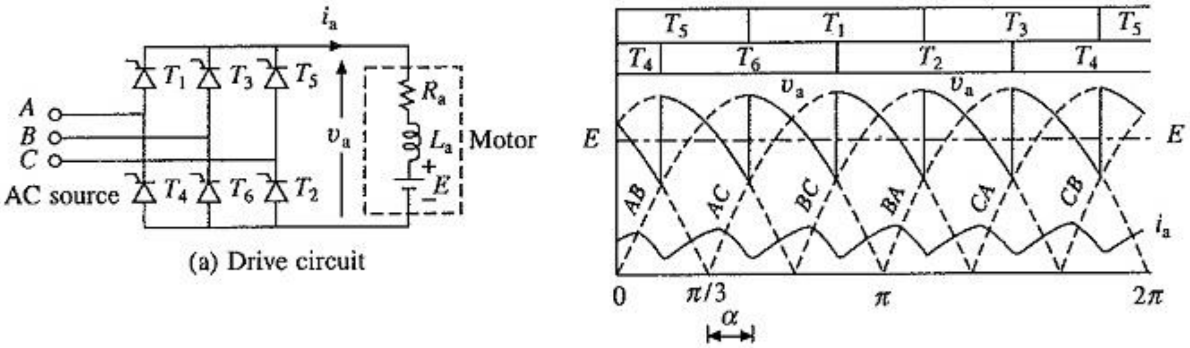
A hoist consists of a rope wound on a drum coupled to the motor shaft. One end of the rope is tied to a cage which is used to transport man or material form one level to another level. Other end of the rope has a counter weight. Weight of the counter weight is chosen to be higher than the weight of an empty cage but lower than of a fully loaded cage.

The quadrant I operation of a hoist requires the movement of the cage upward, which corresponds to the positive motor speed which is in anticlockwise direction here. This motion will be obtained if the motor produces positive torque in anticlockwise direction equal to the magnitude of load torque T_{l1}. Since developed motor power is positive, this is forward motoring operation.

Quadrant IV operation is obtained when a loaded cage is lowered. Since the weight of a loaded cage is higher than that of a counter weight, it is able to come down due to the gravity itself. In order to limit the speed of cage within a safe value, motor must produce a positive torque T equal to T_{l2} in anticlockwise direction. As both power and speed are negative, drive is operating in reverse braking.

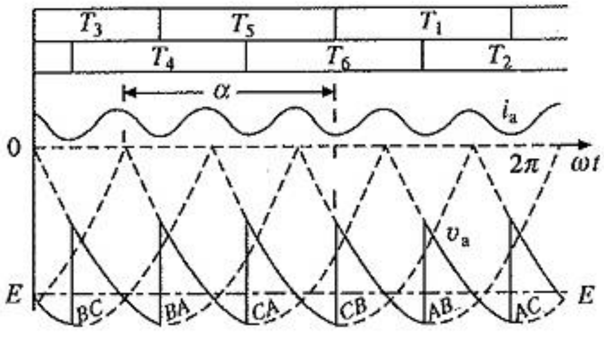
Operation in quadrant II is obtained when an empty cage is moved up. Since a counter weight is heavier than an empty cage, it is able to pull it up. In order to limit the speed within a safe value, motor must produce a braking torque equal to T_{l2} in clockwise (negative) direction. Since speed is positive and developed power negative, it is forward braking operation.

3.a. With a neat circuit diagram and waveform, explain 3-phase fully controlled rectifier control of separately excited DC motor.



(a) Drive circuit

(b) Motoring operation, $\alpha = 30°$



(c) Braking operation $\alpha \simeq 140°$

Fig. 5.32 Three-phase fully-controlled converter control of separately excited motor

Transfer of current from an outgoing to incoming thyristor can take place when the respective line voltage is of such a polarity that not only if forward biases the incoming thyristor, but also leads to the reverse biasing of the outgoing when incoming turns-on. Thus, firing angle for a thyristor is measured from the instant when the respective line voltage is zero and increasing. For example, the transfer of current from thyristor $T_5$to thyristor T_1 can occur as long as the line voltage v_{AC} is positive. Hence, for thyristor T_1, firing angle α is measured from the instant $v_{AC} = 0$ and increases as shown in Figs. 5.32(b) and (c).

If line voltage v_{AB} is taken as the reference voltage, then

$$v_{AB} = V_m \sin \omega t \tag{5.95}$$

$$\alpha = \omega t - \pi/3 \tag{5.96}$$

where V_m is the peak of line voltage.

Motor terminal voltage and current waveforms for continuous conduction are shown in Figs. 5.32(b) and (c) for motoring and braking operations, respectively. Devices under conduction are also shown in the figure. The discontinuous conduction is neglected here because it occurs is a narrow region of its operation. For the motor terminal voltage cycle from α + π/3 to α + 2π/3 (from Figs. 5.32(b) and (c)).

$$V_a = \frac{3}{\pi} \int_{\alpha+\pi/3}^{\alpha+2\pi/3} V_m \sin \omega t \, d(\omega t)$$

$$= \frac{3}{\pi} V_m \cos \alpha \tag{5.97}$$

From Eqs. (5.7), (5.8), (5.79) and (5.97)

$$\omega_m = \frac{3V_m}{\pi K} \cos \alpha - \frac{R_a}{K^2} T \tag{5.98}$$

When discontinuous conduction is ignored, speed-torque curves of Fig. 5.33 are obtained. The V_a vs α curve has same nature as shown in Fig. 5.28(a) for single-phase case. Consequently, drive operates in quadrants I and IV.

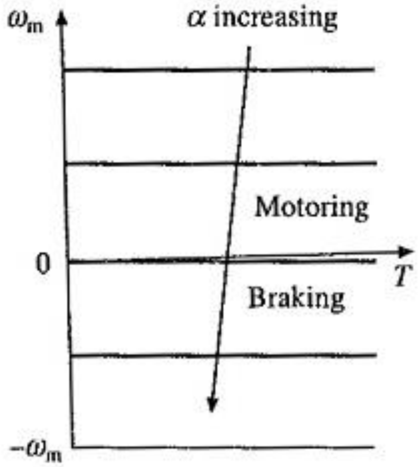
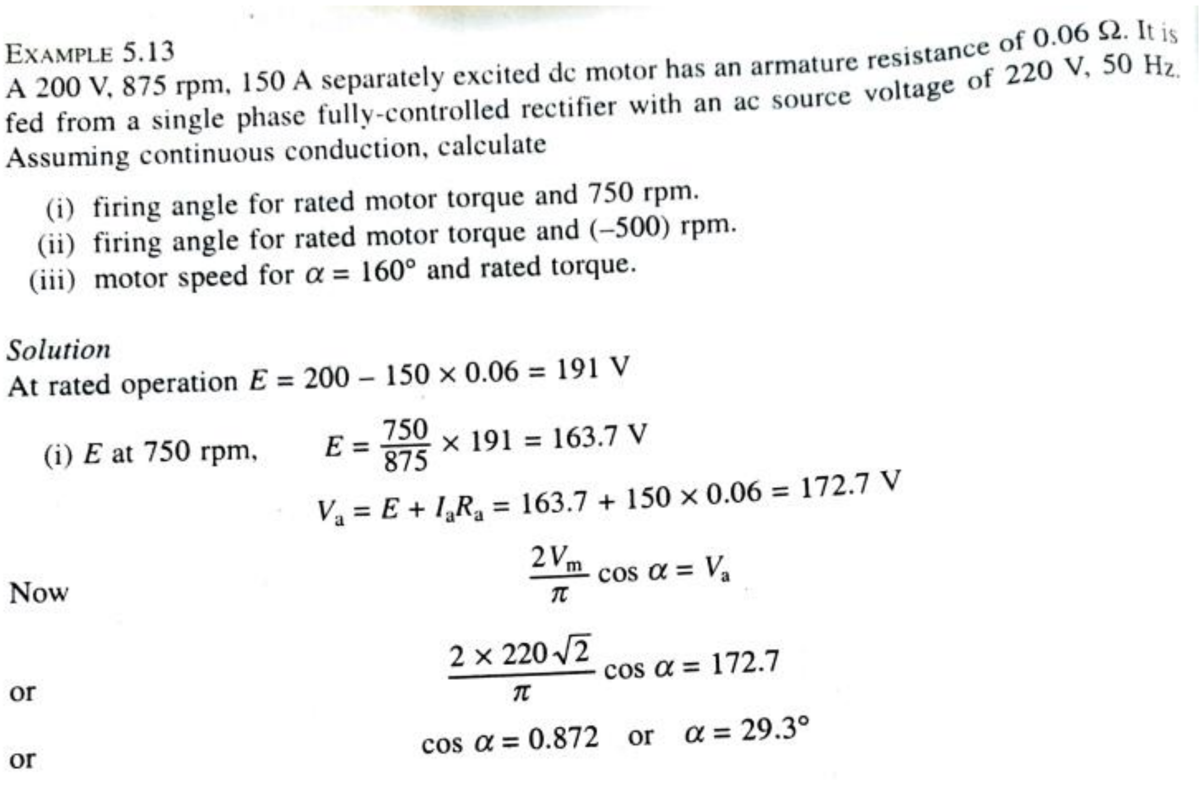


Fig. 5.33 Speed torque curves of drive of Fig. 5.32(a) neglecting discontinuous conduction

3.b.



EXAMPLE 5.13

A 200 V, 875 rpm, 150 A separately excited dc motor has an armature resistance of 0.06 Ω. It is fed from a single phase fully-controlled rectifier with an ac source voltage of 220 V, 50 Hz. Assuming continuous conduction, calculate

(i) firing angle for rated motor torque and 750 rpm.
(ii) firing angle for rated motor torque and (–500) rpm.
(iii) motor speed for $\alpha = 160°$ and rated torque.

Solution

At rated operation $E = 200 - 150 \times 0.06 = 191$ V

(i) E at 750 rpm, $E = \frac{750}{875} \times 191 = 163.7$ V

$$V_a = E + I_a R_a = 163.7 + 150 \times 0.06 = 172.7 \text{ V}$$

Now
$$\frac{2V_m}{\pi} \cos\alpha = V_a$$

or
$$\frac{2 \times 220\sqrt{2}}{\pi} \cos\alpha = 172.7$$

or
$$\cos\alpha = 0.872 \quad \text{or} \quad \alpha = 29.3°$$

(ii) At –500 rpm $E = \frac{-500}{875} \times 191 = -109\text{ V}$

Since $V_a = E + I_a R_a$

$V_a = -109 + 150 \times 0.06 = -100\text{ V}$

Now $$\frac{2V_m}{\pi}\cos\alpha = V_a$$

or $$\frac{2 \times 220\sqrt{2}}{\pi}\cos\alpha = -100$$

or $\cos\alpha = -0.5$ or $\alpha = 120°$

(iii) At $\alpha = 160°$

$$V_a = \frac{2V_m}{\pi}\cos\alpha = \frac{2 \times 220\sqrt{2}}{\pi}\cos 160° = -186\text{ V}$$

Since $V_a = E + I_a R_a$

$-186 = E + 150 \times 0.06$

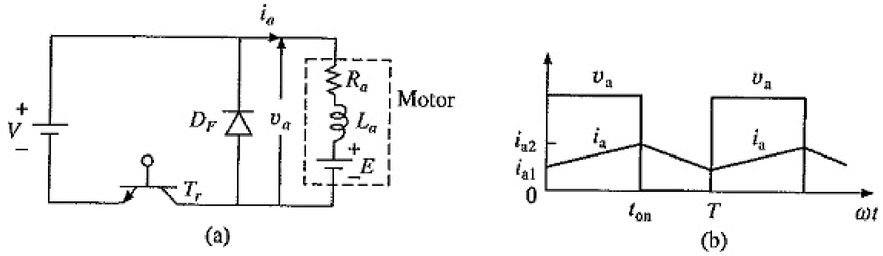
or $E = -195\text{ V}$

$$\text{Speed} = \frac{-195}{191} \times 875 = -893.2\text{ rpm}$$

4.a. Explain chopper control of separately excited DC motor.

Chopper Control of Separately Excited DC Motor:

Motoring Control : A transistor Chopper Control of Separately Excited DC Motor drive is shown in Fig. 5.41(a). Transistor T_r is operated periodically with period T and remains on for a duration t_{on}. Present day choppers operate at a frequency which is high enough to ensure continuous conduction. Waveforms of motor terminal voltage v_a and armature current i_a for continuous conduction are shown in Fig. 5.41(b). During on-period of the transistor, $0 \le t \le t_{on}$, the motor terminal voltage is V.



(a) (b)

Fig. 5.41 Chopper control of separately excited motor

The operation is described by

$$R_a i_a + L_a \frac{di_a}{dt} + E = V, \quad 0 \le t \le t_{on} \tag{5.110}$$

In this interval, armature current increases from i_{al} to i_{a2}. Since motor is connected to the source during this interval, it is called **Duty Interval**.

At t = t_{on}, T_r is turned-off. Motor current freewheels through diode D_F and motor terminal voltage is zero during interval $t_{on} \le t \le T$. Motor operation during this interval, known as freewheeling interval, is described by

$$R_a i_a + L_a \frac{di_a}{dt} + E = 0, \quad t_{on} \le t \le T \tag{5.111}$$

Ratio of duty interval t_{on} to chopper period T is called **duty ratio or duty cycle** (δ). Thus

$$\delta = \frac{\text{Duty interval}}{T} = \frac{t_{\text{on}}}{T} \tag{5.112}$$

From Fig. 5.41(b)

$$V_a = \frac{1}{T}\int_0^{t_{\text{on}}} V\,dt = \delta V \tag{5.113}$$

Equation (5.2) and (5.7) are also applicable here

$$I_a = \frac{\delta V - E}{R_a} \tag{5.114}$$

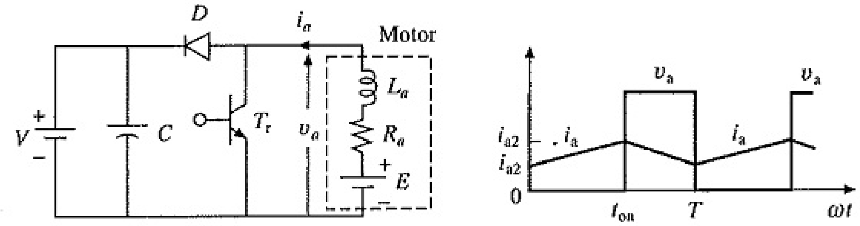
From Eqs. (5.7), (5.8). and (5.114)

$$\omega_m = \frac{\delta V}{K} - \frac{R_a}{K^2} T \tag{5.115}$$

The nature of speed torque characteristic is shown in Fig. 5.43.

Regenerative Braking:

Chopper Control of Separately Excited DC Motor for regenerative braking operation is shown in Fig. 5.42(a). Transistor T_r is operated periodically with a period T and on-period of t_{on}. Waveforms of motor terminal voltage v_a and armature current i_a for continuous conduction are shown in Fig. 5.42(b). Usually an external inductance is added to increase the value of L_a. When T_r is on, i_a increase from i_{a1} to i_{a2}.



(a) (b)

Fig. 5.42 Regenerative braking of separately excited motor by chopper control

The mechanical energy converted into electrical by the motor, now working as a generator, partly increases the stored magnetic energy in armature circuit inductance and remainder is dissipated in armature resistance and transistor. When T_r is turned off, armature current flows through diode D and source V, and reduces from i_{a2} to i_{a1}. The stored electromagnetic energy and energy supplied by machine is fed to the source. The interval $0 \le t \le t_{on}$ is now called **energy storage interval** and interval $t_{on} \le t \le T$ **the duty interval**. If δ is again defined as the ratio of duty interval to period T, then

4.b.

EXAMPLE 5.19

A 230 V, 960 rpm and 200 A separately excited dc motor has an armature resistance of 0.02 Ω. The motor is fed from a chopper which provides both motoring and braking operations. The source has a voltage of 230 V. Assuming continuous conduction.

(i) Calculate duty ratio of chopper for motoring operation at rated torque and 350 rpm.
(ii) Calculate duty ratio of chopper for braking operation at rated torque and 350 rpm.
(iii) If maximum duty ratio of chopper is limited to 0.95 and maximum permissible motor current is twice the rated, calculate maximum permissible motor speed obtainable without field weakening and power fed to the source.
(iv) If motor field is also controlled in (iii), calculate field current as a fraction of its rated value for a speed of 1200 rpm.

Solution

At rated operation

$$E = 230 - (200 \times 0.02) = 226 \text{ V}$$

(i)

$$E \text{ at } 350 \text{ rpm} = \frac{350}{960} \times 226 = 82.4 \text{ V}$$

$$\text{Motor terminal voltage } V_a = E + I_a R_a = 82.4 + (200 \times 0.02) = 86.4 \text{ V}$$

$$\text{Duty ratio } \delta = \frac{86.4}{230} = 0.376$$

(ii)

$$V_a = E - I_a R_a = 82.4 - (200 \times 0.02) = 78.4 \text{ V}$$

$$\delta = \frac{78.4}{230} = 0.34$$

(iii) Maximum available $V_a = 0.95 \times 230 = 218.5$ V

$$E = V_a + I_a R_a = 218.5 + (200 \times 2 \times 0.02) = 226.5 \text{ V}$$

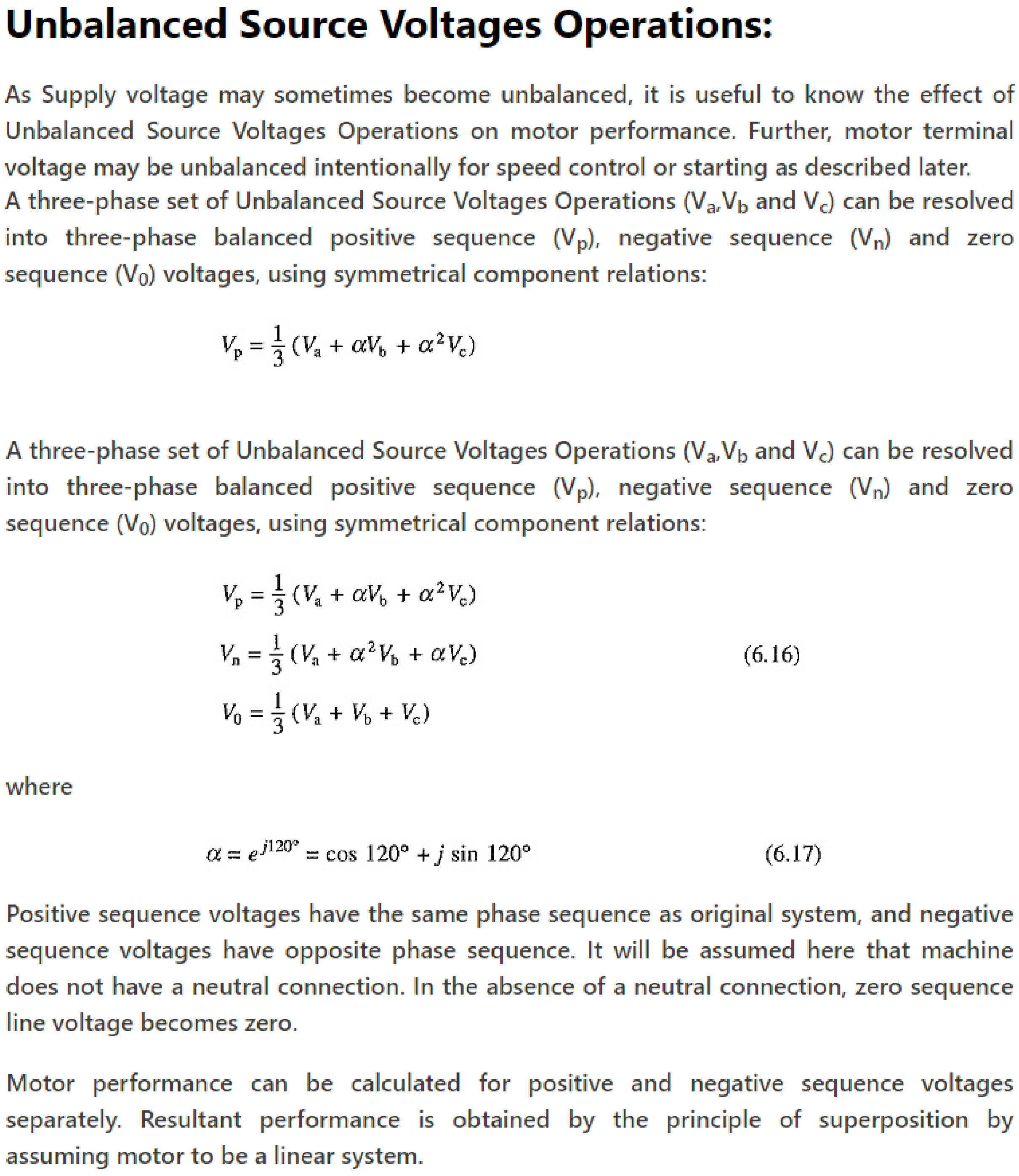
$$\text{Maximum permissible motor speed} = \frac{226.5}{226} \times 960 = 962 \text{ rpm}$$

Assuming lossless chopper, power fed into the source

$$V_a I_a = 218.5 \times 400 = 87.4 \text{ kW}$$

(iv) As in (iii) $E = 226.5$ V for which at rated field current speed = 960 rpm. Assuming linear magnetic circuit, E will be inversely proportional to field current. Field current as a ratio of its rated value = 960/1200 = 0.8.

5.a. Explain the effect of unbalance source voltage and single phasing on a 3-phase IM.



Unbalanced Source Voltages Operations:

As Supply voltage may sometimes become unbalanced, it is useful to know the effect of Unbalanced Source Voltages Operations on motor performance. Further, motor terminal voltage may be unbalanced intentionally for speed control or starting as described later.
A three-phase set of Unbalanced Source Voltages Operations (V_a, V_b and V_c) can be resolved into three-phase balanced positive sequence (V_p), negative sequence (V_n) and zero sequence (V_0) voltages, using symmetrical component relations:

$$V_p = \frac{1}{3}(V_a + \alpha V_b + \alpha^2 V_c)$$

A three-phase set of Unbalanced Source Voltages Operations (V_a, V_b and V_c) can be resolved into three-phase balanced positive sequence (V_p), negative sequence (V_n) and zero sequence (V_0) voltages, using symmetrical component relations:

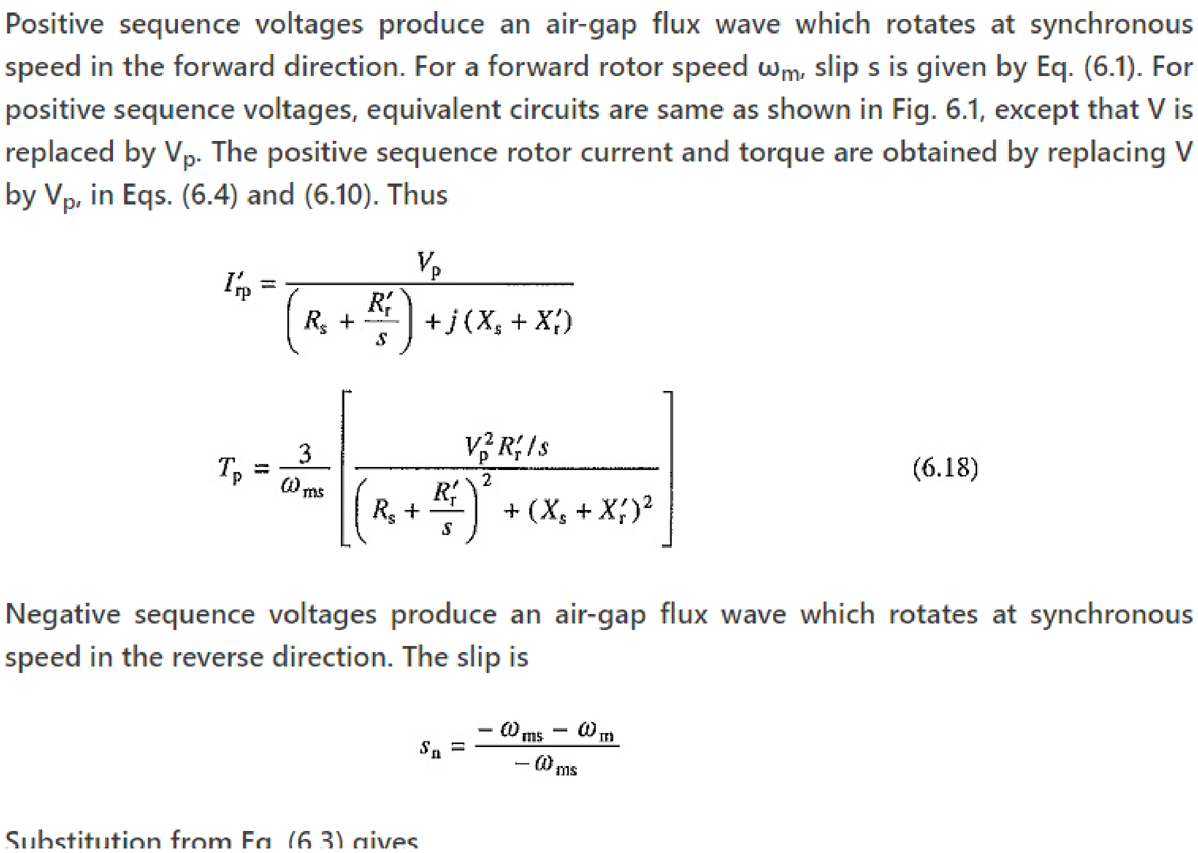
$$\begin{aligned} V_p &= \frac{1}{3}(V_a + \alpha V_b + \alpha^2 V_c) \\ V_n &= \frac{1}{3}(V_a + \alpha^2 V_b + \alpha V_c) \qquad (6.16) \\ V_0 &= \frac{1}{3}(V_a + V_b + V_c) \end{aligned}$$

where

$$\alpha = e^{j120^\circ} = \cos 120^\circ + j \sin 120^\circ \qquad (6.17)$$

Positive sequence voltages have the same phase sequence as original system, and negative sequence voltages have opposite phase sequence. It will be assumed here that machine does not have a neutral connection. In the absence of a neutral connection, zero sequence line voltage becomes zero.

Motor performance can be calculated for positive and negative sequence voltages separately. Resultant performance is obtained by the principle of superposition by assuming motor to be a linear system.



Positive sequence voltages produce an air-gap flux wave which rotates at synchronous speed in the forward direction. For a forward rotor speed ω_m, slip s is given by Eq. (6.1). For positive sequence voltages, equivalent circuits are same as shown in Fig. 6.1, except that V is replaced by V_p. The positive sequence rotor current and torque are obtained by replacing V by V_p, in Eqs. (6.4) and (6.10). Thus

$$I'_{rp} = \frac{V_p}{\left(R_s + \frac{R'_r}{s}\right) + j(X_s + X'_r)}$$

$$T_p = \frac{3}{\omega_{ms}} \left[\frac{V_p^2 R'_r / s}{\left(R_s + \frac{R'_r}{s}\right)^2 + (X_s + X'_r)^2} \right] \tag{6.18}$$

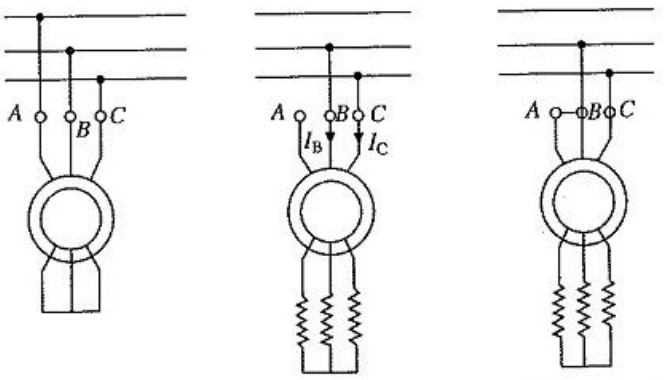
Negative sequence voltages produce an air-gap flux wave which rotates at synchronous speed in the reverse direction. The slip is

$$s_n = \frac{-\omega_{ms} - \omega_m}{-\omega_{ms}}$$

Substitution from Eq. (6.3) gives

6.a. Explain AC Dynamic braking of IM with 2lead and 3lead connection.

(a) AC Dynamic Braking – AC Dynamic Braking of Induction Motor is obtained when the motor is run on a single phase supply by disconnecting one phase from the source and either leaving it open (Fig. 6.15(b)) or connecting it with another machine phase (Fig. 6.15(c)). The two connections of Figs. 6.15(b) and (c) are, respectively, known as two and three lead connections. When connected to a 1-phase supply, the motor can be considered to be fed by positive and negative sequence three-phase set of voltages. Net torque produced by the machine is sum of torques due to positive and negative sequence voltages. When rotor has a high resistance, the net torque is negative and braking operation is obtained. The motor analysis for two and three lead connections is done as follows:



(a) Motoring (b) Two lead connection (c) Three lead connection

Fig. 6.15 ac dynamic braking of a wound rotor motor

Two Lead Connection: Assume that phase A of a Y-connected motor is open circuited. Then $I_A = 0$ and $I_C = -I_B$. Hence positive and negative sequence components I_p and I_n, respectively, are given by

$$\bar{I}_p = \frac{1}{3}(\bar{I}_A + \alpha\bar{I}_B + \alpha^2\bar{I}_C) = \frac{1}{3}(0 + \alpha\bar{I}_B - \alpha^2\bar{I}_B) = j\bar{I}_B/\sqrt{3} \qquad (6.28)$$

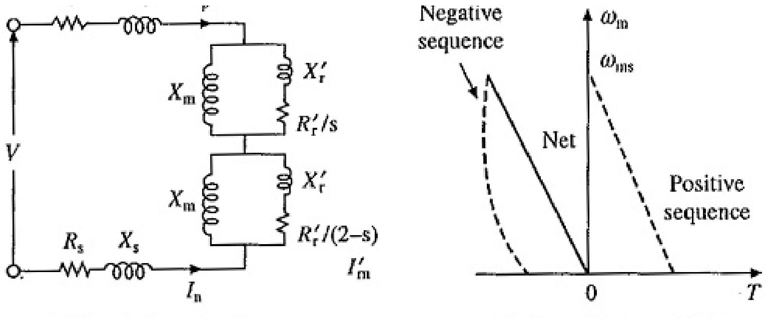
$$\bar{I}_n = \frac{1}{3}(\bar{I}_A + \alpha^2\bar{I}_B + \alpha\bar{I}_C) = \frac{1}{\sqrt{3}}(0 + \alpha^2\bar{I}_B - \alpha\bar{I}_B) = -j\bar{I}_B/\sqrt{3} \qquad (6.29)$$

As positive and negative sequence components are equal and opposite, two equivalent circuits can be connected in series opposition. Voltage to be applied to this series combination will be

$$(\bar{V}_p - \bar{V}_n) = \frac{1}{3}(\bar{V}_A + \alpha\bar{V}_B + \alpha^2\bar{V}_C) - \frac{1}{3}(\bar{V}_A + \alpha^2\bar{V}_B + \alpha\bar{V}_C)$$

$$= \frac{1}{3}(\alpha - \alpha^2)(\bar{V}_B - \bar{V}_C) = \frac{1}{3}(j\sqrt{3})(\bar{V}_{BC}) = j\bar{V}_{BC}/\sqrt{3} \qquad (6.30)$$

With an applied voltage $jV_{BC}/\sqrt{3}$ if current is $I_p = -I_n = jI_B/\sqrt{3}$, it follows that with an applied phase voltage V the current would be $I_B/\sqrt{3}$. Equivalent circuit may therefore be drawn as shown in Fig. 6.16(a). Although the values of positive and negative sequence components of current are equal, the corresponding torques are not. The nature of speed-torque curves for positive and negative sequence currents, and net torque are shown in Fig. 6.16(b). By suitable choice of rotor resistance, braking torque can be obtained in the entire speed range. As the rotor resistance required is large, ac Dynamic Braking of Induction Motor can only be used in wound-rotor motors.



(a) Equivalent circuit (b) Speed-torque curves

Fig. 6.16 ac dynamic braking with two lead connection

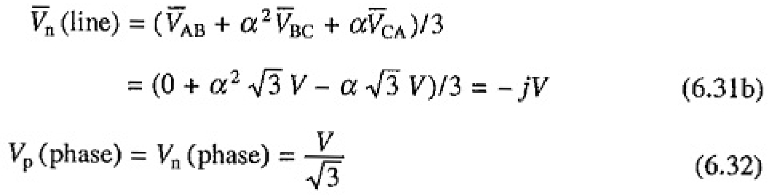
In this connection at high speeds (or at low values of slip), the impedance of positive sequence component part becomes very high. As positive and negative sequence components of current have to be equal, net braking torque is small, and therefore, braking is not very effective.

Three Lead Connection: Here two phases of Y-connected motor winding are connected in parallel in series with the third phase (Fig. 6.15(c)). Let phases A and B be connected together, then

$$\overline{V}_{AB} = 0, \overline{V}_{BC} = \sqrt{3}\, V \quad \text{and} \quad \overline{V}_{CA} = -\sqrt{3}\, V$$

$$\overline{V}_p\,(\text{line}) = \overline{V}_{AB} + \alpha\overline{V}_{BC} + \alpha^2\overline{V}_{CA})/3$$

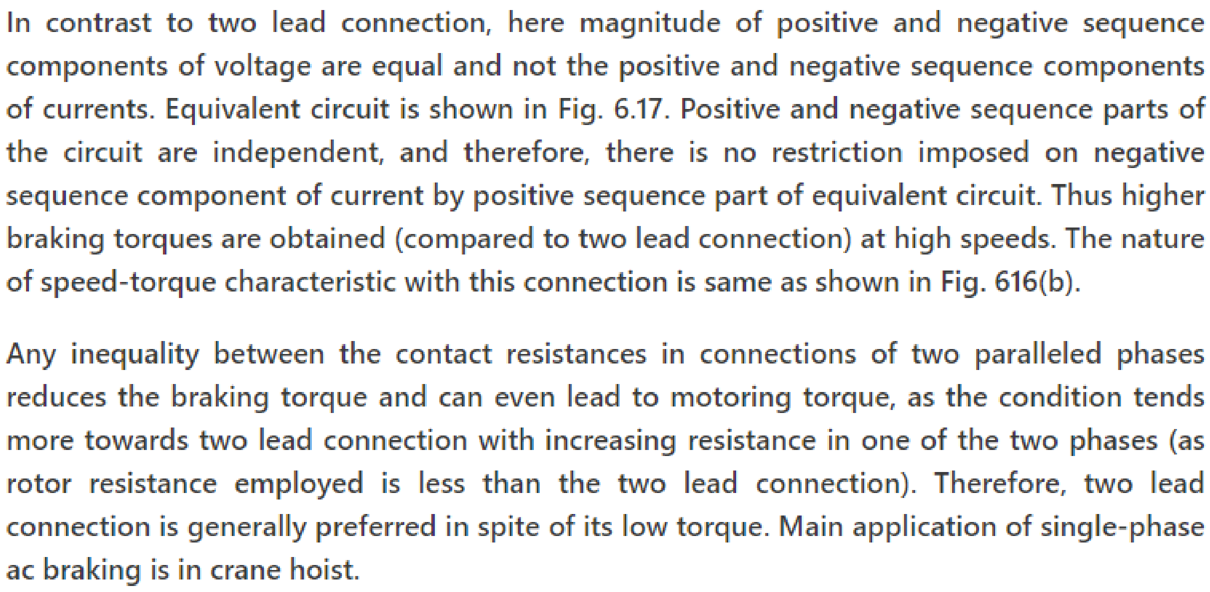
$$= (0 + \alpha\sqrt{3}\, V - \alpha^2\sqrt{3}\, V)/3 = jV \qquad (6.31a)$$



$$\overline{V}_{n}(\text{line}) = (\overline{V}_{AB} + \alpha^{2}\overline{V}_{BC} + \alpha\overline{V}_{CA})/3$$

$$= (0 + \alpha^{2}\sqrt{3}\,V - \alpha\sqrt{3}\,V)/3 = -jV \qquad (6.31b)$$

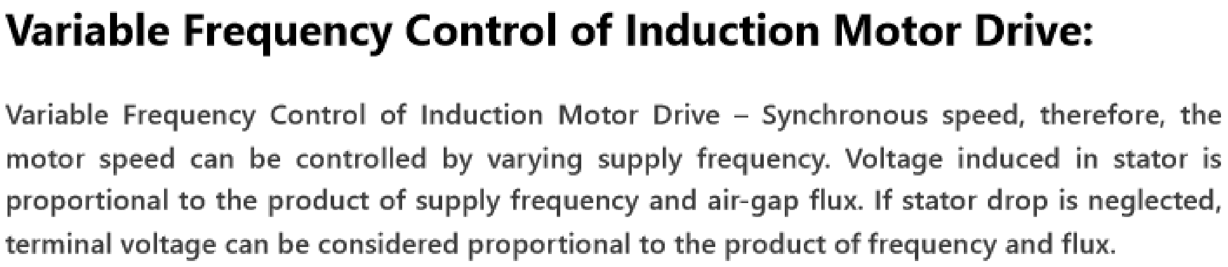
$$V_{p}(\text{phase}) = V_{n}(\text{phase}) = \frac{V}{\sqrt{3}} \qquad (6.32)$$



In contrast to two lead connection, here magnitude of positive and negative sequence components of voltage are equal and not the positive and negative sequence components of currents. Equivalent circuit is shown in Fig. 6.17. Positive and negative sequence parts of the circuit are independent, and therefore, there is no restriction imposed on negative sequence component of current by positive sequence part of equivalent circuit. Thus higher braking torques are obtained (compared to two lead connection) at high speeds. The nature of speed-torque characteristic with this connection is same as shown in Fig. 616(b).

Any inequality between the contact resistances in connections of two paralleled phases reduces the braking torque and can even lead to motoring torque, as the condition tends more towards two lead connection with increasing resistance in one of the two phases (as rotor resistance employed is less than the two lead connection). Therefore, two lead connection is generally preferred in spite of its low torque. Main application of single-phase ac braking is in crane hoist.

6.b. Explain variable frequency control of Induction Motor from voltage sources.



Variable Frequency Control of Induction Motor Drive:

Variable Frequency Control of Induction Motor Drive – 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.

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

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, $(R_s/f) \ll 2\pi(L_s + L'_r)$ and therefore, from

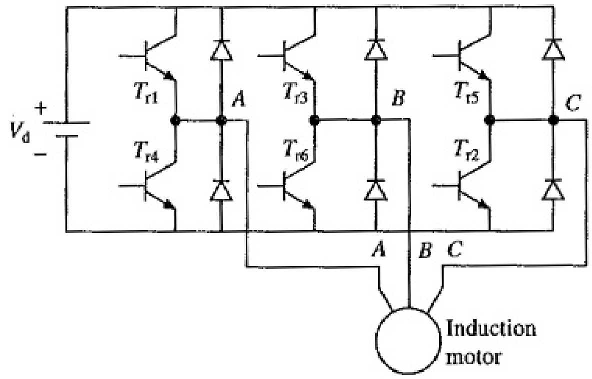
$$T_{\max} = \pm \frac{K(V/f)^2}{2\pi(L_s + L_r')}$$

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 (-Eve 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.

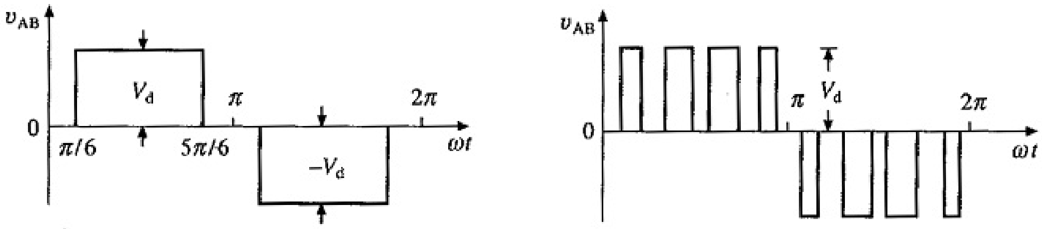
7.a. Explain the operation of VSI fed IM drive. Also explain the various schemes of VSI fed IM drive.

VSI Induction Motor Drives:

Voltage Source Inverter Control of Induction Motor 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, IGET (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.



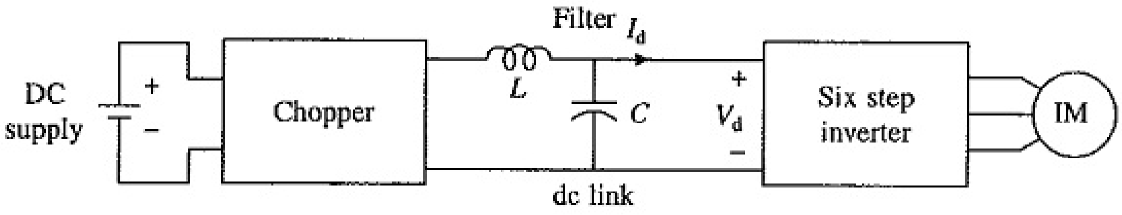
(a) Transistor inverter-fed induction motor drive



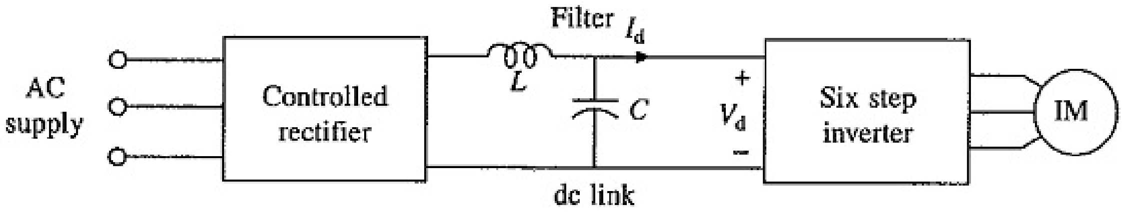
(b) Stepped wave inverter line voltage waveform (c) PWM inverter line voltage waveform

Fig. 6.37 VSI fed induction motor drives:

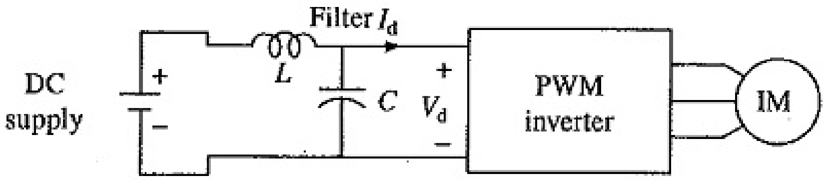
Voltage Source Inverter Control of Induction Motor can be operated as a stepped wave inverter or a pulse-width modulated (PWM) inverter. When operated as a stepped wave inverter, transistors are switched in the sequence of their numbers with a time difference of T/6 and each transistor is kept on for 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.


DC supply
+
−
Chopper
Filter
I_d
L
C
+
V_d
−
dc link
Six step inverter
IM

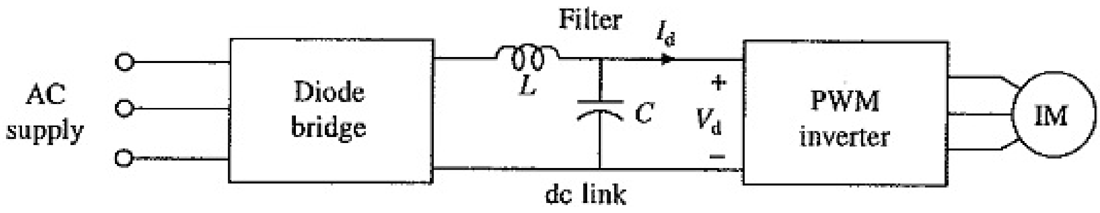
(a)


AC supply
Controlled rectifier
Filter
I_d
L
C
+
V_d
−
dc link
Six step inverter
IM

(b)


DC supply
+
−
Filter
I_d
L
C
+
V_d
−
PWM inverter
IM

(c)


AC supply
Diode bridge
Filter
I_d
L
C
+
V_d
−
dc link
PWM inverter
IM

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

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

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

The rms value of the fundamental phase voltage

$$V=\frac{\sqrt{2}}{\pi}V_d \quad (6.79)$$

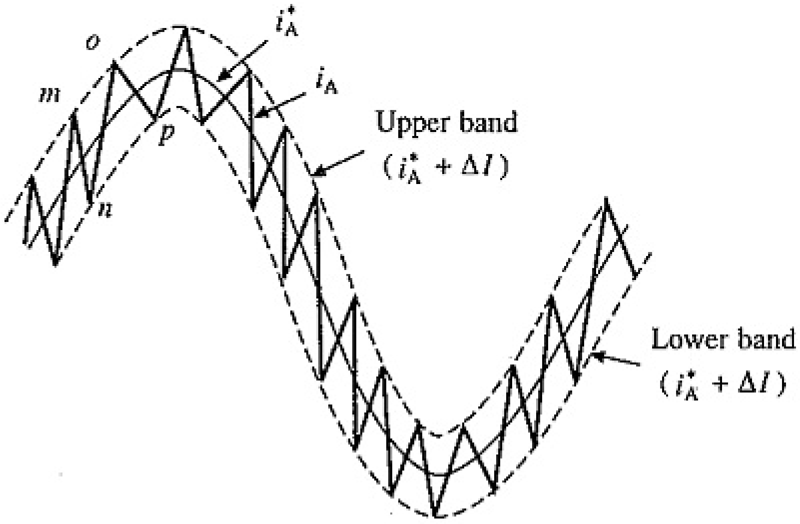
The torque for a given speed can be calculated by considering only fundamental component. The main drawback of stepped wave inverter is the large harmonics of low frequency in the output voltage. Consequently, an induction motor drive fed from a stepped wave inverter suffers from the following drawbacks:

- **Because of low frequency harmonics, the motor losses are increased at all speeds causing derating of the motor.**
- **Motor develops pulsating torques due to fifth, seventh, eleventh and thirteenth harmonics which cause jerky motion of the rotor at low speeds.**
- **Harmonic content in motor current increases at low speeds. The machine saturates at light loads at low speeds due to high (Vlf) ratio. These two effects overheat the machine at low speeds, thus limiting lowest speed to around 40% of**

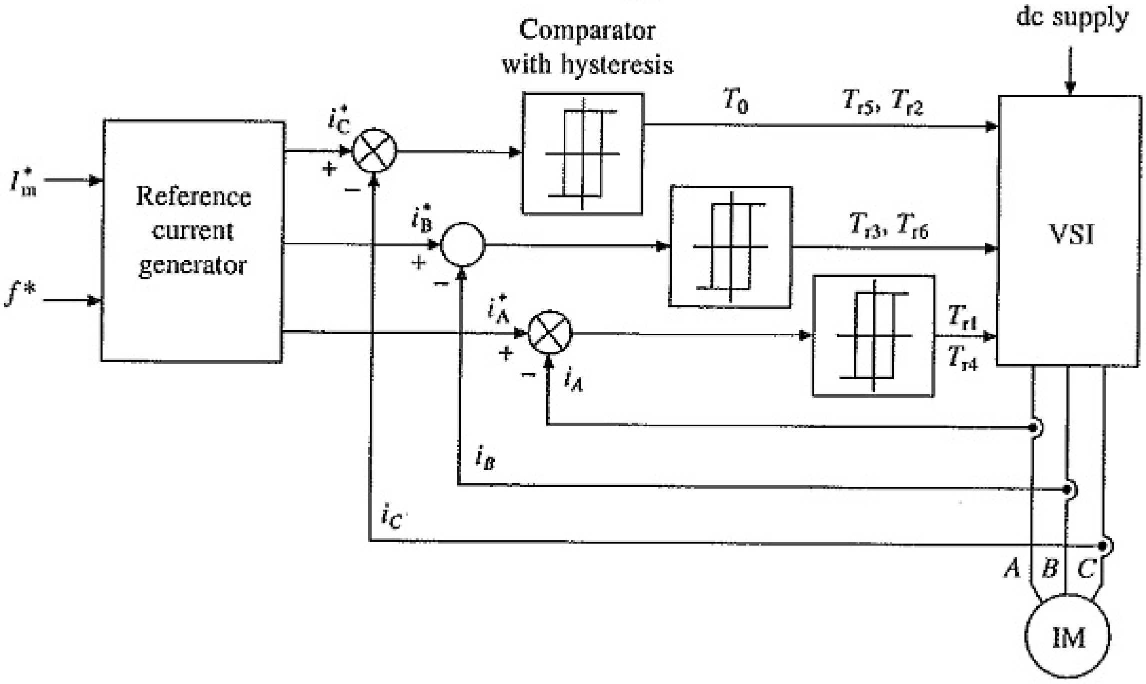
7.b. With the neat driver circuit diagram, Explain the current regulated Voltage Source Inverter Control.

Current Regulated Voltage Source Inverter:

Current Regulated Voltage Source Inverter 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 0, 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 Voltage Source Inverter. 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 Voltage Source Inverter 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.

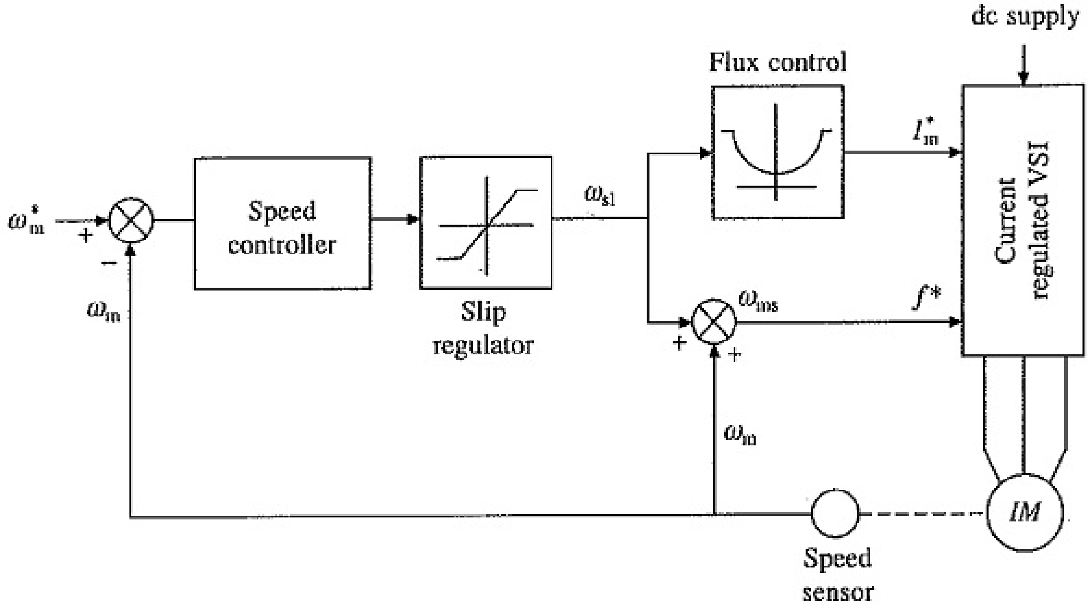


Fig. 6.49 Closed-loop control of current regulated voltage source inverter fed induction motor drive

8.a. Explain the operation of synchronous motor fed from fixed frequency supply.

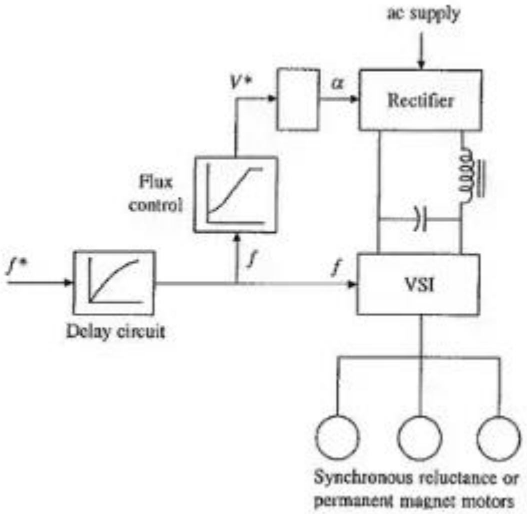
Synchronous motors are constant speed motors. They run at the synchronous speed of the supply. They are generally used for constant speed operation under no load conditions such as to improve the power factor. Synchronous motors have fewer losses than induction motors at a given rating.

The speed of a synchronous motor is given by

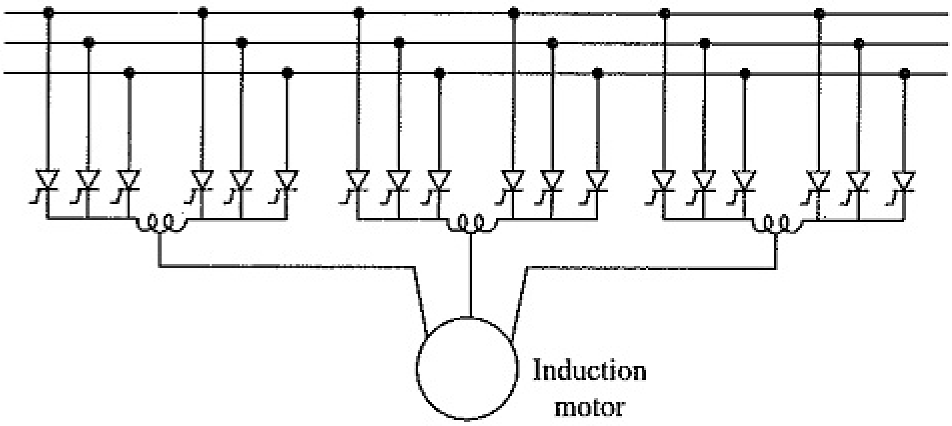
$$N_s = \frac{120f}{p}$$

Where, f = supply frequency and p = number of poles.

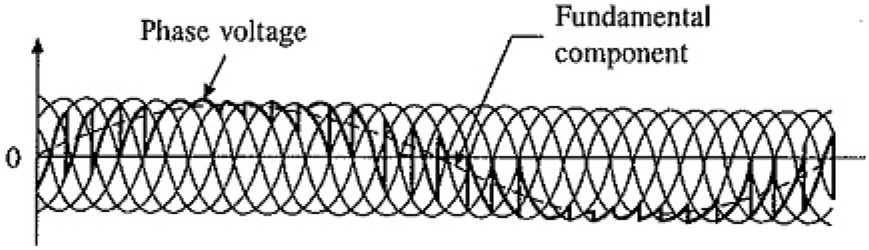
As you can see, the synchronous speed depends on the frequency of the supply and the number of poles of the rotor. Changing the number of poles is not easy, so we do not use that method. However, with the invention of solid-state devices, the frequency of the current fed to the synchronous motor can be varied. We can control the speed of the synchronous motor by changing the frequency of the supply to the motor.



8.b. With the neat circuit diagram, explain the closed loop speed control and converter rating for VSI and cycloconverter IM drive.



(a) Half wave cycloconverter-fed induction motor



(b) Phase voltage waveform

Fig. 6.42 Cycloconverter controlled induction motor drive

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.

Cycloconverter Control of Induction Motor 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.

9.a. Explain self-controlled synchronous motor drive employing load commutated thyristor inverter

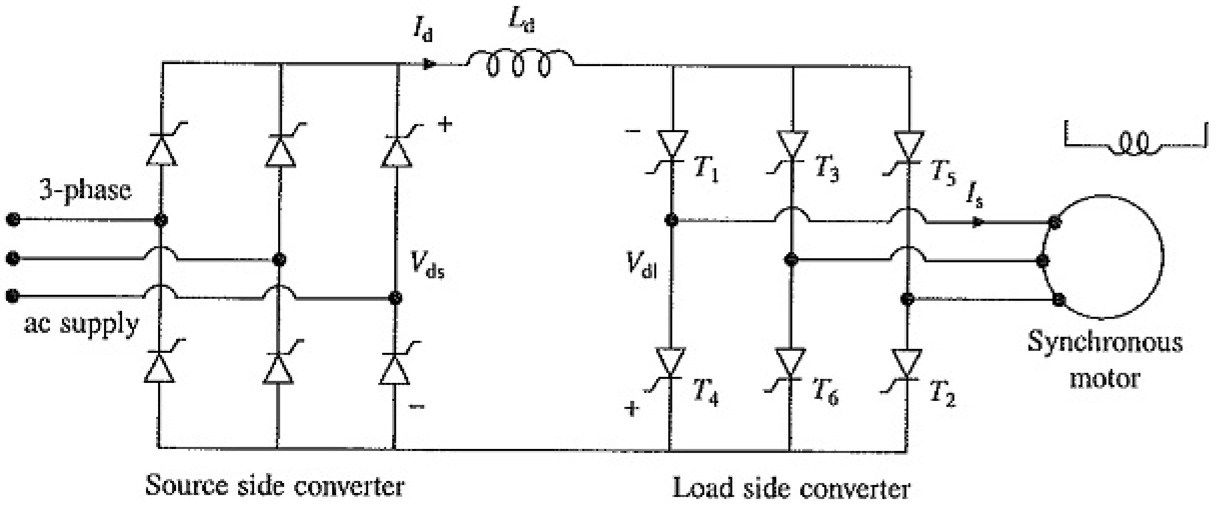


Fig. 7.10 Self-controlled synchronous motor drive employing load commutated inverter

When Self Controlled Synchronous Motor Drive 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 $90° \leq \alpha_l \leq 180°$. For $0 \leq \alpha_l \leq 90°$ it works as a rectifier giving positive V_{dl}. For $0 \leq \alpha_s \leq 90°$, $90° \leq \alpha_l \leq 180°$ 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 $90° \leq \alpha_s \leq 180°$ and $0° \leq \alpha_l \leq 90°$, 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

$$\beta_l = 180° - \alpha_l$$

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 $\beta_l = 180°$ (or $\alpha_l = 0°$) 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

$$\gamma > \omega t_n$$

$$\gamma > \omega t_q$$

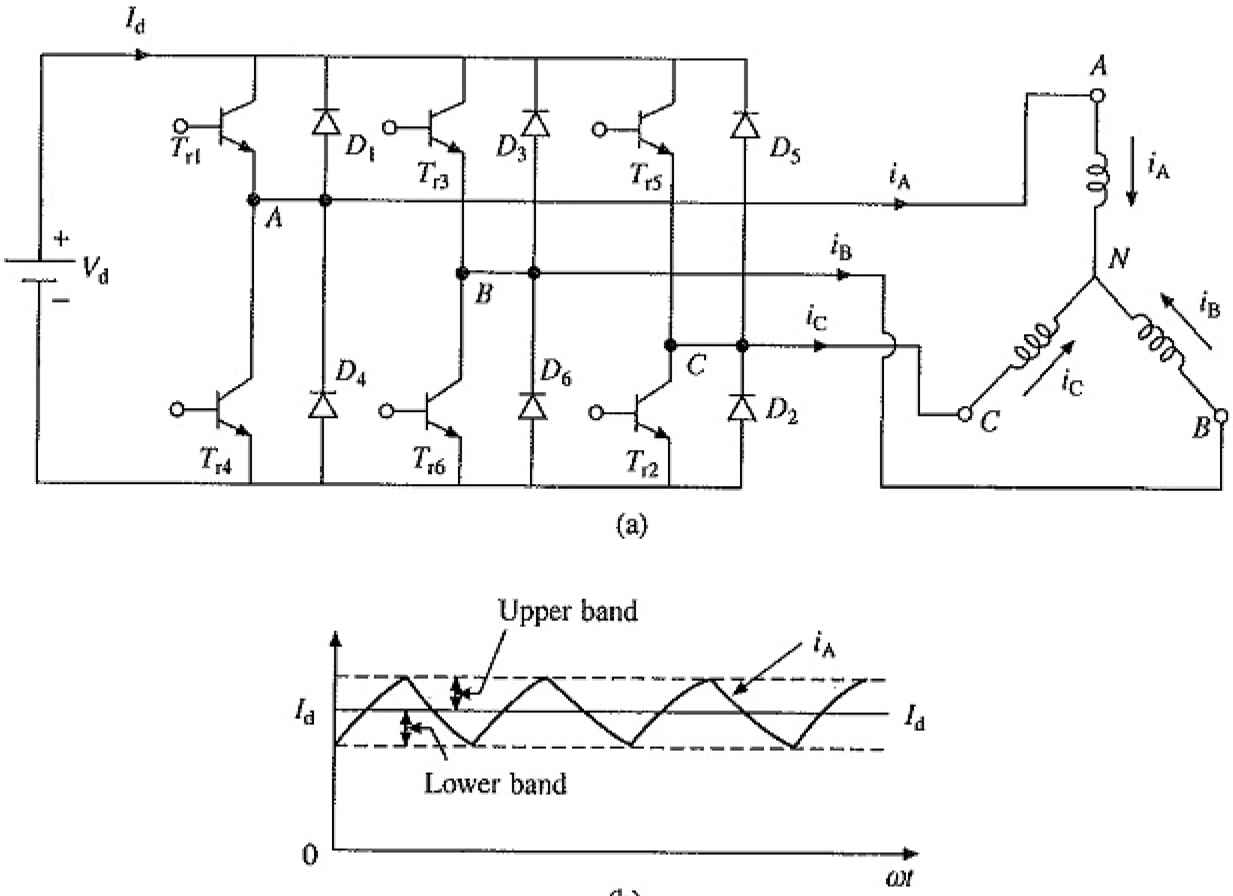
where t_q is the turn-off time of thytistors and ω the frequency of motor voltage in radians/sec. Since u is proportional to I_d, for a given I_d, β_l can be calculated such that the thyristor under commutation is reverse biased for a duration γ_{min} which is just enough for its commutation. This in 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

$$I_s = \frac{\sqrt{6}}{\pi} I_d \qquad (7.24)$$

9.b. Explain Brushless DC Motor Drive for Servo Applications?



(a)

(b)

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

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 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

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

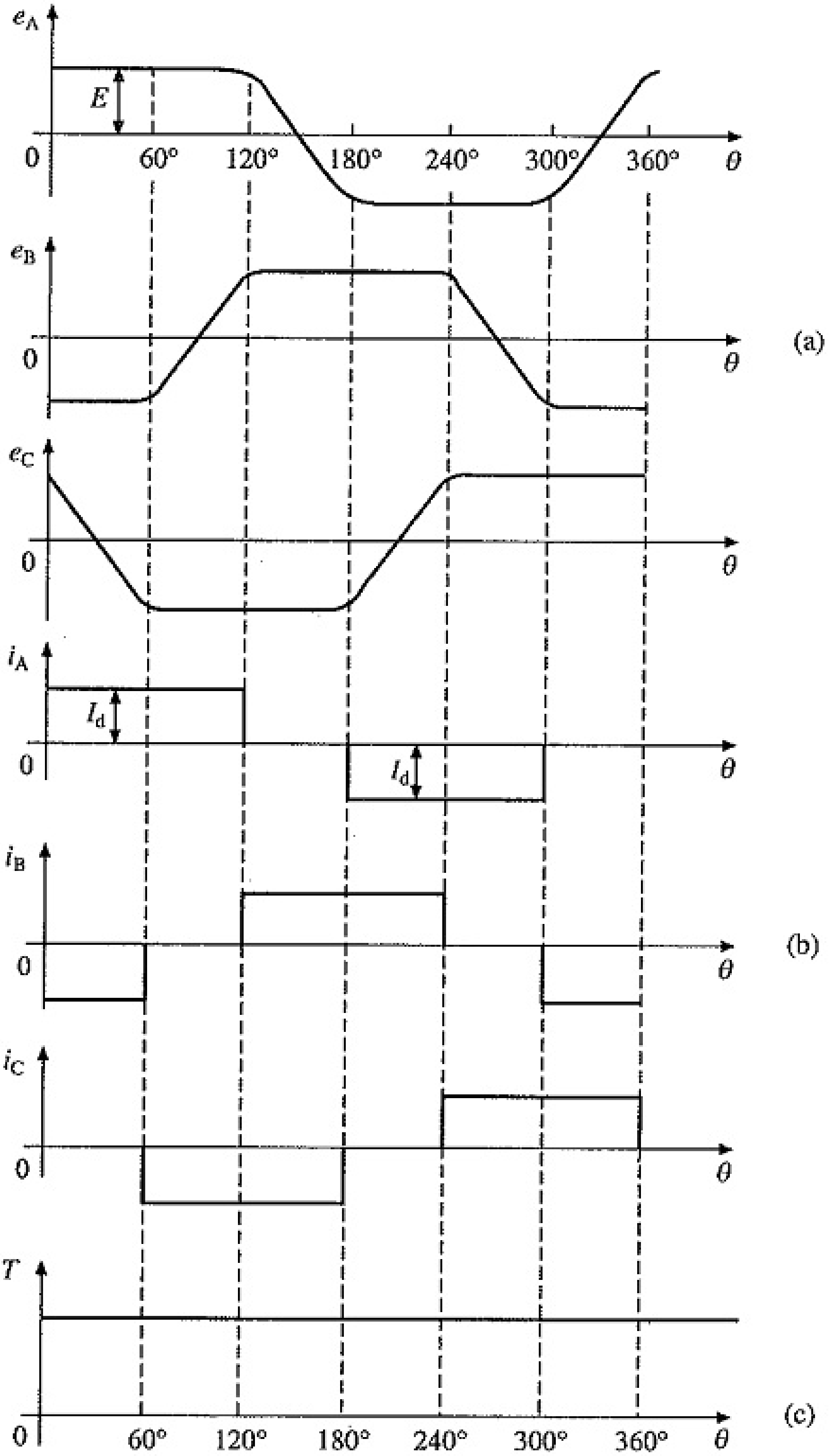
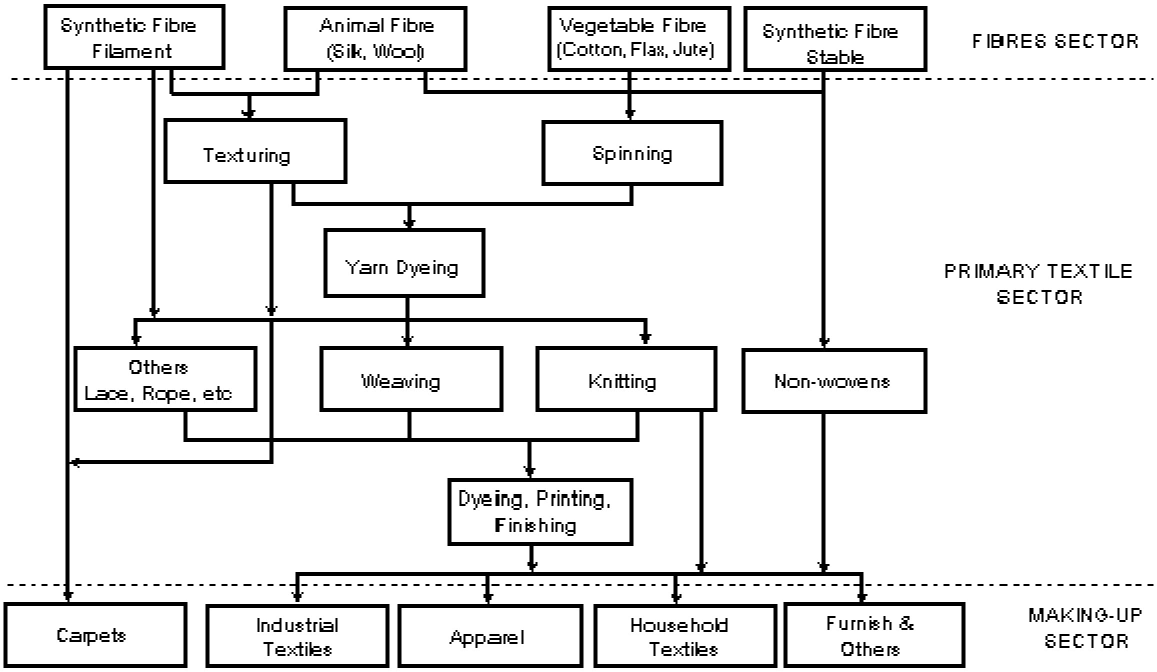


Fig. 7.17 Induced voltage, phase current and torque wavefors of a brushless dc motor

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 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 T_{r6} 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.

10.a. With a neat process flow diagram, explain the process flow of textile mill, and list the requirements of drive.



Ginning: The process of separating seeds from the raw cotton picked from the field is called ginning. This may be done in the mills located near the fields or in the industrial location itself. In the former the ginned cotton is transported to the industrial area in the form of hales. The ginning motors must have speed ranges of 250 to 1450 rpm. The load speeds are fairly constant. No speed control is required.

Commercially available squirrel cage induction motors may be employed.

Blowing: The ginned cotton in the form of bales is opened up and is cleaned up very well. Normally three phase Induction Motor may be used for the purpose. No speed control is required. The motors having synchronous speed of 1000 or 1500 rpm may be employed.

Cording: The process of converting cleaned cotton into laps is done by lap machines which are normal three-phase standard squirrel cage motors. These laps are converted to slivers by a process called cording. A motor used for cording is required to accelerate a drum having a large moment of inertia. It is required to withstand prolonged accelerating periods. To meet these requirements the motor selection must be made. The motor selected must have a very high starting torque and low starting current so that starting losses are kept to a minimum. The motor must have sufficient thermal capacity to withstand the heat produced by the losses occurring during prolonged acceleration. These cord motors are standardised in IS:2972 (part II) 1964 which gives the specifications for cord motors.

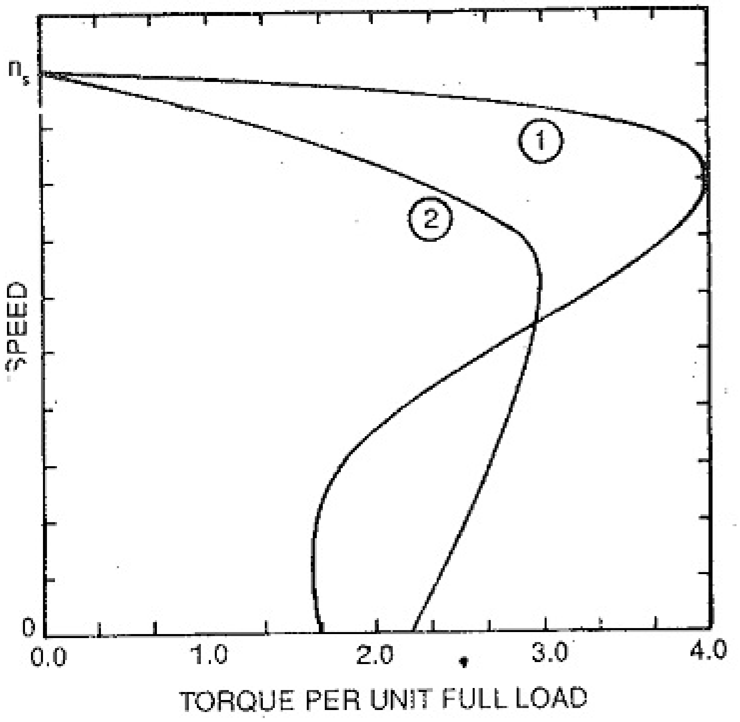
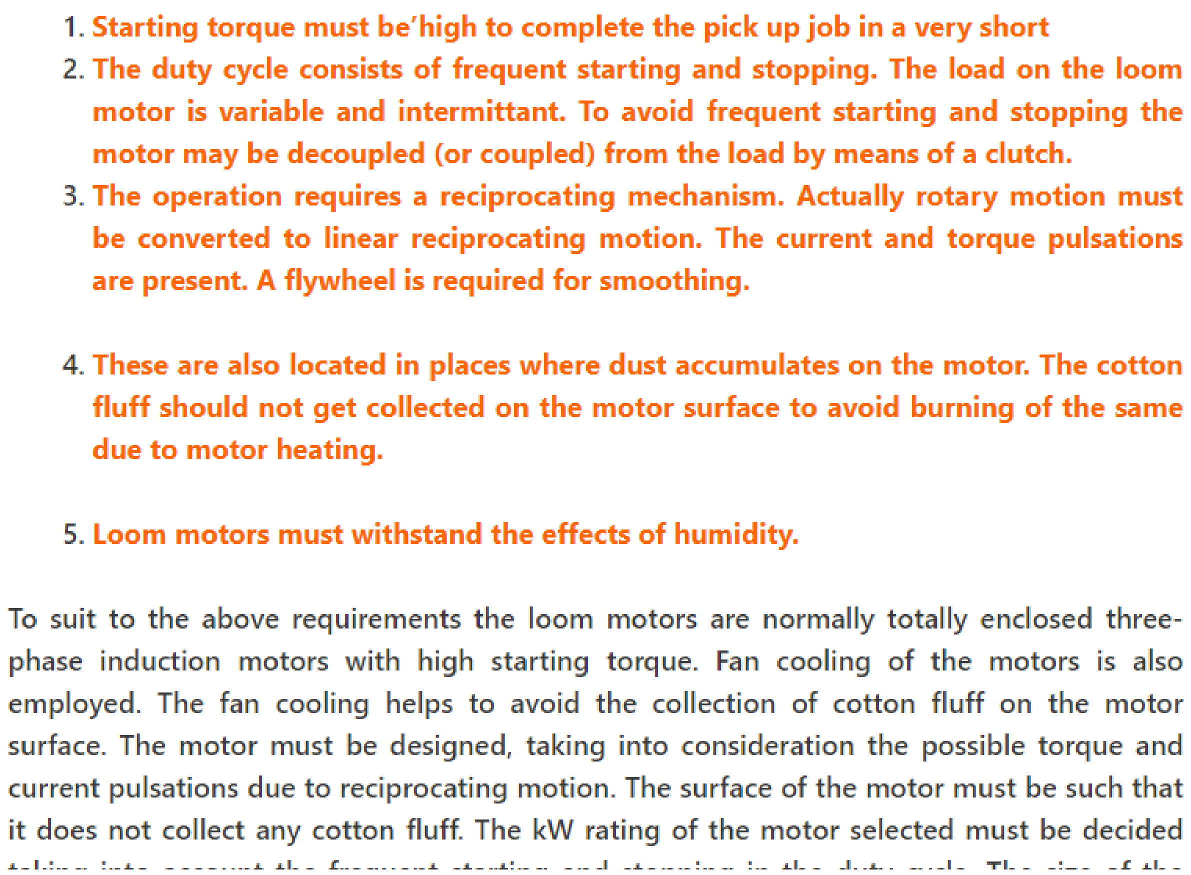


Fig. 7.1 *Typical speed-torque of spinning motor for uniform acceleration* ① *Normal motor* ② *Spinning motor*



1. Starting torque must be’high to complete the pick up job in a very short
2. The duty cycle consists of frequent starting and stopping. The load on the loom motor is variable and intermittant. To avoid frequent starting and stopping the motor may be decoupled (or coupled) from the load by means of a clutch.
3. The operation requires a reciprocating mechanism. Actually rotary motion must be converted to linear reciprocating motion. The current and torque pulsations are present. A flywheel is required for smoothing.

4. These are also located in places where dust accumulates on the motor. The cotton fluff should not get collected on the motor surface to avoid burning of the same due to motor heating.

5. Loom motors must withstand the effects of humidity.

To suit to the above requirements the loom motors are normally totally enclosed three-phase induction motors with high starting torque. Fan cooling of the motors is also employed. The fan cooling helps to avoid the collection of cotton fluff on the motor surface. The motor must be designed, taking into consideration the possible torque and current pulsations due to reciprocating motion. The surface of the motor must be such that it does not collect any cotton fluff. The kW rating of the motor selected must be decided

10. b. List the advantages and Disadvantages of stepper motor.

Advantages

1. They are compatible with digital systems and do not require digital to analog conversion at the input, as do conventional servos, when used with digital systems or a computer.
2. While simple open-loop control is good enough for the control of position and speed, it can also be used in closed loop position and speed control systems with either analog or digital feedback.
3. A wide range of step angles is available off-the-shelf from most manufacturers, in the range of 1.8 to 90°. The range of torque is from 1 µNm (tiny wristwatch motor) to 50 Nm (machine tool applications).
4. Bidirectional control is available.
5. Maximum torque occurs at low pulse rates. The stepper motor can, therefore, accelerate its load easily.
6. Low speeds are possible without a reduction gear.
7. Moment of inertia is usually low.
8. The starting current is low.
9. Multiple stepper motors driven from the same source can maintain perfect synchronisation.

Disadvantages

1. Efficiency is low.
2. Proper matching between load, motor and its drive is required.
3. Resonance can be a problem with variable reluctance motors.