Module-1: Electric Drives

Syllabus

Electrical Drives:

Electrical Drives, Advantages of Electrical Drives. Parts of Electrical Drives, Choice of Electrical Drives, Status of DC and ac Drives.

Dynamics of Electrical Drives:

Fundamental Torque Equations, Speed Torque Conventions and Multi-quadrant Operation. Equivalent Values of Drive Parameters, Components of Load Torques, Nature and Classification of Load Torques, Calculation of Time and Energy Loss in Transient Operations, Steady State Stability, Load Equalization.

Control Electrical Drives:

Modes of Operation, Speed Control and Drive Classifications, Closed loop Control of Drives.

Introduction to Drives

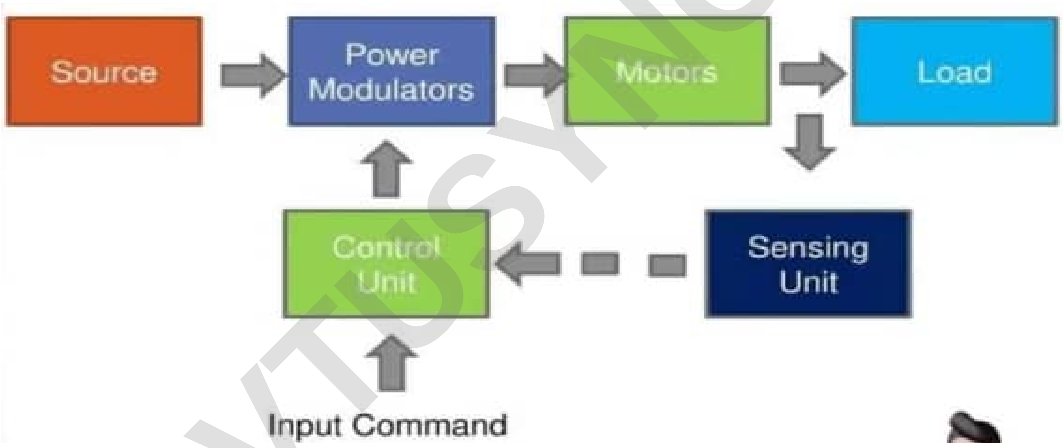
Drive: Systems employed for motion control are called drives.

It employs any of the prime movers such as diesel or petrol engines, gas or steam turbines, steam engines, hydraulic motors and electric motors for supplying mechanical energy for motion control.

Electric Drive: Drives employing electric motors are known as electrical drives.

- Motion control is required in large number of industrial and domestic applications.
- Systems employed for motion control are called DRIVES, and may employ any of prime movers such as diesel or petrol engines, gas or steam turbines, steam engines, hydraulic motors and electric motors, for supplying mechanical energy for motion control

Block diagram of electric drive



Parts of Electric Drive:

1. **Electrical Sources:**
   - Very low power drives are generally fed from single phase sources.
   - Rest of the drives is powered from a 3 phase source.
   - Low and medium power motors are fed from a 400V supply.
   - For higher ratings, motors may be rated at 3.3KV, 6.6KV and 11 KV.
   - Some drives are powered from battery.

2. **Power modulator**

It is most commonly used as a converter. These are the devices which alter the nature or frequency as well as changes the intensity of power to control electrical drives.

Functions :

Modulates flow of power from the source to the motor in such a manner that motor is imparted speed-torque characteristics required by the load.

- During transient operation, such as starting, braking and speed reversal, it restricts source and motor currents with in permissible limits.
- It converts electrical energy of the source in the form of suitable to the motor.
- Selects the mode of operation of the motor (i.e.) Motoring and Braking.

Power Modulators Classification

power modulators can be classified into three types,

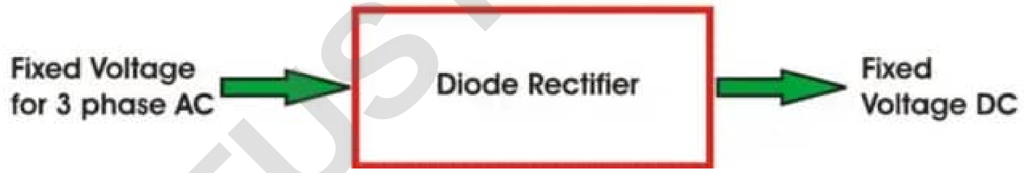
a) Converters,
b) Variable impedance circuits,
c) Switching circuits.

a) Converters:

As the name suggests, converters are used to convert currents from one type to other type. Depending on the type of function, converters can be divided into 5 types -

i. ***AC to DC converters:***

AC to DC converters are used to obtain fixed DC supply from the AC supply of fixed voltage. The very basic diagram of AC to DC converters is like.



ii. ***AC regulators***

AC Regulators are used to obtain the regulated AC voltage, mainly auto transformers or tap changer transformers are used in this regulators.

iii. ***Choppers or DC - DC converters***

Choppers or DC-DC converters are used to get a variable DC voltage. Power transistors, IGBT's, GPO's, power MOSFET's are mainly used for this purpose.

iv. ***Inverters***

Inverters are used to get AC from DC, the operation is just opposite to that of AC to DC converters. PWM semiconductors are used to invert the current.

v. ***Cycloconverters***

Cycloconverters are used to convert the fixed frequency and fixed voltage AC into variable frequency and variable voltage AC. Thyristors are used in these converters to control the firing signals.

b) <u>Variable Impedance circuits:</u>

- These are used to control speed by varying the resistance or impedance of the circuit. But these controlling methods are used in low cost DC and AC drives.
- There can be two or more steps which can be controlled manually or automatically with the help of contactors.
- To limit the starting current inductors are used in AC motors.

c) <u>Switching circuits:</u>

- These are used in motors and electrical drives for running the motor smoothly and they also protects the machine during faults.
- These circuits are used for changing the quadrant of operations during the running condition of a motor.
- These circuits are implemented to operate the motor and drives according to predetermined sequence, to provide interlocking, to disconnect the motor from the main circuit during any abnormal condition or faults.

3. Sensing Unit

- Speed Sensing (From Motor for closed loop operation)
- Torque Sensing
- Position Sensing
- Current sensing and Voltage Sensing from Lines or from motor terminals from Load

- Torque sensing
- Temperature Sensing

4. **Control Unit:**

Choice of control unit depends upon the type of power modulator that is used. These are of many types, like when semiconductor converters are used, then the control unit consists of firing circuits, which employ linear devices and which employ linear and digital integrated circuits and transistors, and a microprocessor when sophisticated control is required.

5. **Motors:**

DC Machines

Shunt, series, compound, separately excited DC motors and switched reluctance machines.

AC Machines

Induction, wound rotor, synchronous, PM (Permanent Magnet) synchronous and synchronous reluctance machines

Special Machines

Brush less DC motors, stepper motors, switched reluctance motors are used.

Comparison between DC and AC drives

DC Drive	AC Drive
The power circuit and control circuit is simple and inexpensive	The power circuit and control circuit are complex
It requires frequent maintenance	Less Maintenance
The commutator makes the motor bulky, costly and heavy	These problems are not there in these motors and are inexpensive, particularly squirrel cage induction motors

DC Drive	AC Drive
Fast response and wide speed range of control, can be achieved smoothly by conventional and solid state control	In solid state control the speed range is wide and conventional method is stepped and limited
Speed and design ratings are limited due to commutations	Speed and design ratings have upper limits

Advantage of Electrical drives.

1. These drives are available in wide range torque, speed and power.
2. The control characteristics of these drives are flexible. According to load requirements these can be shaped to steady state and dynamic characteristics. As well as speed control, electric braking, gearing, starting many things can be accomplished.
3. The are adaptable to any type of operating conditions, no matter how much vigorous or rough it is.
4. They can operate in all the four quadrants of speed torque plane, which is not applicable for other prime movers.
5. They do not pollute the environment.
6. They do not need refueling or preheating, they can be started instantly and can be loaded immediately.
7. They are powered by electrical energy which is atmosphere friendly and cheap source of power.

Choice (or) Selection of Electrical Drives

Choice of an electric drive depends on a number of factors. Some of the important factors are.

1. ***Steady State Operating conditions requirements***: Nature of speed torque characteristics, speed regulation, speed range, efficiency, duty cycle, quadrants of operation, speed fluctuations if any, ratings etc

2. ***Transient operation requirements:*** Values of acceleration and deceleration, starting, braking and reversing performance.

3. ***Requirements related to the source:*** Types of source and its capacity, magnitude of voltage, voltage fluctuations, power factor, harmonics and their effect on other loads, ability to accept regenerative power

4. ***Capital and running cost*****:** maintenance needs life.

5. ***Space and weight restriction***

6. ***Environment and location.***

7. ***Reliability.***

Classification of Electric Drives

- According to Mode of Operation
    - Continuous duty drives
    - Short time duty drives
    - Intermittent duty drives

- According to Means of Control
    - Manual
    - Semi automatic
    - Automatic
- According to Number of machines
    - Individual drive
    - Group drive
    - Multi-motor drive
- According to Dynamics and Transients
    - Uncontrolled transient period
    - Controlled transient period
- According to Methods of Speed Control
    - Reversible and non-reversible uncontrolled constant speed.
    - Reversible and non-reversible step speed control.
    - Variable position control.
    - Reversible and non-reversible smooth speed contro

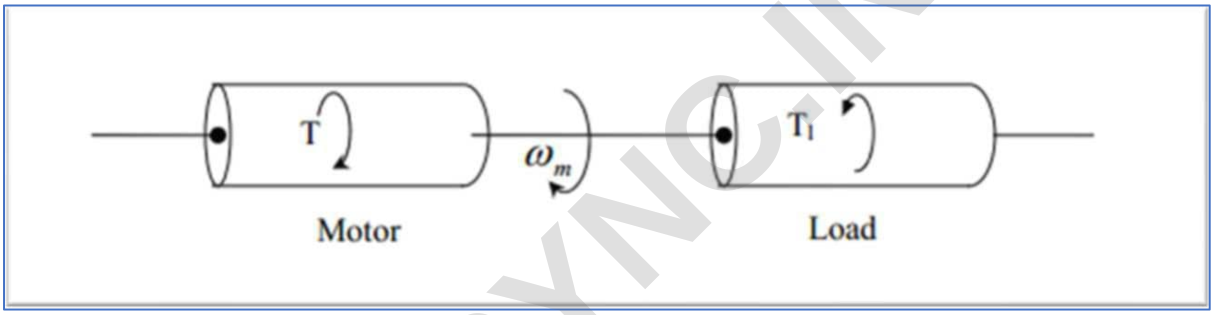
Applications

- Paper mills
- Cement Mills
- Textile mills
- Sugar Mills
- Steel Mills
- Electric Traction
- Petrochemical Industries
- Electrical Vehicles

Module-1: Dynamics of Electrical Drives

Fundamentals of Torque Equations

- A motor generally drives a load (Machines) through some transmission system.
- While motor always rotates, the load may rotate or undergo a translational motion.
- Load speed may be different from that of motor, and if the load has many parts, their speed may be different and while some parts rotate others may go through a translational motion.
- Equivalent rotational system of motor and load is shown in the figure.



Where,

J = Moment of inertia of motor load system referred to the motor shaft $kg-m^2$

ω_m= Instantaneous angular velocity of motor shaft, rad/sec.

T = Instantaneous value of developed motor torque, N-m

T_l=Instantaneous value of load torque, referred to the motor shaft N-m

Load torque includes friction and windage torque of motor. Motor-load system shown in figure can be described by the following fundamental torque equation

$$T - T_l = \frac{d}{dt}(J\omega_m) = J\frac{d\omega_m}{dt} + \omega_m\frac{dJ}{dt} ------------(1)$$

For drives with constant inertia $\frac{dJ}{dt} = 0$

Equation (1) is applicable to variable inertia drives such as mine winders, reel drives, Industrial robots.

For drives with constant inertia $\frac{dJ}{dt} = 0$

$$T = T_l + J\frac{d\omega_m}{dt}$$

Equation (2) shows that torque developed by motor is counter balanced by load torque T_l and a dynamic torque $\left(J\frac{d\omega_m}{dt}\right)$. Torque component $\left(J\frac{d\omega_m}{dt}\right)$ is called dynamic torque because it is present only during the transient operations.

Speed Torque Conventions and Multi-quadrant Operation

- For consideration of multi-quadrant operation of drives, it is useful to establish suitable conventions about the signs of torque and speed.
- Motor is considered positive when rotating in the forward direction.
- For drives which operate only in one direction, forward speed will be their normal speed.
- In loads involving up-and-down motions, the speed of motor which causes upward motion is considered forward motion.
- For reversible drives, forward speed is chosen arbitrarily. Then the rotation in opposite direction gives reverse speed which is assigned the negative sign.
- Positive motor torque is defined as the torque which produces acceleration or the positive rate of change of speed in forward direction.
- According to Eq. (1) positive load torque is opposite in direction to the positive motor torque. Motor torque is considered negative if it produces deceleration.

$$T = T_l + J\frac{d\omega_m}{dt} \quad (1)$$

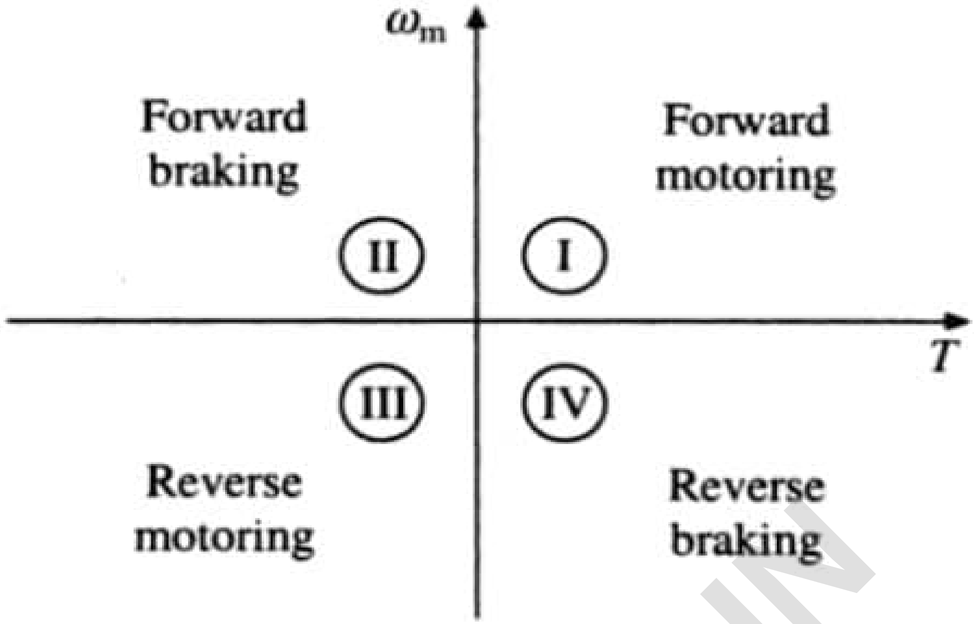


Fig. 2.2 Multiquadrant-operation of drives

- 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 for both forward and reverse directions.
- Figure 2.2 shows the torque and speed coordinates for both forward (positive) and reverse (negative) motions.
- 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, in quadrant Ill and IV can identified as reverse motoring and braking respectively.

Orientation of a hoist in four quadrants

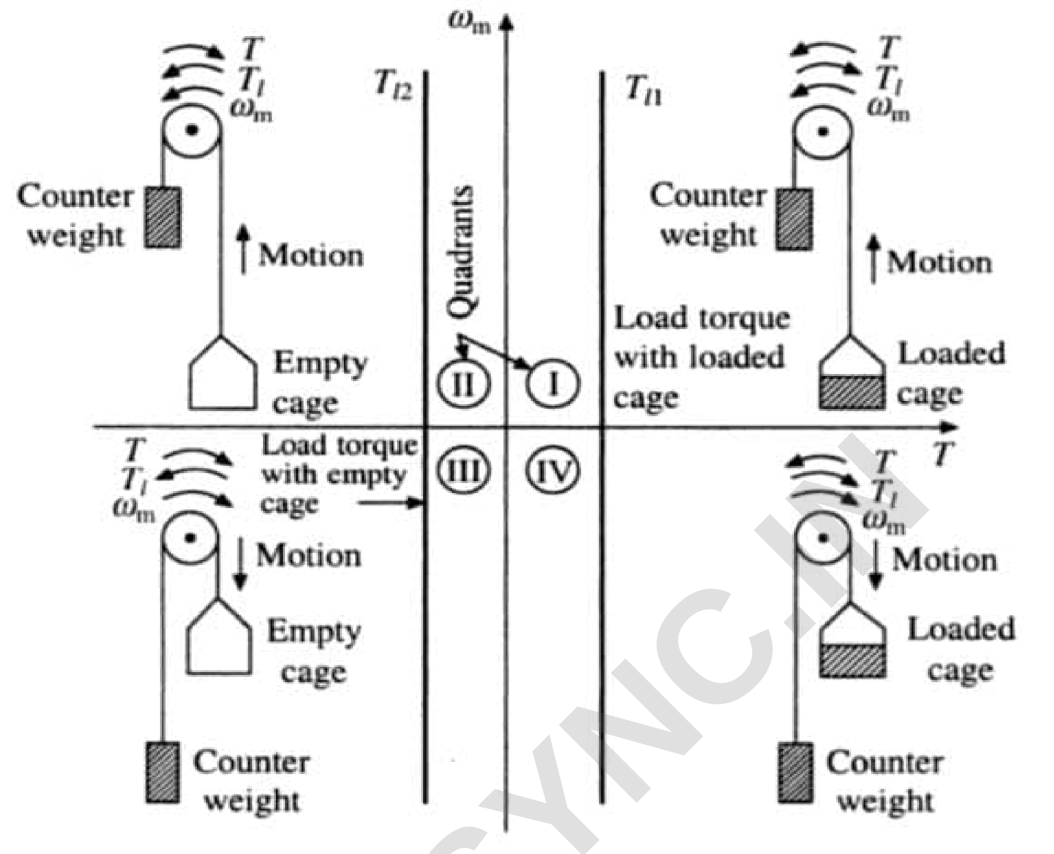


Fig. 2.3 Four quadrant operation of a motor driving a hoist load

- For better understanding of the above notations, **let us consider orientation of a hoist in four quadrants** as shown in Fig. 2.3. Directions of motor and load torques, and direction of speed are marked by arrows.
- 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.
- Forward direction of motor speed will be one which gives upward motion of the cage. Speed- torque characteristics of the hoist load are also shown in Fig. 2.3.
- Though the positive load torque is opposite in sign to the positive motor torque, according to Eq. (2.2), it is convenient to plot it on the same axes.
- Load-torque curve drawn in this manner is, in fact, negative of the actual.
- Load torque line T_{L1} in quadrants I and IV represents speed-torque characteristic for the loaded hoist. -This torque is the difference of torques due to loaded hoist and counter weight.

- The load torque line T_{L2} in quadrants II and III is the speed- torque characteristic for an empty hoist.- This torque is the difference of torques due to counter weight and the empty hoist. Its sign is negative because the weight of a counter weight is always higher than that of an empty 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 power negative, it is forward braking.
- Operation in **quadrant III** is obtained when an empty cage is lowered. Since an empty cage has a lesser weight than a counter weight, the motor should produce a torque in clockwise direction. Since speed is negative and developed power positive, this is reverse motoring operation.

Equivalent Values of Drive Parameters

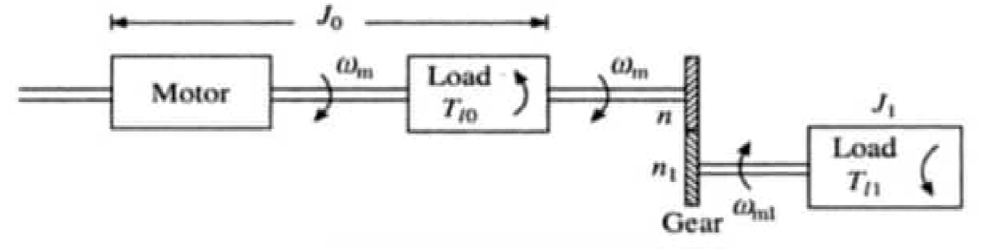
- Different parts of a load may be coupled through different mechanisms, such as gears, V-belts and crankshaft. These parts may have different speeds and different types of motions such as **rotational and translational.**
- The following presents the methods of finding the equivalent moment of inertia (J) of motor-load system and equivalent torque components, all referred to motor shaft.

1. Loads with Rotational Motion

Let us consider a motor driving two loads, one coupled directly to its shaft and other through a gear with n and n_1 and teeth as shown in Fig. (a).

Let the moment of inertia of motor and load directly coupled to its shaft be Jo, motor speed and torque of the directly coupled load be ω_m and T_{LO} respectively.

Let the moment of inertia, and torque of the load coupled through a gear be J_1, ω_{m1} and T_{L1} respectively. Now,



(a) Loads with rotational motion

$$\frac{\omega_{m1}}{\omega_m} = \frac{n}{n_1} = a_1$$ (1) *where a_1 is the gear tooth ratio.* $\omega_{m1} = a_1 . \omega_m$

If the losses in transmission are neglected, then the **kinetic energy due to equivalent inertia** must be the same as kinetic energy of various moving parts. Thus

$$\frac{1}{2} J\omega_m^2 = \frac{1}{2} J_0\omega_m^2 + \frac{1}{2} J_1\omega_{m1}^2$$ (2)

From equations 1 and 2

$$J = J_0 + a_1^2 J_1$$

Power at the loads and motor must be the same. If transmission efficiency of the gears be m, then

$$T_l\omega_m = T_{l0}\omega_m + \frac{T_{l1}\omega_{m1}}{\eta_1}$$

where T_l is the total equivalent torque referred to motor shaft.

From Eqs. (2.3) and (2.6)

$$T_l = T_{l0} + \frac{a_1 T_{l1}}{\eta_1} \tag{2.7}$$

If in addition to load directly coupled to the motor with inertia J_0 there are m other loads with moment of inertias $J_1, J_2, \ldots, J_m$ and gear teeth ratios of $a_1, a_2, \ldots a_m$ then

$$J = J_0 + a_1^2 J_1 + a_2^2 J_2 + \ldots + a_m^2 J_m \tag{2.8}$$

If m loads with torques $T_{l1}, T_{l2}, \ldots, T_{lm}$ are coupled through gears with teeth ratios $a_1, a_2, \ldots a_m$ and transmission efficiencies $\eta_1, \eta_2, \ldots, \eta_m$, in addition to one directly coupled, then

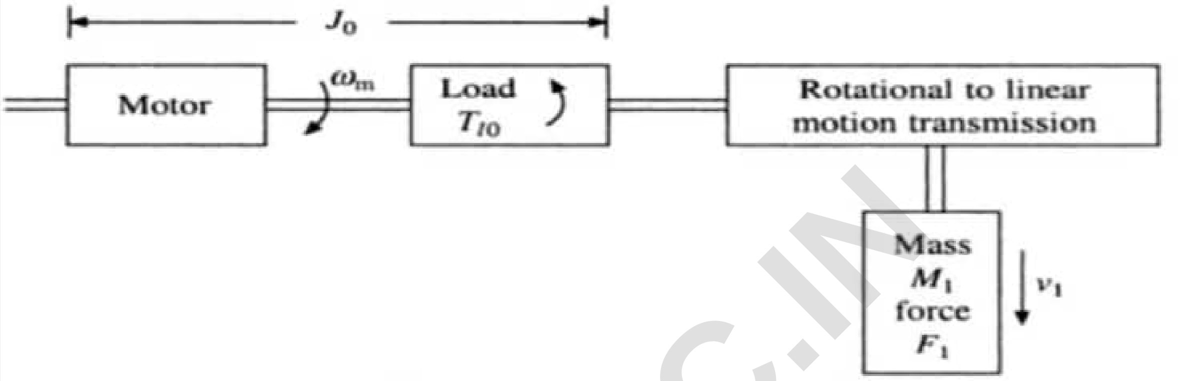
$$T_l = T_{l0} + \frac{a_1 T_{l1}}{\eta_1} + \frac{a_2 T_{l2}}{\eta_2} + \ldots + \frac{a_m T_{lm}}{\eta_m} \tag{2.9}$$

If loads are driven through a belt drive instead of gears, then, neglecting slippage, the equivalent inertia and torque can be obtained from Eqs. (2.8) and (2.9) by considering $a_1, a_2, \ldots, a_m$ each to be the ratios of diameters of wheels driven by motor to the diameters of wheels mounted on the load shaft.

2. Loads with Translational Motion

Let us consider a motor driving two loads, one coupled directly to its shaft and other through a transmission system converting rotational motion to linear motion Fig (b).

Let moment of inertia of the motor and load directly coupled to it be Jo, load torque directly coupled to motor be T_{LO}), and the mass, velocity and force of load with translational motion be M_1 (kg), V_1 (m/sec) and F_1 (Newtons), respectively.



(b) Loads with translational and rotational motion

If the transmission losses are neglected, then kinetic energy due to equivalent inertia J must be the same as kinetic energy of various moving parts. Thus

$$\frac{1}{2} J\omega_m^2 = \frac{1}{2} J_0\omega_m^2 + \frac{1}{2} M_1 v_1^2$$

or
$$J = J_0 + M_1\left(\frac{v_1}{\omega_m}\right)^2 \qquad (2.10)$$

Similarly, power at the motor and load should be the same, thus if efficiency of transmission be η_1

$$T_l\omega_m = T_{l0} \cdot \omega_m + \frac{F_1 v_1}{\eta_1}$$

or
$$T_l = T_{l0} + \frac{F_1}{\eta_1}\left(\frac{v_1}{\omega_m}\right) \qquad (2.11)$$

If, in addition to one load directly coupled to the motor shaft, there are m other loads with translational motion with velocities $v_1, v_2, \ldots v_m$ and masses $M_1, M_2, \ldots, M_m$, respectively, then

$$J = J_0 + M_1\left(\frac{v_1}{\omega_m}\right)^2 + M_2\left(\frac{v_2}{\omega_m}\right)^2 + \ldots + M_m\left(\frac{v_m}{\omega_m}\right)^2 \qquad (2.12)$$

and
$$T_l = T_{l0} + \frac{F_1}{\eta_1}\left(\frac{v_1}{\omega_m}\right) + \frac{F_2}{\eta_2}\left(\frac{v_2}{\omega_m}\right) + \ldots + \frac{F_m}{\eta_m}\left(\frac{v_m}{\omega_m}\right) \qquad (2.13)$$

Classification of Load Torques

1. Active load torques
2. Passive load torques

1. **Active load torques:** Load torques which has the potential to drive the motor under equilibrium conditions are called active load torques. Such load torques usually retain their sign when the drive rotation is changed (reversed)

Examples

- Torque due to force of gravity
- Torque due to tension
- Torque due to compression and torsion etc

2. **Passive load torques**: Load torques which always oppose the motion and change their sign on the reversal of motion are called passive load torques

Examples

- Torque due to friction, cutting etc.

Components of Load Torques

Load torque T_l can be further divided into following components:

(i) Friction torque T_F: Friction will be present at the motor shaft and also in various parts of the load. T_F is equivalent value of various friction torques referred to the motor shaft.

(ii) Windage torque, T_W: When a motor runs, wind generates a torque opposing the motion. This is known as windage torque.

(iii) Torque required to do the useful mechanical work, T_L: Nature of this torque depends on particular application. It may be constant and independent of speed; it may some function of speed; it may depend on the position or path followed by load; it may be time invariant or time-variant; also depends on the modes of operations of load.

Friction Torque with Speed:

Value of friction torque with speed is shown in figure below

- Its value at stand still is much higher than its value slightly above zero speed. Friction at zero speed is called stiction or static friction.
- In order to start the drive the motor should at least exceed stiction.
- Hence friction torque is resolved into 3 components.
  i. Component **T_V** which varies linearly with speed is called viscous friction and is given by:
  $$T_v = B\omega_m$$
  where B is the viscous friction coefficient.
  ii. Another component **Tc,** which is independent of is known as Coulomb friction.

iii. Third component **Ts** accounts for additional torque present at standstill.

iv. Windage torque **Tw**, which is proportional to speed squared, is given by

$$T_w = C\omega_m^2$$

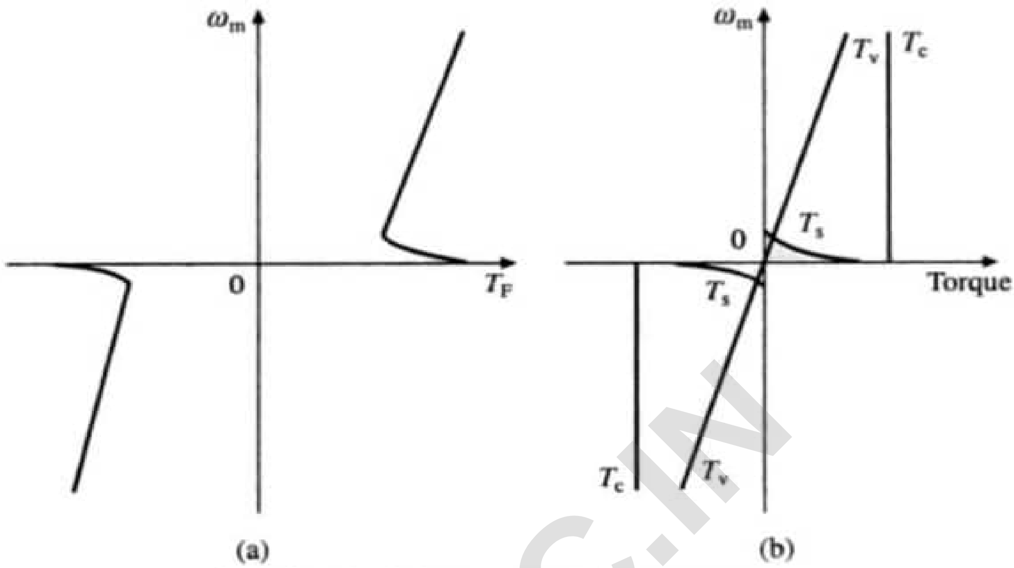


Fig. 2.6 Friction torque and its components

Therefore from above equations: $$T_l = T_L + B\omega_m + T_c + C\omega_m^2$$

$$T = J\frac{d\omega_m}{dt} + T_L + B\omega_m$$

Nature and Classification of Load Torques

The nature of load torque depends on particular application.

Fig(a) Load torque is proportional to square of the speed: Fans, compressors, aeroplanes, centrifugal pumps, ship-propellors, coilers, high speed hoists, traction etc,

Fig (b) In a high speed hoist, viscous friction and windage also have appreciable magnitude, in addition to gravity, thus giving the speed-torque curve shown.

Fig (c) Nature of speed-torque characteristic of a traction load when moving on a levelled ground is shown.

Fig. 2.7(d). Hyperbolic in nature as shown. Because of its heavy mass, the stiction is large. Near zero speed, net torque is mainly due to stiction. Because of large stiction and need for accelerating a heavy mass, the motor torque required for starting a train is much larger than what is required to run it at full speed.

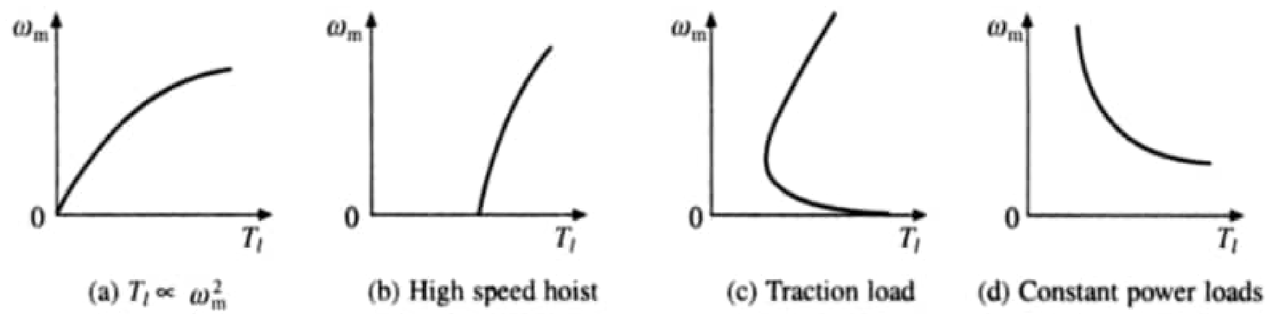


Fig. 2.7 Steady state load torque speed curves

Steady State Stability

- Equilibrium speed of a motor- load system is obtained when motor torque equals the load torque .
- A drive will operate in steady state at this speed, provided it is the speed of stable equilibrium.
- In most drives the electrical time constant of the motor is negligible compared to its mechanical time constant.
- Therefore, during transient operations, motor can be assumed to be in electrical equilibrium implying that steady-state speed-torque curves are also applicable to the transient operations.
- Let us see the following example.

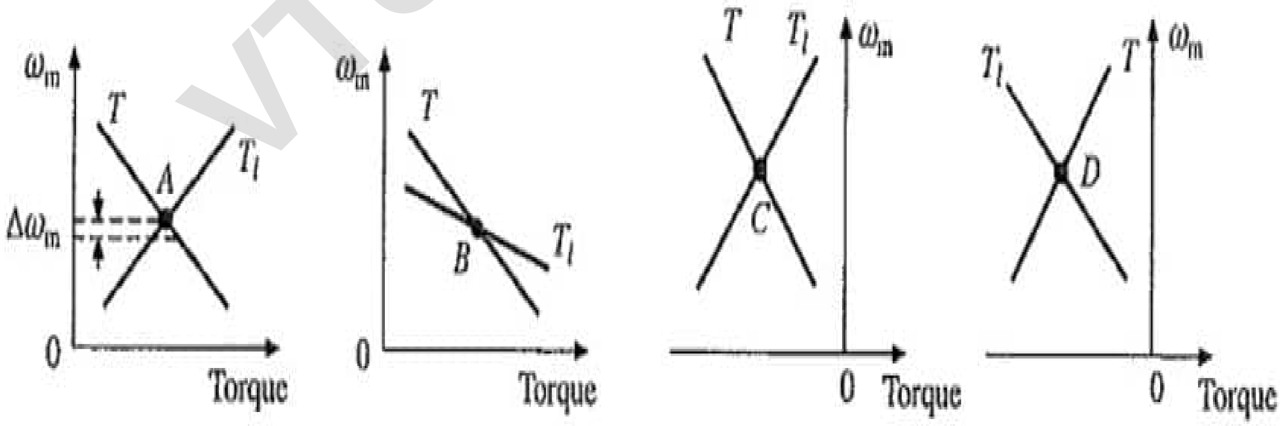
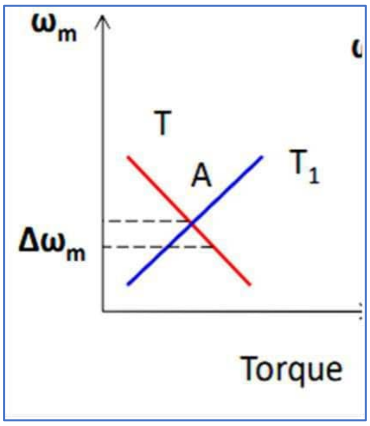


Fig. 2.9 Points A and C are stable and B and D are unstable

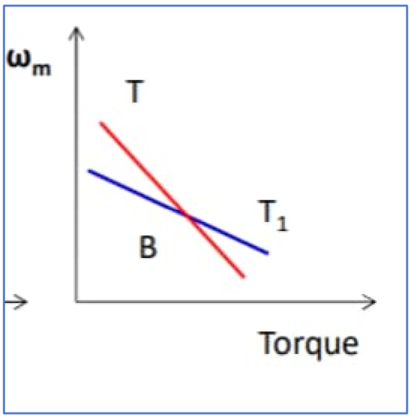
- Concept of steady state stability is used to evaluate the stability of an equilibrium point from the steady-state speed-torque curves of the motor and load.

i. Equilibrium point A



- The equilibrium point A will be termed as stable when the **operation will be restored** to its initial position after a small departure from it due to a disturbance in the motor or load.
- Let the disturbance causes a reduction of $\Delta\omega_m$ in speed. At new speed, motor torque is greater than the load torque, consequently, motor will accelerate and **operation will be restored to A.**
- Similarly, an increase of $\Delta\omega_m$ in speed caused by a disturbance will make load torque greater than the motor torque, resulting into deceleration and **restoration of operation to point A**. Hence, the drive is **steady state stable at point A.**

ii. Equilibrium point B



- This is obtained when the same motor drives another load.
- A decrease in speed causes the load torque to become greater than the motor torque, drive decelerates and **operating point moves away from B**
- Similarly, an increase in speed will make motor torque greater than the load torque which will move the operating point away from B. Thus, **B is an unstable point of equilibrium**

Similarly case iii and case iv could be analysed

Hence an equilibrium point will be stable when an increase in speed causes load-torque to exceed the motor torque, i.e. when at equilibrium point following condition is satisfied

$$\frac{dT_l}{d\omega_m} > \frac{dT}{d\omega_m}$$

Inequality in equation can be derived by an alternative approach. Let a small perturbation in speed,

$$T + \Delta T = T_l + \Delta T_l + J\frac{d\omega_m}{dt} + J\frac{d\Delta\omega_m}{dt}$$

$$\Delta T = \left(\frac{dT}{d\omega_m}\right)\Delta\omega_m$$

$$\Delta T_l = \left(\frac{dT_l}{d\omega_m}\right)\Delta\omega_m$$

$$\Delta\omega_m = (\Delta\omega_m)_0 \exp\left\{-\frac{1}{J}\left(\frac{dT_l}{d\omega_m} - \frac{dT}{d\omega_m}\right)t\right\}$$

An operating point will be stable when $\Delta\omega_m$ approaches zero as t approaches infinity.

Load Equalisation

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:

i. Motor rating has to be high.
ii. 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.
iii. 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.

Above mentioned problems of fluctuating loads are overcome by mounting a **flywheel** on the motor shaft in non-reversible drives.

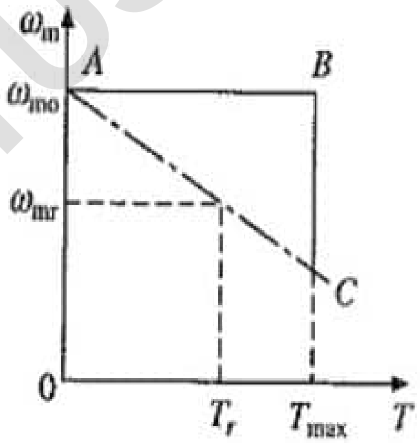


Fig. 2.10 Shapes of motor speed torque curves for fluctuating roads

- Motor speed-torque characteristic is made drooping(characteristic AC in Fig. 2.10).
- Alternatively by closed loop current control, torque is prevented from exceeding a permissible value (characteristic ABC in Fig. 2.10).

- 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. Because of 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.

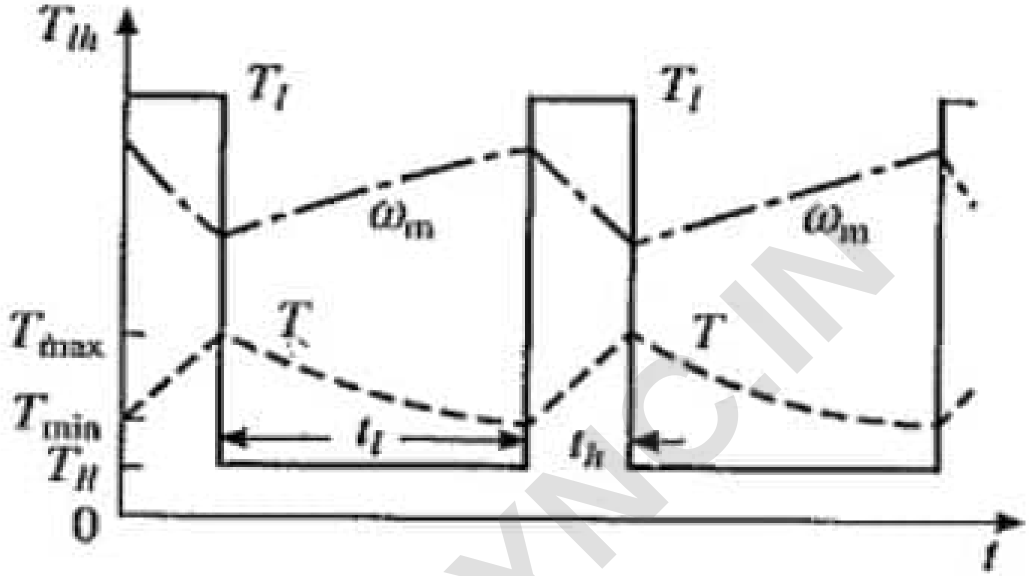


Fig. 2.11

***T_{lh}**- High load torque*, ***T_{ll}**- Light load torque*

***t_h**-High load period duration*, ***t_l**- light load period duration*

- Variation of motor and load torques, and speed or a periodic load and for a drooping motor speed-torque curve (AC in Fig. 2.10) are shown in Fig. 2.11.
- It shows that peak 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.**
- In variable speed and reversible drives, a flywheel cannot be mounted on the motor shaft, as it will increase transient time of the drive by a large amount.
- If motor is fed from a motor- generator set (Ward-Leonard Drive), then flywheel can be mounted on the shaft of the motor- generator set. This arrangement equalises load on the source, but not the load on motor.
- Consequently, motor capable of supplying peak-load-torque is required.

Moment of inertia of the flywheel required for load equalisation is calculated as follows:

- Assuming a linear motor-speed-torque curve in the region of interest (drooping characteristic AC of Fig. 2.10)

$$\omega_m = \omega_{m0} - \frac{\omega_{m0} - \omega_{mr}}{T_r} \cdot T \qquad (2.31)$$

Where ω_{m0}, ω_{mr}, 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.

$$J = \frac{T_r}{(\omega_{m0} - \omega_{mr})}\left[\frac{t_h}{\log_e\left(\dfrac{T_{lh} - T_{min}}{T_{lh} - T_{max}}\right)}\right]$$

$$J = \frac{T_r}{(\omega_{m0} - \omega_{mr})}\left[\frac{t_l}{\log_e\left(\dfrac{T_{max} - T_{ll}}{T_{min} - T_{ll}}\right)}\right]$$

Moment of inertia of the flywheel required can be calculated either from above 2 equations. Hence,

$$J = WR^2, \text{ kg-m}^2 \qquad (2.45)$$

where W is the weight of the flywheel (kg) and R is the radius (m).

Control of Drives

Modes of Operation:

An electrical drive operates in three modes:

- **i.** Steady state
- **ii.** Acceleration including Starting
- **iii.** Deceleration including Stopping

i. Steady state

We know that $T = T_l + J\dfrac{d\omega_m}{dt}$

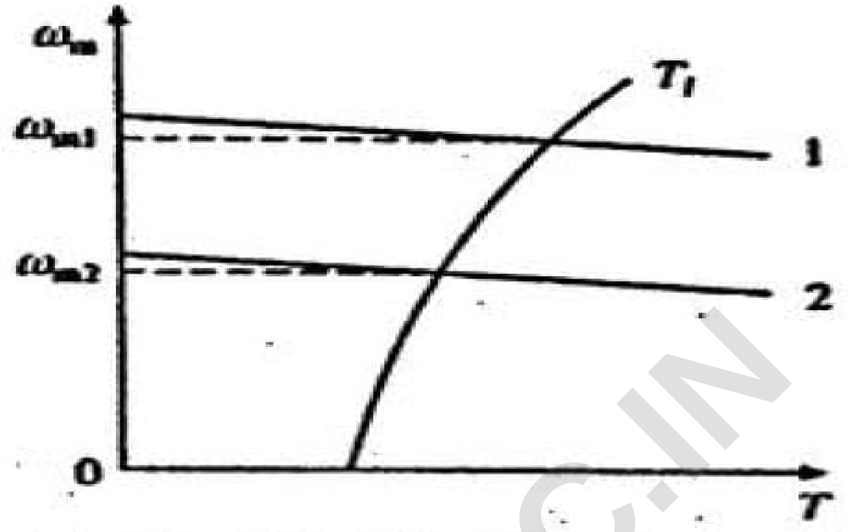


Fig. 3.1 Principle of speed control

- According to the above expression the steady state operation takes place when motor torque equals the load torque.
- Adjustment: 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 the figure shown, 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.
- 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 equal the load torque.
- Drive operates in quadrant II or IV depending upon the rotation.

ii. Acceleration State:

- Acceleration and Deceleration modes are transient modes.
- Drive operates in acceleration mode whenever an increase in its speed is required.
- For this, motor speed torque curve must be changed so that motor torque exceeds the load torque.
- Time taken for a given change in speed depends on inertia of motor load system and the amount by which motor torque exceeds the load torque.
- Increase in motor torque is accompanied by an increase in motor current.
- Motor current must be with in a value which is safe for both motor and power modulator.
- For long duration acceleration, current must not be allowed to exceed the rated value. For short duration acceleration a current should be higher than the rated value.
- In closed loop drives requiring fast response, motor current may be intentionally forced to the maximum value in order to achieve high acceleration.

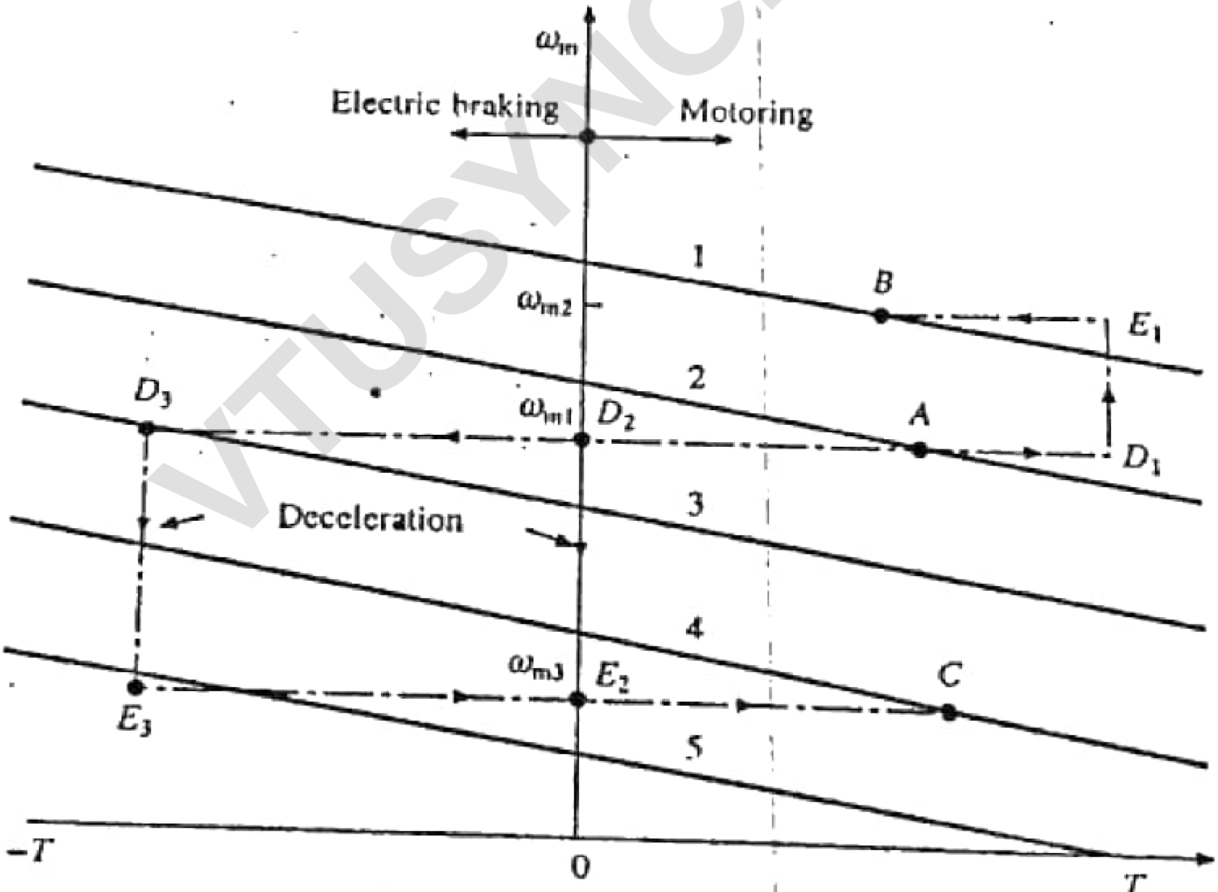


Fig. 3.2 Speed transition paths (1 to 5 are motor speed torque curves)

- Figure shows the transition from operating point A at speed ω_{m1} to operating point B at a **higher speed ω_{m2}**–when the motor torque is held constant during acceleration. The Path consists of AD_1E_1B.

- In the fig,1 to 5 are motor speed torque curves. All points mentioned in relation to acceleration are applicable to starting.
- The maximum current allowed should not only be safe for motor and power modulator but drop in source voltage caused due to it should also be in acceptable limits.
- In some applications the motor should accelerate smoothly, without any jerk. This is achieved when the starting torque can be increased steplessly from its zero value. Such a start is known as soft start.

iii. Deceleration State:

- Motor operation in deceleration mode is required when a decrease in its speed is required. Deceleration occurs when load torque exceeds the motor torque.
- In few applications, load torque with substantial magnitude, enough deceleration can be achieved by simply reducing the motor torque to zero.
- In applications, load torque without substantial magnitude or where simply reducing the motor torque to zero does not provide enough deceleration, **mechanical brakes** may be used.
- Alternatively, **electric braking** may be employed. Now both motor and the load torque oppose the motion, thus producing larger deceleration.
- During electric braking motor current tends to exceed the safe limit. Current is restricted within the safe limit.
- Figure shows paths followed during transition from point A at speed ω_{m1} to point C at a **lower speed ω_{m3}**.When deceleration is carried out using electric braking at a constant braking torque, the operating point moves along the path AD_3E_3C
- When sufficient load torque is present or when mechanical braking is used the operation takes place along the path AD_2E_2C.
- Stopping is a special case of deceleration where the speed of a running motor is changed to zero.

Speed Control and Drive Classifications:

- **Constant Speed** or **Single Speed Drives**- Drives where the driving motor runs at a nearly fixed speed.
- **Multi-speed drives-** are those which operate at discrete speed settings.
- **Variable Speed Drives**- Drives needing stepless change in speed and multispeed drives
- **Multi-motor drive** -When a number of motors are fed from a common converter, or when a load is driven by more than one motor.
- **Constant Torque Mode -A variable speed drive-** also called as **constant torque drive,** if the drive's maximum torque capability does not change with a change in speed setting. It must be noted that the term **'Constant Torque'** refers to maximum torque

capability of the drive and not to the actual output torque, which may vary from no load to full load torque.

- The **Constant Power Drive** and **Constant Power Mode** (or region) are defined in the same way.
- Ideally it is desired that for a given speed setting, the motor speed should remain constant as load torque is changed from no load to full load.
- In practice, speed drops with an increase in the load torque.
- Quality of a speed control system is measured in terms of speed-regulation which is defined as

$$\text{Speed regulation} = \frac{\text{No load speed} - \text{Full load speed}}{\text{Full load speed}} \times 100\%$$

Closed Loop control of drives

- In closed loop system, the output of the system is feedback to the input.
- The closed loop system controls the electrical drive, and the system is self-adjusted.
- Feedback loops in an electrical drive may be provided to satisfy the following requirements.
  - ✓ **Enhancement of speed of torque**
  - ✓ **To improve steady-state accuracy**
  - ✓ **Protection**
- The main parts of the closed-loop system are the controller, converter, current limiter, current sensor, etc.
- The converter converts the variable frequency into fixed frequency and vice-versa.
- The current limiter limits the current from rising above the maximum set value.
- The different types of closed loop configuration are explained below.

  i. Current Limit Control

  ii. Closed-Loop Torque Control

  iii. Closed-Loop Speed Control

  iv. Closed-Loop Speed Control of Multi Motor Drives

1. Current Limit control

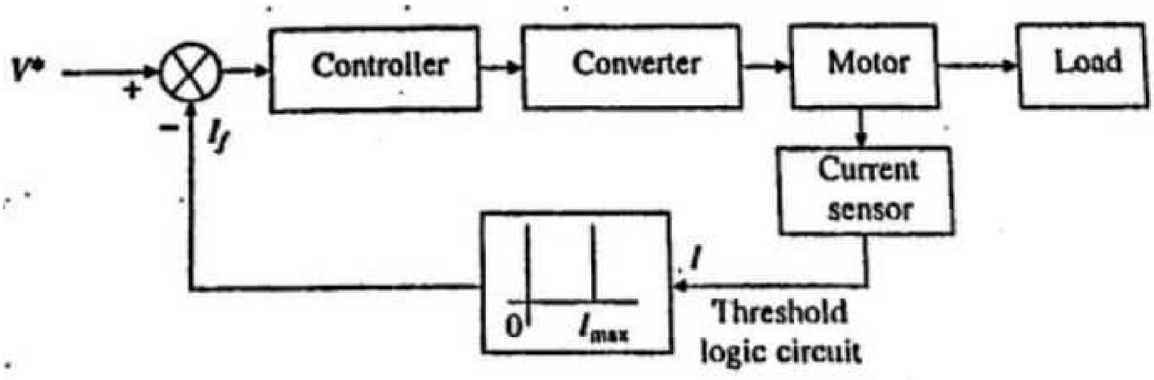


Fig. 3.3 Current limit control

- This scheme is used to limit the converter and motor current below a safe limit during the transient operation.
- The system has a current feedback loop with a threshold logic circuit.
- The logic circuit protects the system from a maximum current.
- If the current is raised above maximum set value due to a transient operation, the feedback circuit becomes active and force the current to remains below the maximum value.
- When the current become normal, the feedback loop remains inactive.

ii. Closed-Loop Torque Control

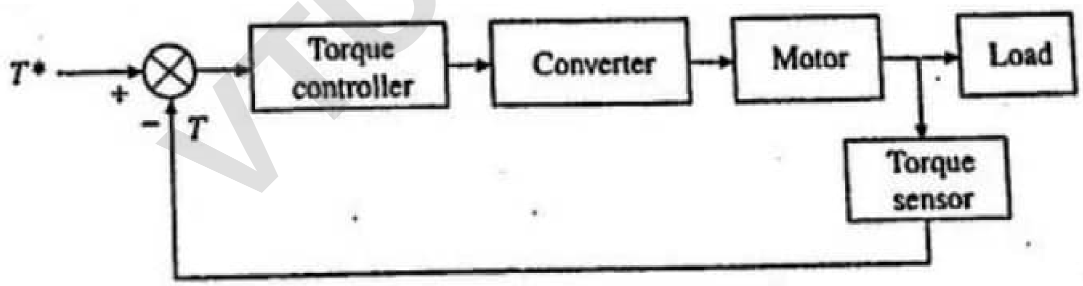


Fig. 3.4 Closed-loop torque control

- Such types of loop are used in battery powered vehicles, rails, and electric trains.
- The reference torque T* is set through the accelerator, and this T* follows by the loop controller and the motor.
- The speed of the drive is controlled by putting pressure on the accelerator.

iii.Closed-Loop Speed Control

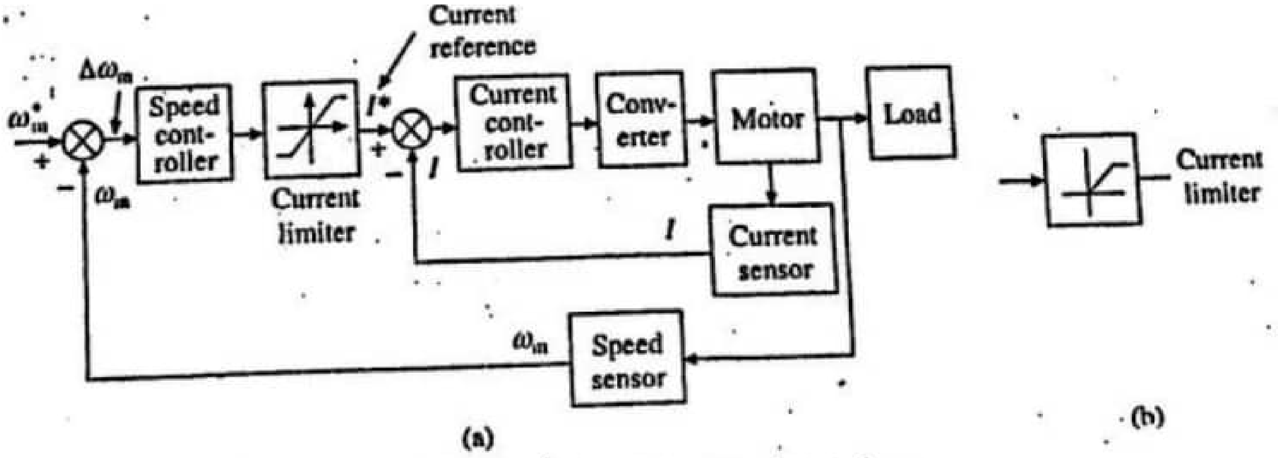


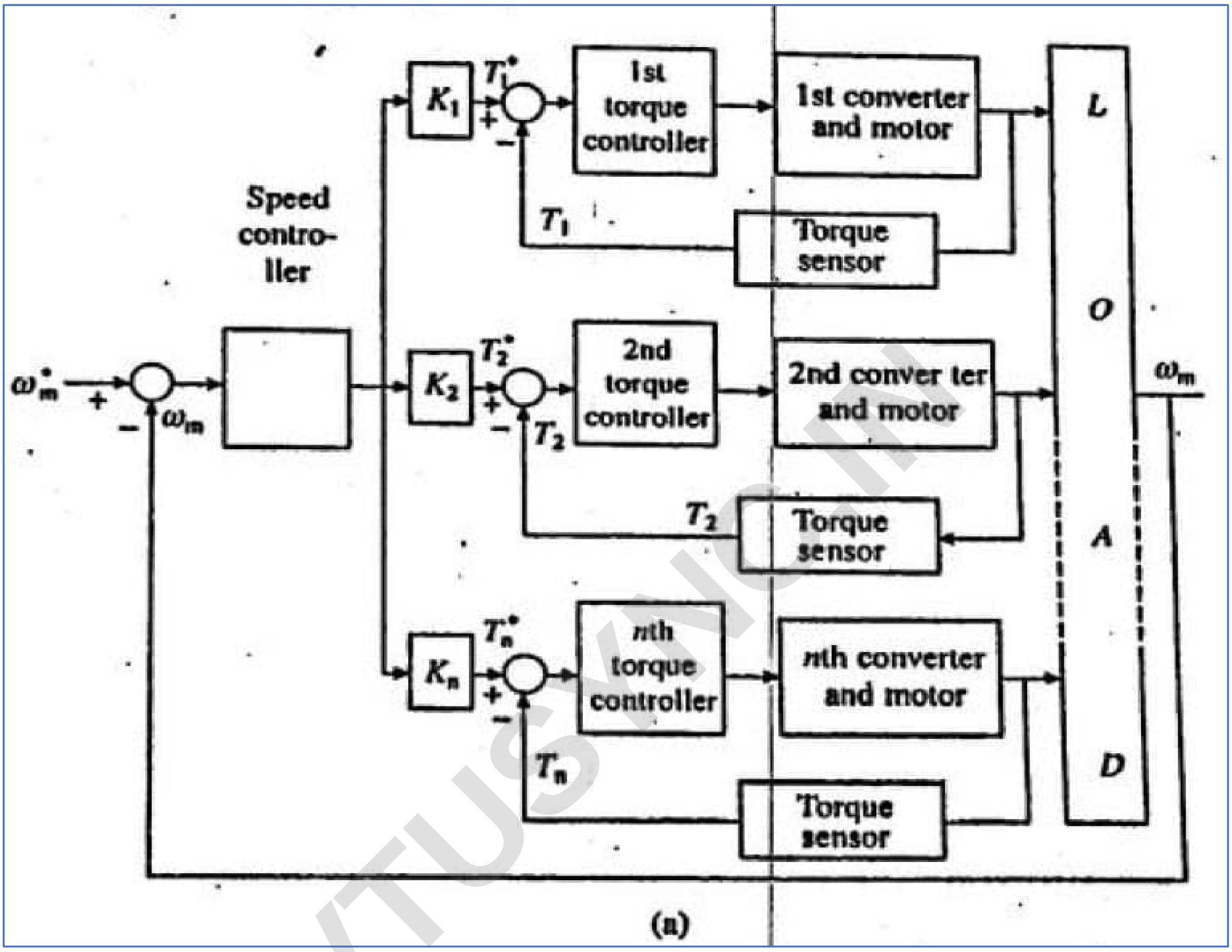
Fig. 3.5 Closed-loop speed control

- The block diagram of the closed loop speed control system is shown in the figure.
- This system uses an inner control loop within an outer speed loop.
- The inner control loop controls the motor current and motor torque below a safe limit.
- Consider a reference speed ω^*_m which produces a positive error $\Delta \omega^*_m$. The speed error is operated through a speed controller and applied to a current limiter which is overloaded even for a small speed error.
- The current limiter set current for the inner current control loop. Then, the drive accelerates, and when the speed of the drive is equal to the desired speed, then the motor torque is equal to the load torque. This, decrease the reference speed and produces a negative speed error.
- When the current limiter saturates, then the drive becomes de-accelerate in a braking mode.
- When the current limiter becomes desaturated, then the drive is transferred from braking to motoring.

iv. Closed-Loop Speed Control of Multi Motor Drives

- In such type of drive, the load is shared between the several motors.
- In this system, each section has its own motor which carries most of its load.
- The rating of the motor is different for the different type of load, but all the motor run at the same speed.
- If the torque requirement of each motor is fulfilled by its own driving motor, then the driving shaft has to carry only small synchronizing torque.
- In a locomotive, because of different amount of wear and tear the wheel of the locomotive revolve at the different speed.
- Thus, the driving speed of the vehicle also vary.
- Along with speed, it is also essential that the torques are shared equally between the various motor; otherwise, the one motor is fully loaded and another, is under loaded.

- Thus, the rated locomotive torque will be less than the sum of the individual motor torque rating.



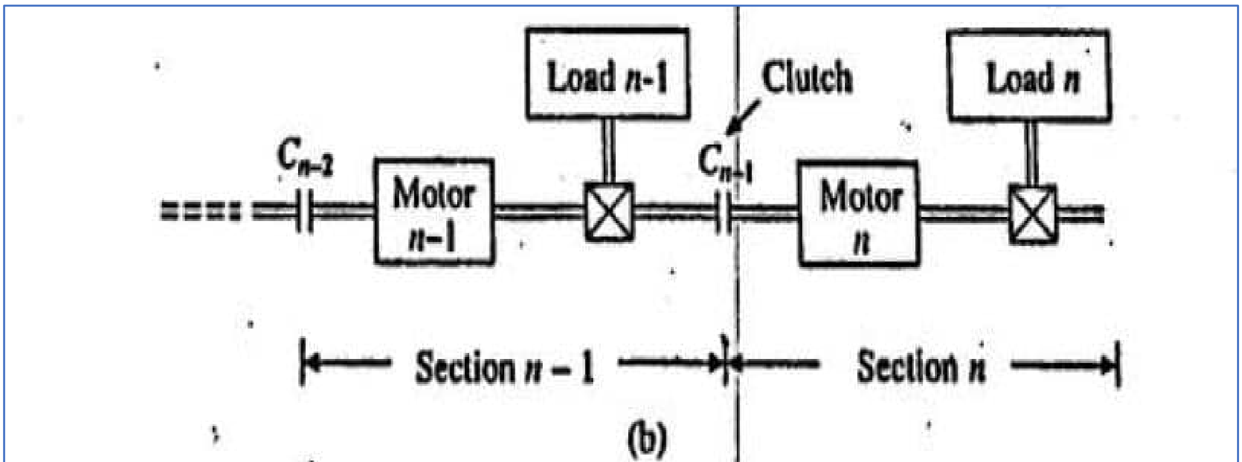


Fig. 3.6 Multi-motor drive with mechanically coupled loads or common drive shaft: (a) closed loop system, (b) mechanical coupling

Numericals:

EXAMPLE 2.1

A motor drives two loads. One has rotational motion. It is coupled to the motor through a reduction gear with $a = 0.1$ and efficiency of 90%. The load has a moment of inertia of 10 kg-m^2 and a torque of 10 N-m. Other load has translational motion and consists of 1000 kg weight to be lifted up at an uniform speed of 1.5 m/s. Coupling between this load and the motor has an efficiency of 85%. Motor has an inertia of 0.2 kg-m^2 and runs at a constant speed of 1420 rpm. Determine equivalent inertia referred to the motor shaft and power developed by the motor.

Solution

From Eqs. (2.8) and (2.12), the total moment of inertia referred to the motor shaft

$$J = J_0 + a_1^2 J_1 + M_1\left(\frac{v_1}{\omega_m}\right)^2 \quad (1)$$

Here $J_0 = 0.2$ kg-m^2, $a_1 = 0.1$, $J_1 = 10$ kg-m^2, $v = 1.5$ m/s and $\omega_m = (1420 \times \pi)/30 = 148.7$ rad/sec.

Substituting in Eq. (1) gives

$$J = 0.2 + (0.1)^2 \times 10 + 1000\left(\frac{1.5}{148.7}\right)^2 = 0.4 \text{ kg-m}^2$$

From Eqs. (2.9) and (2.13)

$$T_l = \frac{a_1 T_{l1}}{\eta_1} + \frac{F_1}{\eta_1'}\left(\frac{v_1}{\omega_m}\right) \quad (2)$$

Here $\eta_1 = 0.9$, $a_1 = 0.1$, $T_{l1} = 10$ N-m, $\eta_1' = 0.85$, $F_1 = 1000 \times 9.81$ N, $v_1 = 1.5$ m/s and $\omega_m = 148.7$ rad/sec.

Substituting in Eq. (2) gives

$$T_l = \frac{0.1 \times 10}{0.9} + \frac{1000 \times 9.81}{0.85}\left(\frac{1.5}{148.7}\right) = 117.53 \text{ N-m}$$

EXAMPLE 2.2
A drive has following parameters:

$J = 10$ kg-m^2, $T = 100 - 0.1N$, N-m, Passive load torque $T_l = 0.05N$, N-m, where N is the speed in rpm.

Initially the drive is operating in steady-state. Now it is to be reversed. For this motor characteristic is changed to $T = -100 - 0.1N$, N-m. Calculate the time of reversal.

Solution
For steady-state speed

$$T - T_l = 0$$

or

$$100 - 0.1N - 0.05N = 0$$

or

$$0.15N = 100 \quad \text{or} \quad N = 666.7 \text{ rpm}$$

After reversal, for steady-state speed, noting that the load is passive

$$-100 - 0.1N - 0.05N = 0$$

or

$$N = -666.7 \text{ rpm}$$

When reversing, from Eq. (2.2)

$$J\frac{d\omega_m}{dt} = -100 - 0.1N - 0.05N$$

$$\frac{dN}{dt} = \frac{30}{J\pi}(-100 - 0.15N) = -95.49 - 0.143N$$

$$t = \int dt = \int_{N_1}^{N_2} \frac{dN}{-95.49 - 0.143N}$$

where $N_1 = 666.7$ rpm and $N_2 = 0.95 \times -666.7 = -633.4$ rpm*.

Integrating Eq. (1) yields $t = 25.58$ S.

EXAMPLE 2.3

A motor equipped with a flywheel is to supply a load torque of 1000 N-m for 10 sec followed by a light load period of 200 N-m long enough for the flywheel to regain its steady-state speed. It is desired to limit the motor torque to 700 N-m. What should be the moment of inertia of flywheel? Motor has an inertia of 10 kg-m^2. Its no load speed is 500 rpm and the slip at a torque of 500 N-m is 5%. Assume speed-torque characteristic of motor to be a straight line in the region of interest.

Solution

From Eq. (2.42)

$$J = \frac{T_r}{(\omega_{m0} - \omega_{mr})}\left[\frac{t_h}{\log_e\left(\frac{T_{lh} - T_{min}}{T_{lh} - T_{max}}\right)}\right] \quad (1)$$

Here no load speed $= \frac{500 \times 2\pi}{60} = 52.36$ rad/sec

Speed at 500 N-m = (1 – 0.05) 52.36 = 49.74 rad/sec

$$\frac{T_r}{(\omega_{m0} - \omega_{mr})} = \frac{500}{52.36 - 49.74} = 190.84$$

T_{lh} = 1000 N-m, T_{max} = 700 N-m, $T_{min} = T_{ll}$ = 200 N-m, t_h = 10 S.
Substituting in Eq. (1)

T_{lh} = 1000 N-m, T_{max} = 700 N-m, $T_{min} = T_{ll}$ = 200 N-m, t_h = 10 S.
Substituting in Eq. (1)

$$J = 190.84\left[\frac{10}{\log_e\left(\frac{1000 - 200}{1000 - 700}\right)}\right] = 1871.8 \text{ kg-m}^2$$

Moment of inertia of the flywheel = 1871.8 – 10 = 1861.8 kg-m^2.

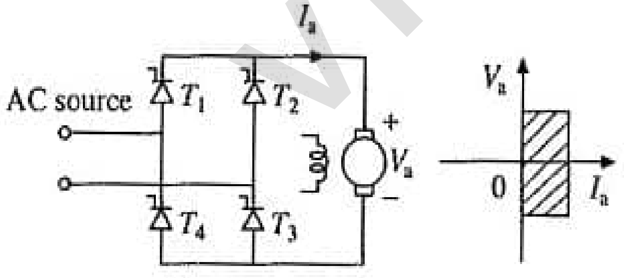
Module-2: Direct Current Motor Drives:

Syllabus

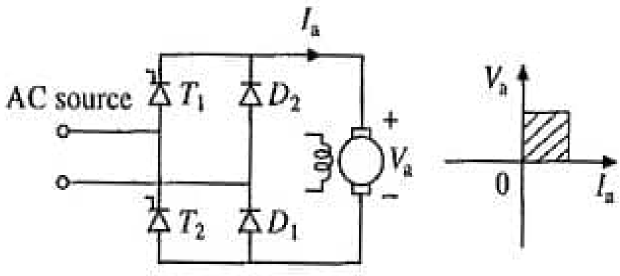
- Controlled Rectifier Fed dc Drives,
- Single Phase Fully Controlled Rectifier Control of dc Separately Excited Motor,
- Single Phase Half Controlled Rectifier Control of dc Separately Excited Motor,
- Three Phase Fully Controlled Rectifier Control of dc Separately Excited Motor,
- Three Phase Half Controlled Rectifier Control of dc Separately Excited Motor,
- Multiquadrant Operation of dc Separately Excited Motor Fed Form Fully Controlled Rectifier,
- Rectifier Control of dc Series Motor,
- Supply Harmonics,
- Power Factor and Ripple in Motor Current,
- Chopper Control of Separately Excited dc Motor,
- Chopper Control of Series Motor

Controlled Rectifier Fed DC Drives

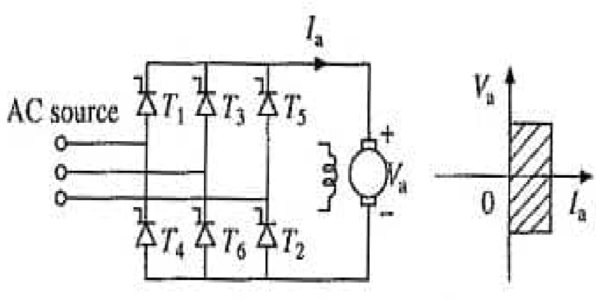
- Controlled Rectifier Fed DC Drives are used to get variable dc voltage from an ac source of fixed voltage.
- Controlled Rectifier Fed DC Drives are also known as Static Ward-Leonard drives.



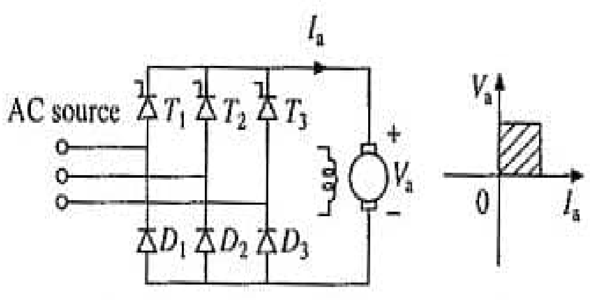
(a) Single-phase fully-controlled rectifier



(b) Single-phase half-controlled rectifier



(c) Three-phase fully-controlled rectifier



(d) Three-phase half-controlled rectifier

Figure shows commonly used Controlled Rectifier Fed DC Drives and quadrants in which they can operate on V_a-I_a plane.

As thyristors are capable of conducting current only in one direction, all these rectifiers are capable of providing current only in one direction.

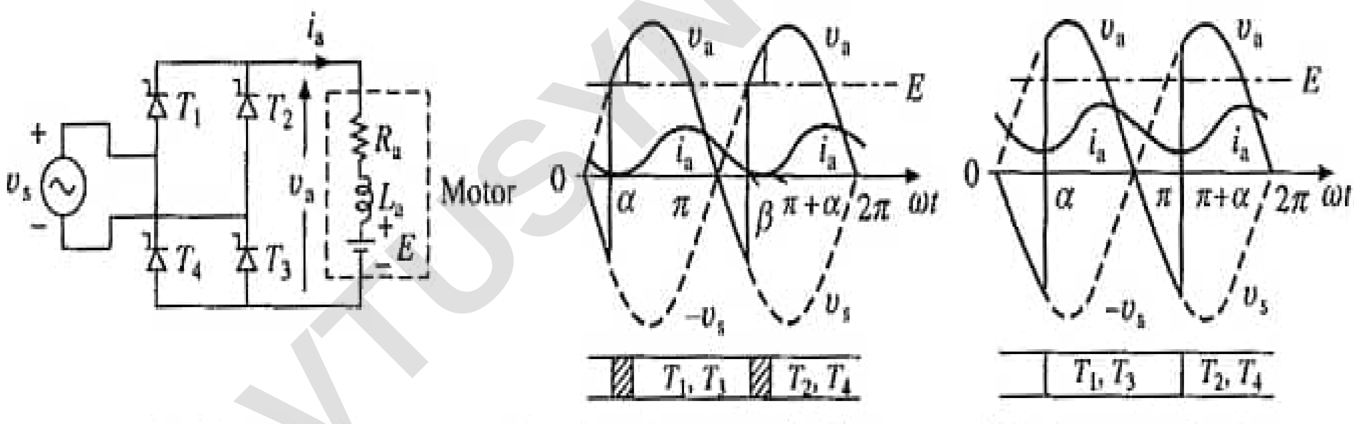
Rectifiers of Figs.(a) and (c) provide control of dc voltage in either direction and therefore, allow motor control in quadrants I and IV. They are known as **Fully Controlled Rectifiers.**

Rectifiers of Figs.(b) and (d) as they allow dc voltage control only in one direction and motor control in quadrant I only. They are called **Half Controlled Rectifiers**

For low power applications (up to around 10 kW) single-phase rectifier drives are employed. For high power applications, three-phase rectifier drives are used. Exception is made in traction where single phase drives are employed for large power ratings.

1. Single Phase Fully Controlled Rectifier Control of DC Motor

The Single Phase Fully Controlled Rectifier Control of DC Motor is shown in Fig. (a).



(a) Drive circuit (b) Discontinuous conduction waveforms (c) Continuous conduction waveforms

- Motor is shown by its equivalent circuit.
- Field supply is not shown.
- When field control is required, field is fed from a controlled rectifier, otherwise from an uncontrolled rectifier.
- The ac input voltage is defined by $v_s = V_m \sin \omega t$
- In a cycle of source voltage, thyristors T_1 and T_3 are given gate signals from α to π, and thyristors T_2 and T_4 are given gate signals from $(\pi + \alpha)$ to 2π.
- When armature current does not flow continuously, the motor is said to operate in discontinuous conduction.
- When current flows continuously, the conduction is said to be continuous.

- The drive under consideration, predominantly operates in discontinuous conduction.
- Discontinuous conduction has several modes of operation.

Discontinuous conduction mode :

- In discontinuous conduction mode of Single Phase Fully Controlled Rectifier Control of DC Motor, current starts flowing with the **turn-on** of thyristors **T_1 and T_3 at ωt = α.**
- Motor gets connected to the source and its terminal voltage equals Vs.
- The current, which flows against both, E and the source voltage after ωt = π, falls to zero at β.
- Due to the absence of current, T_1 and T_3 turn-off. Motor terminal voltage is now equal to its induced voltage E.
- When thyristors T_2 and T_4 are fired at (π + α), next cycle of the motor terminal voltage Va starts.

In a Single Phase Fully Controlled Rectifier Control of DC Motor terminal voltage Va, the drive operates in two intervals

i. Duty interval ($\alpha \le \omega t \le \beta$) when motor is connected to the source and Va = Vs.

ii. Zero current interval ($\beta \le \omega t \le \pi + \alpha$) when $i_a = 0$ and Va = E.

Drive operation is described by the following equations

$$v_a = R_a i_a + L_a \frac{di_a}{dt} + E = V_m \sin \omega t, \text{ for } \alpha \le \omega t \le \beta$$
$$v_a = E \quad \text{and} \quad i_a = 0 \quad \text{for} \quad \beta \le \omega t \le \pi + \alpha \qquad (1)$$

Simplifying eqn (1)

$$i_a(\omega t) = \frac{V_m}{Z}\sin(\omega t - \phi) - \frac{E}{R_a} + K_1 e^{-t/\tau_a} \quad \text{for } \alpha \le \omega t \le \beta$$

$$Z = \sqrt{R_a^2 + (\omega L_a)^2}$$
$$\phi = \tan^{-1}(\omega L_a / R_a)$$

$$i_a(\omega t) = \frac{V_m}{Z}[\sin(\omega t - \phi) - \sin(\alpha - \phi)e^{-(\omega t - \alpha)\cot\phi}]$$
$$-\frac{E}{R_a}[1 - e^{-(\omega t - \alpha)\cot\phi}], \quad \text{for } \alpha \le \omega t \le \beta$$

As $i_a(\beta)=0$ $\quad \frac{V_m}{Z}\sin(\beta - \phi) - \frac{E}{R_a} + \left[\frac{E}{R_a} - \frac{V_m}{Z}\sin(\alpha - \phi)\right]e^{-(\beta - \alpha)\cot\phi} = 0$

Since voltage drop across the armature inductance due to dc component of armature current is zero where

$$V_a = E + I_a R_a$$

V_a and I_a are respectively dc components of armature voltage and current respectively.

Armature voltage: *From Fig (b)*

$$V_a = \frac{1}{\pi}\left[\int_{\alpha}^{\beta} V_m \sin \omega t \, d(\omega t) + \int_{\beta}^{\pi+\alpha} E d(\omega t)\right]$$

$$= \frac{V_m(\cos\alpha - \cos\beta) + (\pi + \alpha - \beta)E}{\pi}$$

- Armature current consists of dc component Ia and harmonics.
- When flux is constant, only dc component produces steady torque.
- Harmonics produce alternating torque components, the average value of which is zero. Therefore, Speed is given by

$$\omega_m = \frac{V_m(\cos\alpha - \cos\beta)}{K(\beta - \alpha)} - \frac{\pi R_a}{K^2(\beta - \alpha)} T$$

- Boundary between continuous and discontinuous conduction is reached when $\beta = \pi + \alpha$. Substituting $\beta = \pi + \alpha$ in Eq. Critical value of speed is given by,

$$\omega_{mc} = \frac{R_a V_m}{ZK} \sin(\alpha - \phi)\left[\frac{1 + e^{-\pi\cot\phi}}{e^{-\pi\cot\phi} - 1}\right]$$

Continuous conduction mode :

- In continuous conduction mode of Single Phase Fully Controlled Rectifier Control of DC Motor, a positive current flows through the motor, and T_2 and T_4 are in conduction just before α.
- Application of gate pulses turns on forward biased thyristors T_1 and T_3 at α.
- Conduction of T_1 and T_3 reverse biases T_2 and T_4 and turns them off.

- A cycle of Va is completed when T_2 and T_4 are turned-on at ($\pi + \alpha$) causing turn-off of T_1 and T_3.

Armature voltage

$$V_a = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin \omega t \, d(\omega t) = \frac{2V_m}{\pi}\cos\alpha$$

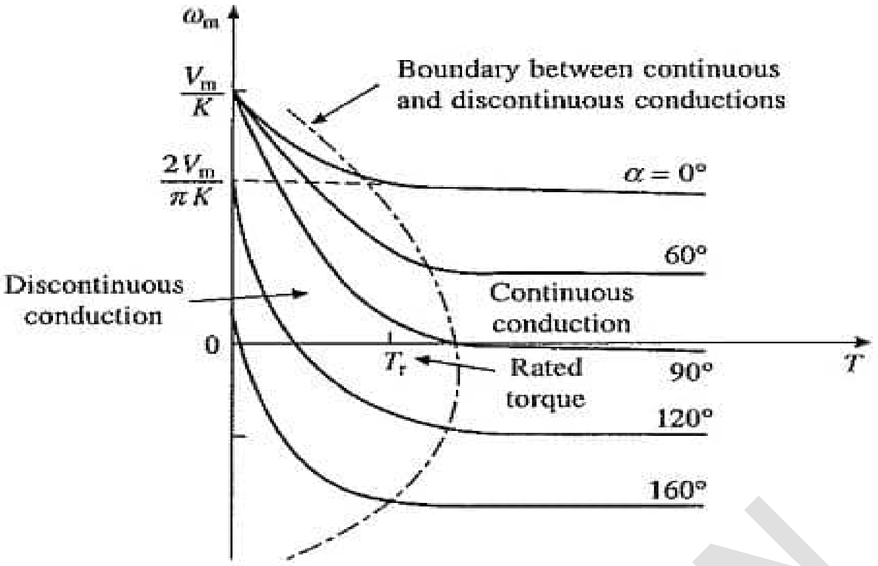
Speed

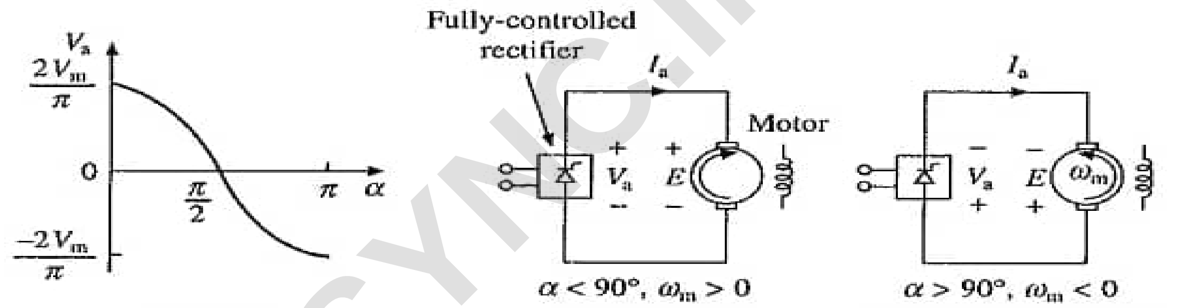
$$\omega_m = \frac{2V_m}{\pi K}\cos\alpha - \frac{R_a}{K^2}T$$

- Speed torque curves for the drive are shown in Fig.
- The ideal no load operation is obtained when Ia = 0.
- When both thyristor pairs (T_1, T_3) and (T_2, T_4) fail to fire, Ia will be zero.
- This will happen when E > Vs throughout the period for which firing pulses are present.
- Therefore, when $\alpha < \pi/2$, E should be greater or equal to Vm and when $\alpha > \pi/2$, E should be greater or equal to Vm sin ωt.
- Therefore, no load speeds are given by

$$\omega_{m0} = \frac{V_m}{K}, \quad \text{for } 0 \le \alpha \le \pi/2$$
$$= \frac{V_m \sin\alpha}{K}, \quad \text{for } \pi/2 \le \alpha \le \pi$$

- Maximum average terminal voltage ($2V_m/\pi$) is chosen equal to the rated motor voltage.
- Ideal no load speed of the motor when fed by a perfect direct voltage of rated value will then be ($2V_m/\pi K$).
- It is interesting is note that the maximum no load speed with rectifier control is ($\pi/2$) times this value.
- Boundary between continuous and discontinuous conduction is shown by dotted line.
- For torques less than rated, a low power drive mainly operates in discontinuous conduction.

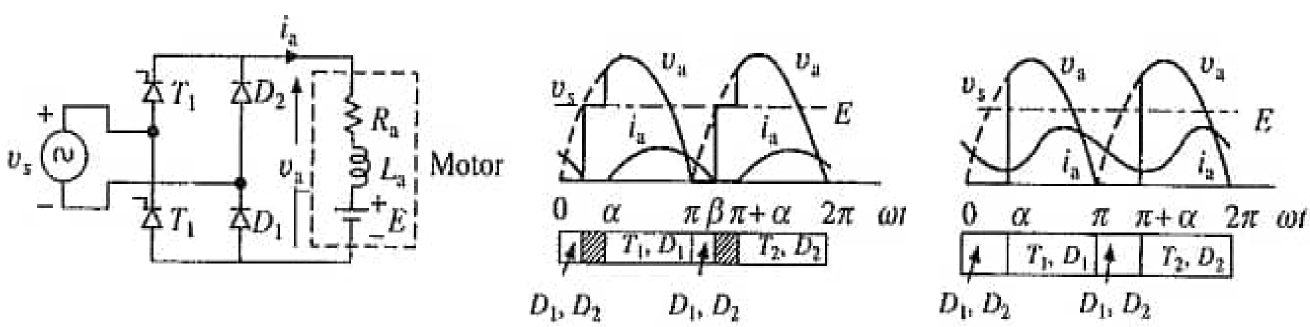




(a) $V_a - \alpha$ curve (b) Motoring (c) Regenerative braking

- Two quadrant operation capability of the drive can be utilized only with overhauling loads or other active loads which can drive the motor in reverse direction.
- In a normal two quadrant operation of a motor one needs forward motoring (quadrant I) and forward braking (quadrant II) which cannot be provided by the drive.

2. Single Phase Half Controlled Rectifier Control of DC Separately Excited Motor



(a) Drive circuit (b) Discontinuous conduction waveforms (c) Continuous conduction waveforms

- Single Phase Half Controlled Rectifier Control is shown in Fig.
- T1 receives gate pulse from α to π and T2 from (π+ α) to 2π. Motor terminal voltage and current waveforms for the dominant discontinuous and continuous conduction mode are shown above.
- In **discontinuous conduction mode**, when T1 is fired at α, motor gets connected to the source through T1 and D1 and Va = Vs.
- The armature current flows and D2 gets forward biased at π.
- Consequently, armature current freewheels through the path formed by D1 and D2, and the motor terminal voltage is zero.
- Conduction of D2 reverse biases T1 and turns it off.
- Armature current drops to 0 at β and stays zero until T2 is fired at (π+ α). Similarly, the continuous conduction mode can be explained.

Discontinuous Conduction

i. Duty interval ($\alpha \le \omega t \le \pi$): Substitution of $\omega t = \pi$ in Armature current equation gives $i_a(\pi)$.

ii. Freewheeling interval ($\pi \le \omega t \le \beta$): Operation is governed by the following equation:

$$i_a R_a + L_a \frac{di_a}{dt} + E = 0$$

$$i_a(\omega t) = \frac{V_m}{Z}\left[\sin\phi \cdot e^{-(\omega t-\pi)\cot\phi} - \sin(\alpha-\phi)\cdot e^{-(\omega t-\alpha)\cot\phi}\right] - \frac{E}{R_a}\left[1 - e^{-(\omega t-\alpha)\cot\phi}\right], \quad \text{for } \pi \le \omega t \le \beta$$

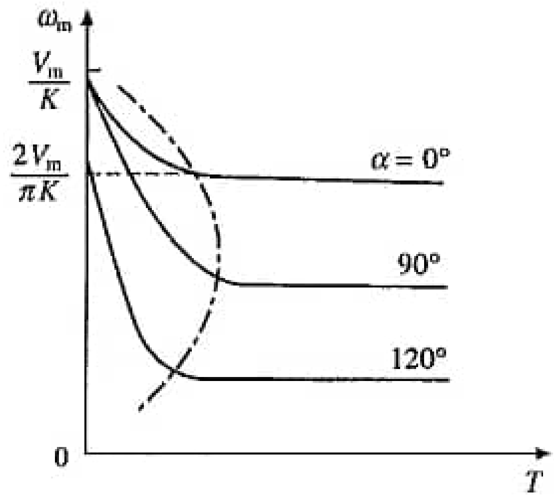
iii. Zero current interval ($\beta \le \omega t \le \pi + \alpha$): Equation (5.73) is applicable. Since ia(β) = 0, one gets from

$$e^{\beta\cot\phi} = \frac{R_a V_m}{ZE}\left[\sin\phi\, e^{\pi\cot\phi} - \sin(\alpha-\phi)e^{\alpha\cot\phi}\right] + e^{\alpha\cot\phi}$$

$$V_a = \frac{1}{\pi}\left[\int_\alpha^\pi V_m \sin\omega t\, d(\omega t) + \int_\beta^{\pi+\alpha} E\, d(\omega t)\right] = \frac{V_m(1+\cos\alpha) + (\pi+\alpha-\beta)E}{\pi}$$

$$\omega_m = \frac{V_m(1+\cos\alpha)}{K(\beta-\alpha)} - \frac{\pi R_a}{K^2(\beta-\alpha)}T$$

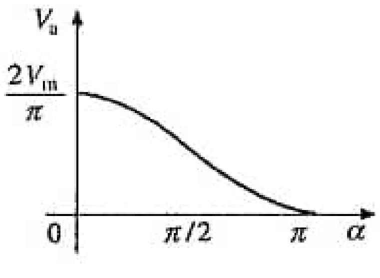
Continuous Conduction



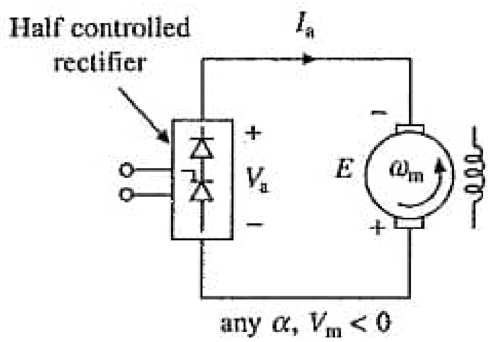
$$V_a = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin \omega t\, d(\omega t) = \frac{V_m}{\pi}(1 + \cos\alpha)$$

$$\omega_m = \frac{V_m}{\pi K}(1 + \cos\alpha) - \frac{R_a}{K^2}T$$

- The output voltage cannot be reversed.
- When coupled to an active load, in the motor speed can reverse, reversing E as shown in Fig. (b).
- As current direction does not change, machine now works as a generator producing braking torque.
- Since, rectifier voltage cannot reverse, generated energy cannot be transferred to ac source, and therefore, it is absorbed in the armature circuit resistance.
  - Braking so obtained is nothing but the reverse voltage braking (plugging).
  - Such a braking is not only inefficient, but also causes a large current [Ia = (Va + E)/Ra] to flow through the rectifier and motor.
  - Since it cannot be regulated by adjustment of firing angle, it will damage the rectifier and motor.
  - Therefore, when load is active, care should be taken to avoid such a operation. If such a operation cannot be avoided, fully-controlled rectifier should be used.
- A Single Phase Half Controlled Rectifier Control is cheaper and gives higher power factor compared to single-phase fully-controlled rectifier. But then it only provides control in quadrant I.

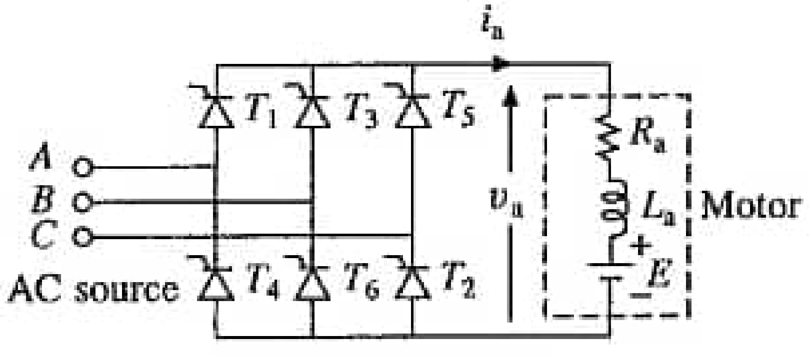


(a) $V_a - \alpha$ curve

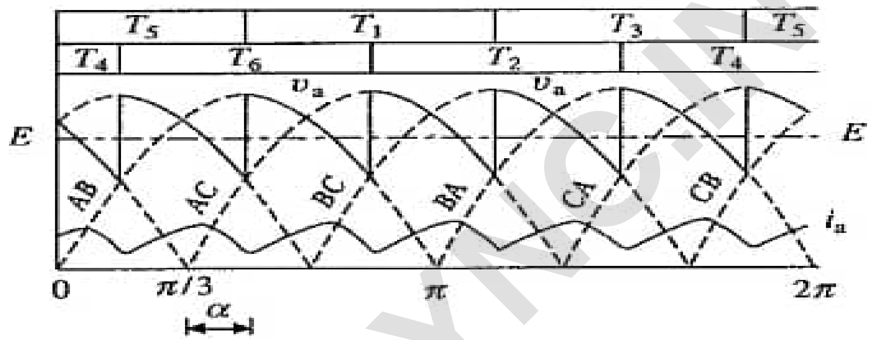


(b) Braking operation

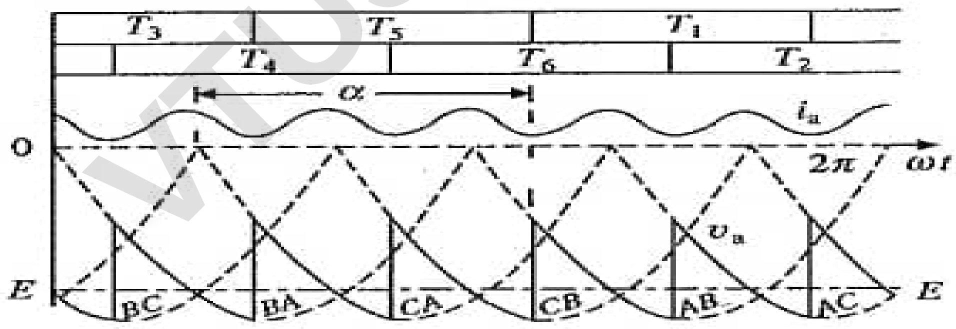
3. Three phase Fully Controlled Rectifier Control of DC Separately Excited Motor



(a) Drive circuit



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



(c) Braking operation $\alpha = 140°$

- Three phase Fully Controlled Rectifier Control (6 pulse) fed separately excited dc motor drive is shown in Fig. (a).
- Thyristors are fired in the sequence of their numbers with a phase difference of 60° by gate pulses of 120°duration.
- Each thyristor conducts for 120, and two thyristors conduct at a time—one from upper group (odd numbered thyristors) and the other from lower group (even numbered thyristors) applying respective line voltage to the motor.

60° A Phase: A- T1 - M – T6 – B

A- T1 – M- T2- C

60° B Phase: B- T3 - M – T2 – C

B- T3 – M- T4- A

60° C Phase: C- T5 - M – T4 – A

C- T5 – M- T6- B

- 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.
- If line voltage V_{AB} is taken as the reference voltage, then.

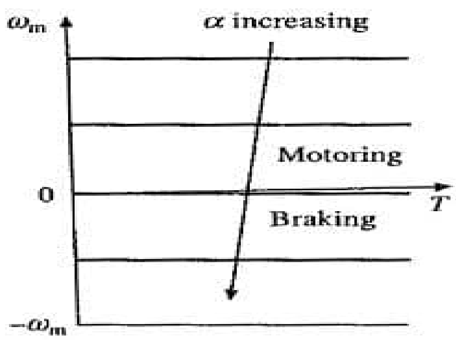
$$v_{AB} = V_m \sin \omega t$$
$$\alpha = \omega t - \pi/3$$

- Motor terminal voltage and current waveforms for continuous conduction are shown in Figs. (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 **π/3 +α** to **2π/3+ α** (from Figs. (b) and (c)).

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

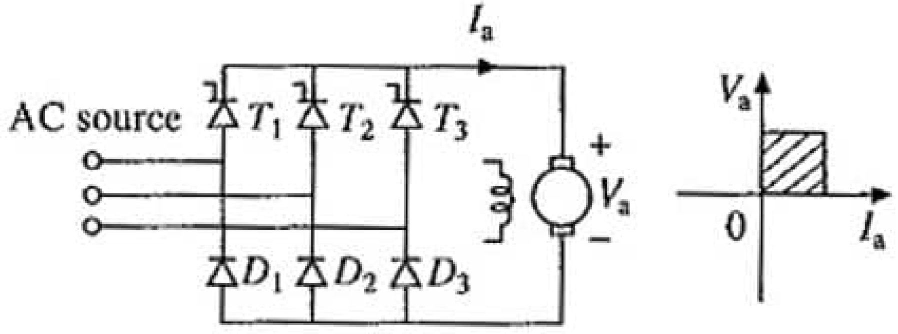
$$\omega_m = \frac{3V_m}{\pi K} \cos \alpha - \frac{R_a}{K^2} T$$

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



4. Three Phase Half Controlled Rectifier Control of DC Separately Excited Motor

- For rectifier circuit, shown in Fig. (d), under continuous conduction

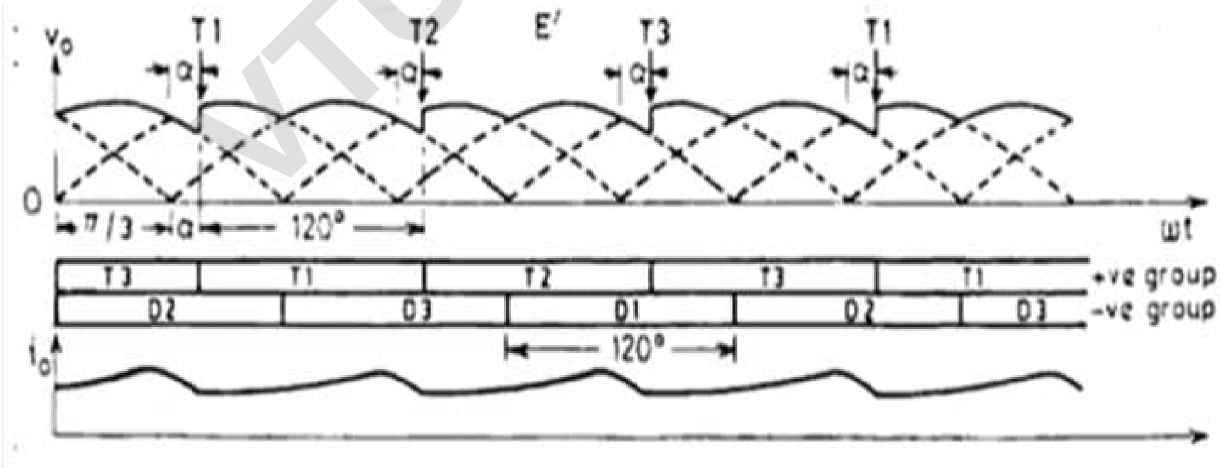


(d) Three-phase half-controlled rectifier

$$V_a = \frac{3V_m}{2\pi}(1 + \cos\alpha)$$

$$\omega_m = \frac{3V_m}{2\pi K}(1 + \cos\alpha) - \frac{R_a}{K^2}T$$

Va vs α curve has same nature as shown in Fig.(a). Consequently, drive operates only in quadrant I.



5. Multi-quadrant Operation of dc Separately Excited Motor Fed From Fully Controlled Rectifier

1. DC Motor Reversing Switch Diagram
2. Dual Converter Control of DC Separately Excited Motor
3. Four Quadrant Drive With Field Reversal

1. DC Motor Reversing Switch Diagram

a) DC Motor Reversing Switch Diagram is shown in Fig. (a).

- A fully-controlled rectifier feeds the motor through a reversing switch RS, a mechanical reversing switch, which is used to reverse the armature connection with respect to the rectifier.
- A fully-controlled rectifier: ia flows from A1 to A2 - capable of providing operation in quadrants I (Forward Motoring) and IV (Reverse Regenerative Braking).
- The reversal of the armature connection: i_a flows from A2 to A1 provides operation in quadrant III (Reverse Motoring) and II (Forward Regenerative Braking).

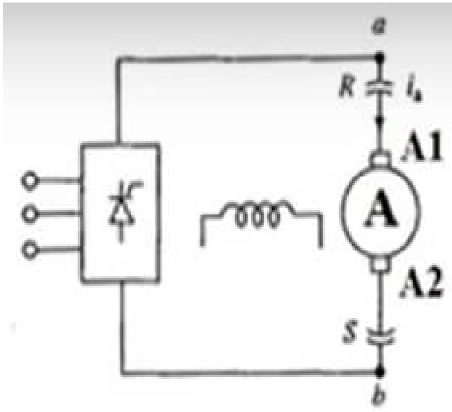
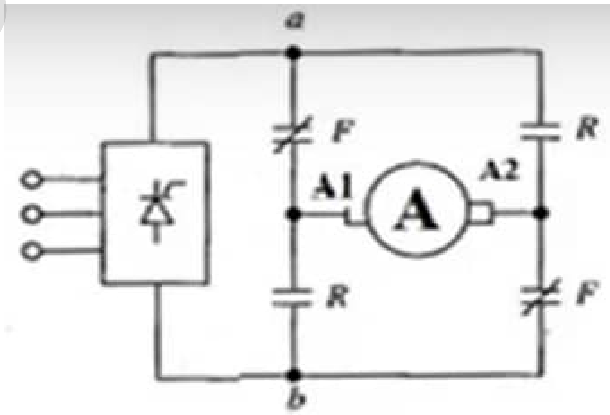


Fig. (a): DC Motor Reversing Switch Diagram.

b) DC Motor Reversing Switch with relay-operated contactor

The DC Motor Reversing Switch Diagram consisting a relay-operated contactor with two contacts- normally open and two normally closed as shown in Fig. (b).

- F contactor Closed- ia flows from A1 to A2, operating in Quadrants I and IV.
- R contactor Closed- ia flows from A2 to A1, operating in Quadrants III and II.

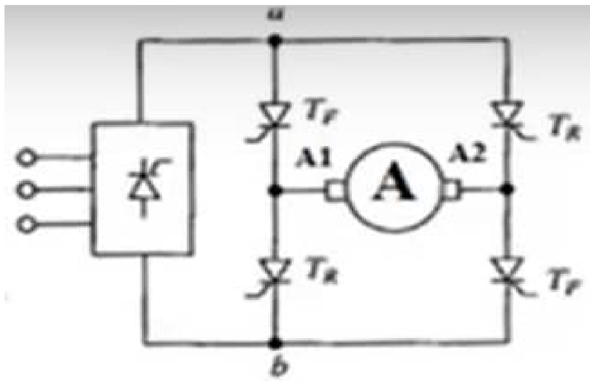


b) DC Motor Reversing Switch with relay-operated contactor

c) DC Motor Reversing Switch with Thyristor

When slow operation and frequent maintenance associated with the contactor is not acceptable, reversing switch is realized using four thyristors as shown in Fig. (c).

- With thyristor pair T_F closed: i_a flows from A1 to A2, operating in Quadrants I and IV.
- With thyristor pair T_R closed: i_a flows from A2 to A1, operating in Quadrants III and II.



c) DC Motor Reversing Switch with Thyristor

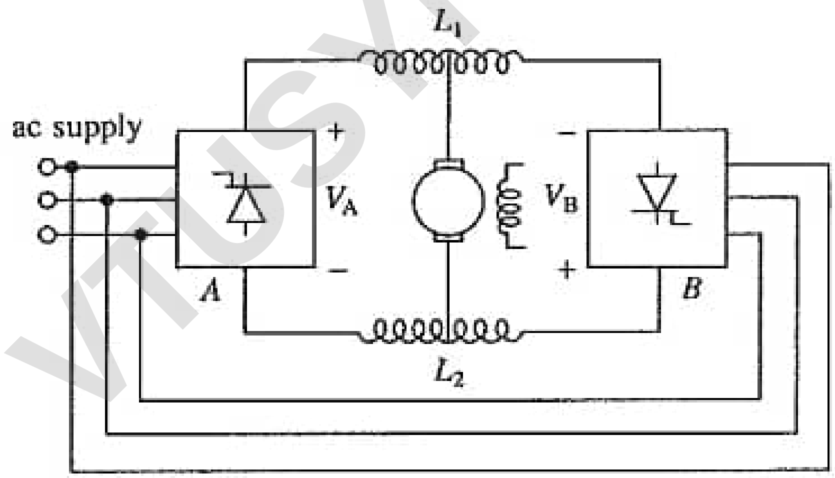
2. Dual Converter Control of DC Separately Excited Motor

- Dual Converter Control of DC Separately Excited Motor consists of two fully-controlled rectifiers connected in anti-parallel across the armature.
- For power ratings upto around 10 kW, single-phase fully-controlled rectifiers can be used.
- For higher ratings, three-phase fully controlled rectifiers are employed.
- **Rectifier A**, which provides positive motor current and voltage in either direction, allows motor control in quadrants I and IV
- **Rectifier B** provides motor control in quadrants III and II, because it gives negative motor current and voltage in either direction

There are two methods of control for the Dual Converter Control of DC Separately Excited Motor:

(a) In **simultaneous control** both the rectifiers are controlled together. In order to avoid dc circulating current between rectifiers, they are operated to produce same dc voltage across the motor terminals.

(b) In **non-simultaneous** or non-circulating current control method, one rectifier is controlled at a time.



a. Simultaneous control

- Both the rectifiers are controlled together
- Although, control of firing angle according to relation prevents dc circulating current, ac current does circulate due to difference between instantaneous output voltages of the two rectifiers. Inductors L_1 and L_2 are added to reduce ac circulating current.
- Because of the flow of ac circulating current, simultaneous control is also known as circulating current control. In a three-phase dual converter, inductors are chosen to allow a circulating current of 30% of full load current.

Rectifier A: $V_a = \frac{3V_m}{\pi} \cos\alpha_A = V_A$

Rectifier B: $V_a = \frac{3V_m}{\pi} \cos\alpha_B = V_B$

$$V_A + V_B = 0$$

$$\frac{3V_m}{\pi} \cos\alpha_A + \frac{3V_m}{\pi} \cos\alpha_B = 0$$

$$\cos\alpha_A + \cos\alpha_B = 0$$

$$\alpha_A + \alpha_B = 180°$$

- This completely eliminates discontinuous conduction, and therefore, gives good speed regulation in the complete range of the drive.

2. Dual Converter Control of DC Separately Excited Motor

In Quadrant-I

A- Rectifier Mode : ($0 < \alpha_A < 90°$)

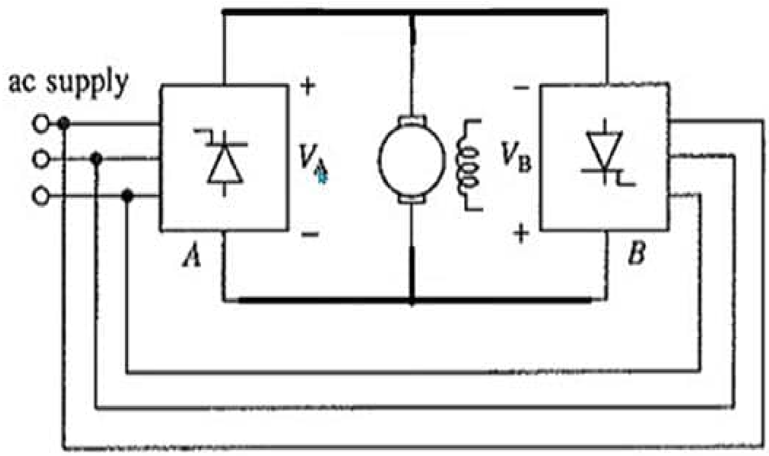
B- Inverter Mode: ($90° < \alpha_B < 180°$)

The speed reversal is done as follows

- For speed reversal α_A is increased and α_B is decreased to satisfy the eqn. $\alpha_A + \alpha_B = 180°$
- The motor back emf exceeds magnitudes of V_A and V_B.
- The armature current shifts to rectifier B and the motor operate in quadrant II.
- The current control loop adjusts the firing angle α_B continuously so as to brake the motor at the maximum allowable current from initial speed to zero speed and then accelerates to the desired speed in the reverse direction.

b. Non-simultaneous or non-circulating current control method

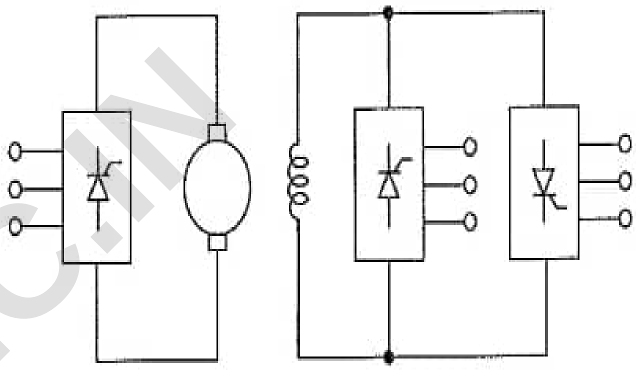
- One rectifier is controlled at a time.
- When operating in quadrant I, rectifier A will be supplying the motor and rectifier B will not be operating.
- The firing angle of rectifier A is set at the highest value- the rectifier works as an inverter and forces the armature current to zero.



- After zero current is sensed, a dead time of 2 to 10 ms is provided to ensure the turn-off of all thyristors of rectifier A.
- Now firing pulses are withdrawn from rectifier A and transferred to rectifier B.
- The firing angle rectifier B i,e αB is set initially at the highest value.
- Now onwards the current control loop adjust the firing angle αB continuously so as to brake the motor at the maximum allowable current from initial speed to zero speed and then accelerates to the desired speed in the reverse direction

3. Field Current Reversal

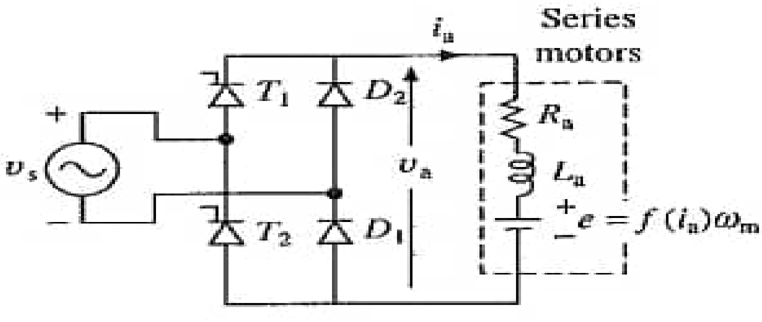
- Four Quadrant Drive With Field Reversal as shown in Fig, armature is fed from a fully-controlled rectifier and the field from a dual converter so that field current can be reversed.
- With field current in one direction *(i_f flows from F1 to F2)*, the motor operates is quadrants I and IV. When field current is reversed *(i_f flows from F2 to F1)*, it operates in quadrants III and II. The dual converter operates with non-simultaneous control.



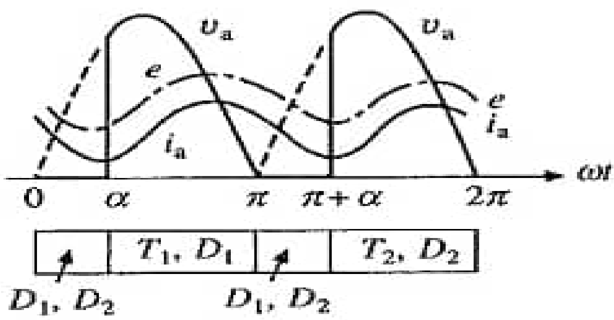
The speed reversal is done as follows:

- The armature rectifier firing angle is set at the highest value to force the armature current to zero and then firing pulses are withdrawn.
- The firing angle of the rectifier supplying the field is now set at the highest value.
- It operates as an inverter and the field current is forced to zero.
- After a suitable dead time, the second rectifier is activated at the lowest firing angle.
- When the field current has nearly settled and the motor back emf has reversed, the firing pulses of the armature rectifier are released so as to set the firing angle at the highest value.

6.Rectifier Control of DC Series Motor



(a) Drive circuit



(b) Waveforms

- Single-phase controlled Rectifier Control of DC Series Motor are employed in traction.
- A single-phase half-controlled Rectifier Control of DC Series Motor is shown in Fig. (a). Equivalent circuit of motor is also shown.
- Since back emf decreases with armature current, discontinuous conduction occurs only in a narrow range of operation.
- The waveforms of v_a , i_a and instantaneous back emf *e* for continuous conduction are shown in Fig. (b).
- Although, in steady state, fluctuations in speed are negligible, e is not constant but fluctuates with ia. For a given speed, e is related to ia through magnetization curve of motor, which is nonlinear owing to saturation.
- Motor operation is described by following equations for duty and freewheeling intervals respectively,

$$V_m \sin \omega t = R_a i_a + L_a \frac{di_a}{dt} + f(i_a)\omega_m, \quad \text{for } \alpha \le \omega t \le \pi$$

$$0 = R_a i_a + L_a \frac{di_a}{dt} + f(i_a)\omega_m, \quad \text{for } \pi \le \omega t \le (\pi + \alpha)$$

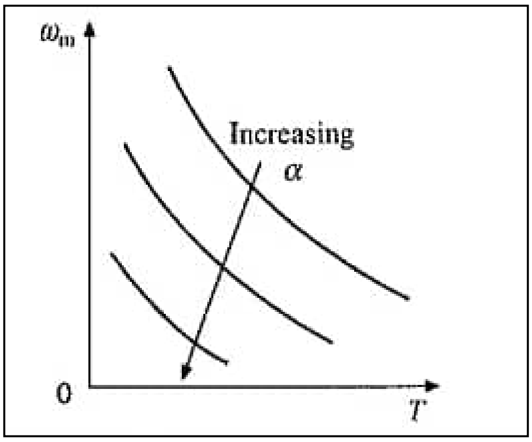
- Because of the presence of term $f(i_a)$, above eqns and are nonlinear differential equations and can only be solved numerically. A simple method of analysis is obtained when e is replaced by its average value E_a such

$$E_a = K_a \omega_m$$
$$K_a = f(I_a)$$

- Since the drop across the inductance L_a due to dc component of armature current I_a is zero

$$V_a = E_a + I_a R_a$$
$$\omega_m = \frac{V_a - I_a R_a}{K_a}$$
$$T = K_a I_a$$

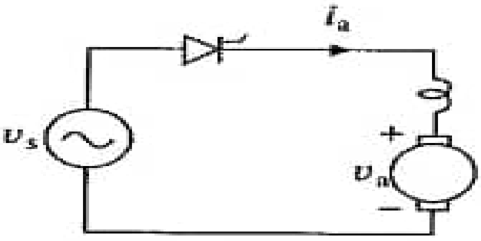
- Following sequence of steps are used to calculate speed-torque characteristic for a given α taking into account non-linearly of the magnetic circuit:
- A value is chosen for Ia. Corresponding value of Ka is obtained from the magnetization characteristic of the motor.



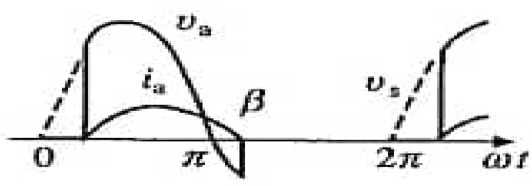
Control of Fractional hp Motors:

Employing a single thyristor, is commonly used for the control of fractional hp universal, dc series and permanent-magnet dc motors. Such drives are employed in hand tools and small domestic appliances.

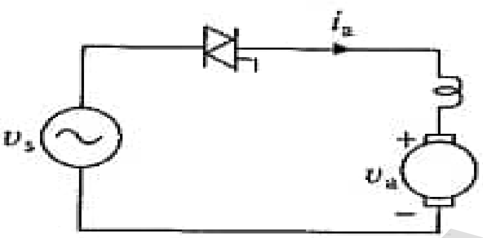
Universal motors may also be controlled by a triac ac voltage controller as shown in Fig



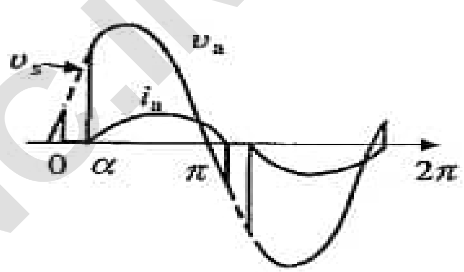
(a)



(b)



(a)



(b)

Supply harmonics, power factor and ripple in motor current

1. Distortion of Supply:

- Source current of a rectifier has harmonics. In a weak ac source, with high internal impedance, current harmonics distort source voltage.
- Source voltage and current distortions have several undesirable effects including interference with other loads connected to the source and radio frequency interference in communication equipment.

2. Low power factor

$$PF = \frac{\text{Real Power}}{\text{Apparent Power}} = \frac{VI_1 \cos \phi_1}{VI_{rms}}$$

$$PF = \frac{I_1}{I_{rms}} \cos \phi_1 = \mu \cos \phi_1$$

where

V = rms source voltage, V

I_{rms} = rms source current, A

I_1 = fundamental component of source current, A

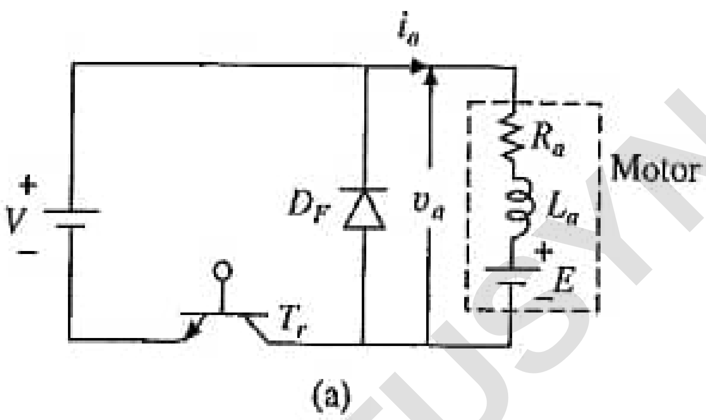
ϕ_1 = phase difference between V and I_1, rad

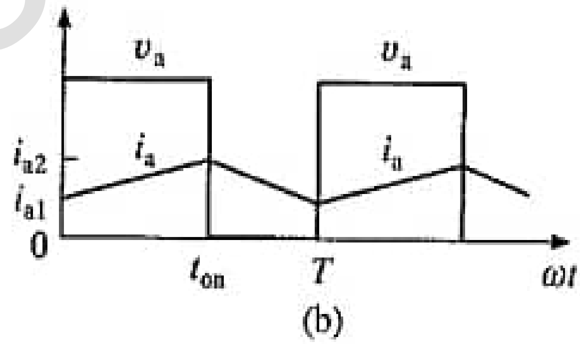
3. Ripple in Motor Current

- The rectifier output voltage is not perfect dc, but consists of harmonics in addition to dc component. Therefore motor current also has harmonics in addition to dc component.

- The presence of harmonics, makes rms and peak values of motor currents higher than average value (dc component). Since flux is constant, torque is contributed only by the average value of current. The harmonics produce fluctuating torques, the average value of which is zero.
- The presence of harmonics increases both copper loss and core loss. Hence for a allowable temperature rise, the torque and power outputs have lesser values than rated values. Due to the presence of harmonics, peak value of current increases and commutation condition deteriorates. Hence, the current that the motor can commutate without sparking at the brushes has a lower dc component than the rated motor current. Thus the derating of motor occur8 due to this also. On the whole the motor output (power and torque) has to be restricted considerably below rated value in order to avoid thermal overloading and sparking at brushes.

7. Chopper Control of Separately Excited DC Motor





i. **Motoring Control** :

A transistor Chopper Control of Separately Excited DC Motor drive is shown in Fig. (a).

Transistor Tr 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 va and armature current ia for continuous conduction are shown in Fig. (b).

During ON-period of the transistor, $0 \leq t \leq t_{on}$, the motor terminal voltage is V.

The operation is described by

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

In this interval, armature current increases from ial to ia2. Since motor is connected to the source during this interval, it is called Duty Interval.

At t = ton, Tr is turned-off. Motor current freewheels through diode DF and motor terminal voltage is zero during interval ton ≤ t ≤ T.

Motor operation during this interval, known as freewheeling interval, is described by

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

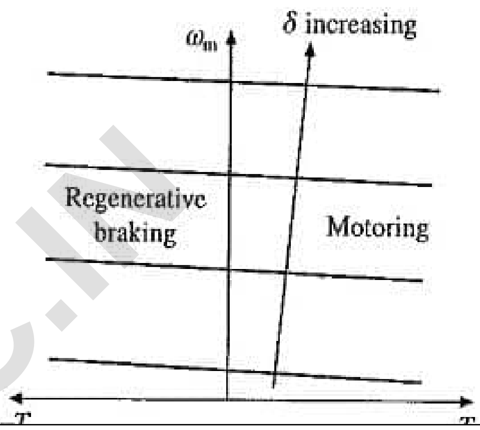
- Motor current decreases from i_{a2} to i_{a1} during this interval.
- Ratio of duty interval t_{on} to chopper period T is called **<u>duty ratio or duty cycle (δ).</u>** Thus

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

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

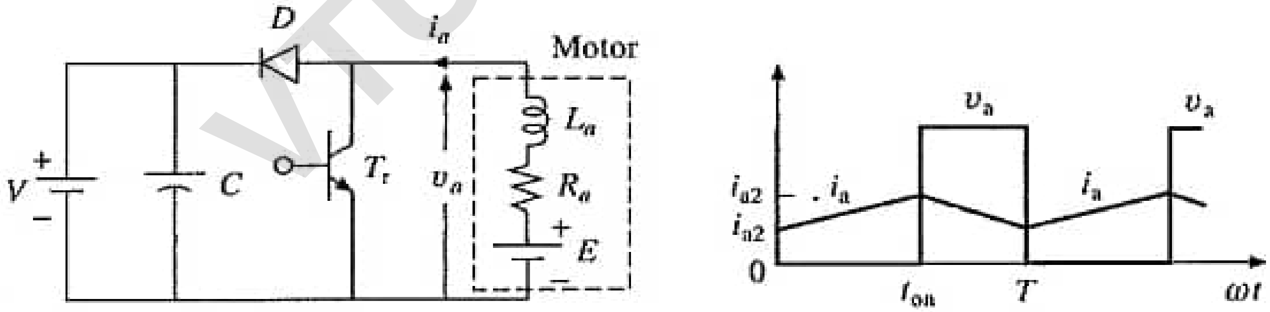
$$I_a = \frac{\delta V - E}{R_a}$$

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



The nature of speed torque characteristic is shown in Fig

ii. Regenerative Braking:



(a) (b)

- Chopper Control of Separately Excited DC Motor for regenerative braking operation is shown in Fig. (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 <u>continuous conduction.</u>
- Usually an external inductance is added to increase the value of L_a.
- When T_r is ON, i_a increase from $\mathbf{i_{a1}}$ **to** $\mathbf{i_{a2}}$.

- If δ is again defined as the ratio of duty interval to period T, then

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

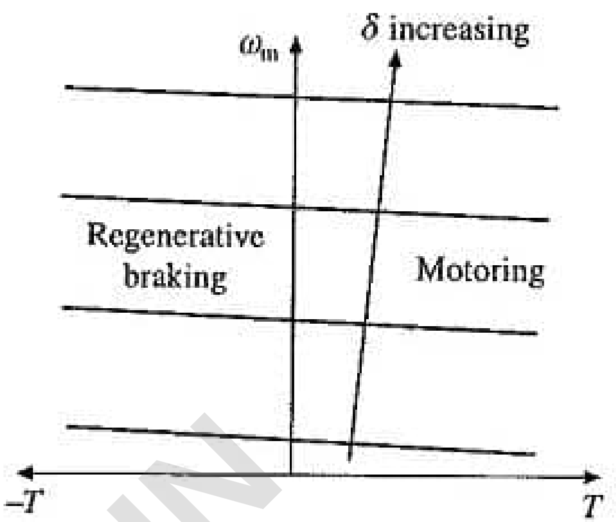
$$V_a = \frac{1}{T}\int_{t_{on}}^{T} V\,dt = \delta V$$

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

Since I_a has reversed

$$T = -KI_a$$

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



The nature of speed torque characteristic is shown in Fig

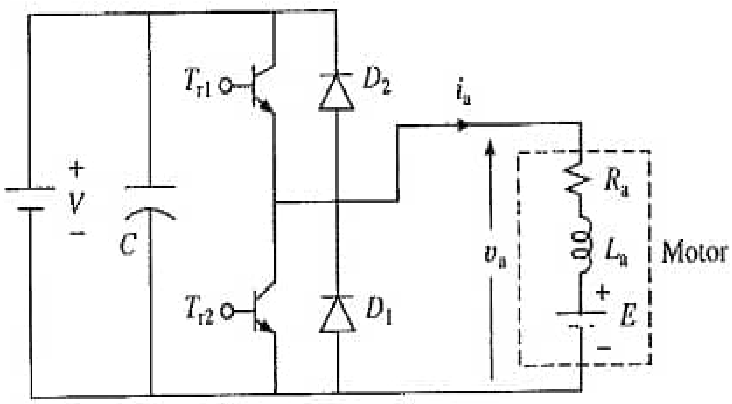
iii. Motoring and Regenerative Braking

In servo drives where fast transition from motoring to braking and vice versa is required, both Trl and Tr2 are controlled simultaneously.

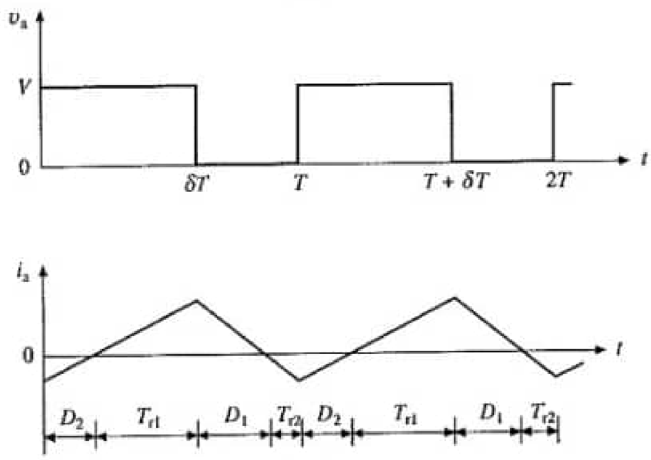
In a period T, Trl is given gate drive from 0 to δT and Tr2 is given gate drive from δT to T, where δ is the duty ratio for Trl. Therefore, from **0 to δT** motor is connected to source either through Trl or D_2 depending on whether the motor current ia is positive or negative.

Since V > E, during this period the rate of change of current is always positive.

Similarly from **δT to T,** motor armature is shorted either through D_1 or Tr2 depending on whether i_a is positive or negative and during this period rate of change of current is always negative.



(a)



(b)

Above equation suggests that motoring operation (+ve Ia) takes place when δ > (E/V) and regenerative braking operation takes place when δ < (E/V) and transition from motoring to braking and vice versa occurs when δ = (E/V).

The above equations are similar to those obtained for chopper of Fig. (5.41), and therefore, given the same numbers.

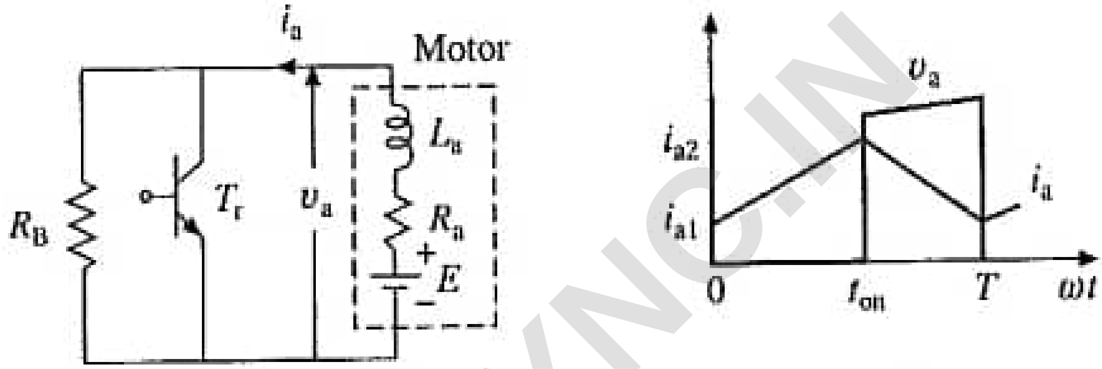
$$V_a = \delta V$$

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

Dynamic Braking:

Dynamic braking circuit and its waveforms are shown in Fig.

During the interval $0 \le t \le t_{on}$, i_a increases from i_{a1} to i_{a2}. A part of generated energy is stored in inductance and rest is dissipated in R_a and T_r. During interval $t_{on} \le t \le T$, i_a decreases from i_{a2} to i_{a2}



(a) (b)

The energies generated and stored in inductance are dissipated in braking resistance RB, Ra.

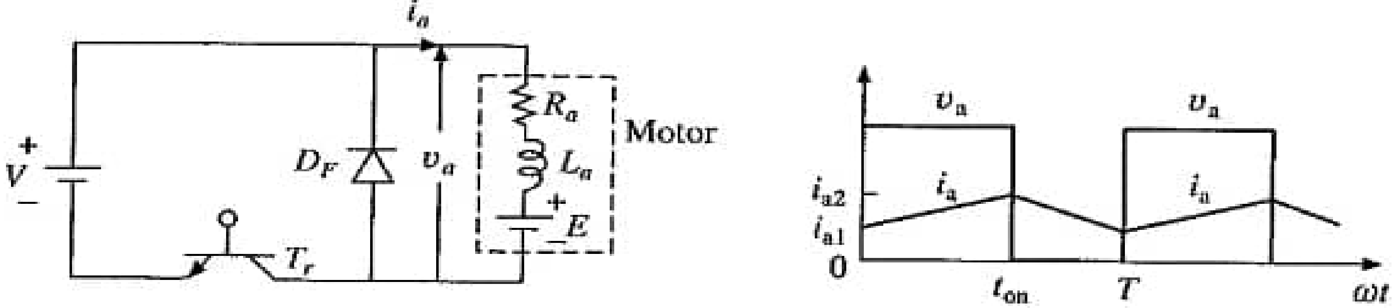
Transistor Tr controls the magnitude of energy dissipated in RB, and therefore, controls its effective value.

If ia is assumed to be rippleless dc, then energy consumed E_N by RB during a cycle of chopper operation is

$$E_N = I_a^2 R_B (T - t_{on}) \qquad P = \frac{E_N}{T} = I_a^2 R_B (1 - \delta) \qquad R_{BE} = \frac{P}{I_a^2} = R_B (1 - \delta) \qquad \delta = \frac{t_{on}}{T}$$

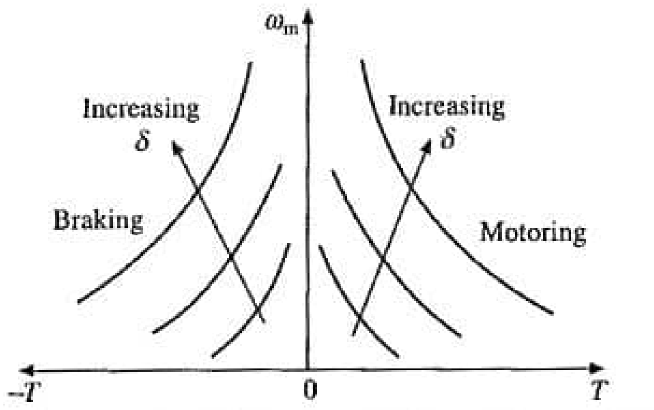
Chopper Control of Series Motor:

Motoring : Chopper Control of Series Motor and va and ia waveforms will be same as shown in Fig. Va is given by Eq.



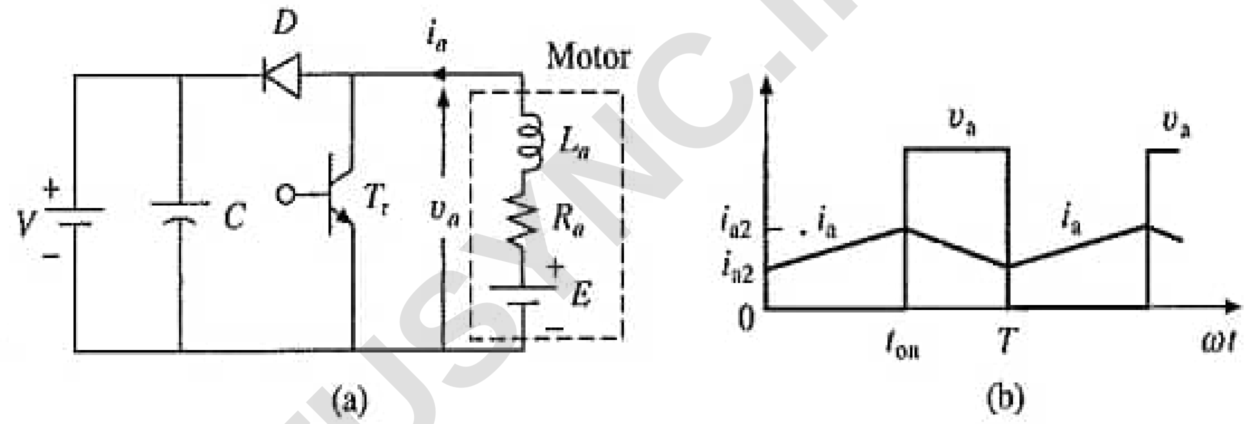
(a) (b)

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



- However, e is not constant but varies with ia. Due to saturation of magnetic circuit, relationship between e and ia is non-linear.
- The approximation is already described and is applicable here.
- Consequently, motor performance can be calculated. The nature of speed torque curves is shown in Fig.

Regenerative braking:



- With Chopper Control of Series Motor, regenerative braking of series motor can also be obtained. Power circuit of Fig.(a) is employed.
- During regenerative braking, series motor functions as a self-excited series generator. For self-excitation, current flowing through field winding should assist residual magnetism.
- Therefore, when changing from motoring to braking connection, while direction of armature current should reverse, field current should flow in the same direction.
- This is achieved by reversing the field with respect to armature when changing from motoring to braking operation. Waveforms of va and ia will be same as those of Fig.(b).
- For a chosen value of I_a, K_a is obtained from magnetization characteristic. Then T and ω_m are obtained from Eqs., respectively.
- The nature of speed-torque characteristics is shown in Fig.. Such characteristics give unstable operation with most loads. Consequently, regenerative braking of the series motor is difficult.

$$\omega_m = \frac{\delta V + I_a R_a}{K_a}$$

$$T = -K_a I_a$$

Module-3

Induction Motor Drives

Syllabus:

Induction Motor Drives:

- Analysis and Performance of Three Phase Induction Motors,
- Operation with Unbalanced Source Voltage and Single Phasing
- Operation with Unbalanced Rotor Impedances
- Analysis of Induction Motor Fed From Non-Sinusoidal Voltage Supply
- Starting, Braking, Transient Analysis.
- Speed Control Techniques-Stator Voltage Control
- Variable Voltage Frequency Control from Voltage Sources.

Introduction

Induction Motor: The motor which runs at a speed less than synchronous speed, due to slip which is the difference in the stator field and rotor field

Induction motors, particularly squirrel cage IM, have many advantages when compared to DC motors. They are,

- Ruggedness
- Lower maintenance requirements
- Better reliability
- Low cost, less weight and volume
- Higher efficiency
- Also induction motors are able to operate in dirty and explosive environments.

Three Phase Induction Motor

Three Phase Induction Motors are of two types:

1. **Squirrel-case IM-**In squirrel-cage, the rotor consists of longitudinal conductor-bars shorted by circular connectors at the two ends
2. **Wound-rotor IM-** In wound-rotor motor, the rotor also has a balanced three-phase distributed winding having same poles as stator winding

- However, in both, stator carries a three-phase balanced distributed winding..

Analysis & Performance of Three Phase Induction Motors

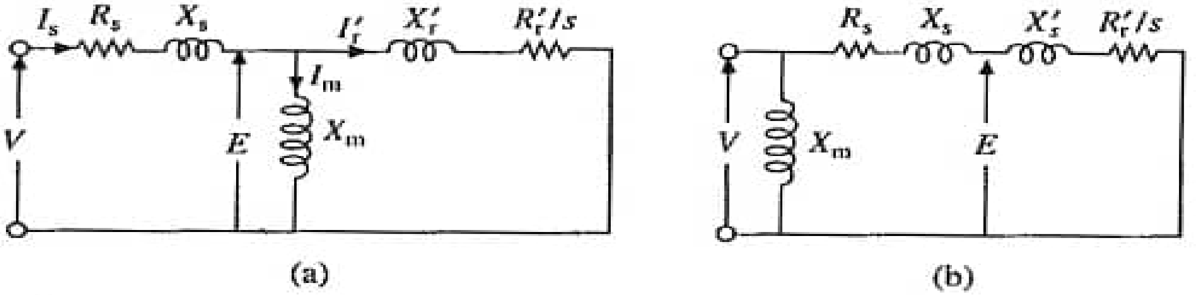


Fig. 1 Per-phase stator referred equivalent circuits of an induction motor

- Per-phase equivalent circuit of a Three Phase Induction Motors is shown in Fig(a), simplified equivalent circuit is shown in Fig(b).
- *R'_r and X'_r - stator referred values of rotor resistance R_r and rotor reactance X_r.*
- Slip is defined by

$$s = \frac{\omega_{ms} - \omega_m}{\omega_{ms}} \quad (1)$$

where ω_m and ω_{ms} are rotor and synchronous speeds, respectively

$$\omega_{ms} = \frac{4\pi f}{p} \text{ rad/sec} \quad (2)$$

where f and p are supply frequency and number of poles, respectively.

From Eq(1):

$$\omega_m = \omega_{ms}(1 - s) \quad (3)$$

Rotor current referred to stator side :

$$\bar{I}'_r = \frac{V}{\left(R_s + \frac{R'_r}{s}\right) + j(X_s + X'_r)} \quad (4)$$

Power transferred to rotor (or air-gap power)

$$P_g = 3I_r'^2 R'_r / s \quad (5)$$

Rotor copper loss is

$$P_{cu} = 3I_r'^2 R'_r \quad (6)$$

Electrical power converted into mechanical power

$$P_m = P_g - P_{cu} = 3I_r'^2 R'_r\left(\frac{1-s}{s}\right) \quad (7)$$

Torque developed by motor

$$T = P_m/\omega_m \qquad (8)$$

Substitute for Pm and ωm:

$$T = \frac{3}{\omega_{ms}} I_r'^2 \frac{R_r'}{s} \qquad (9)$$

Substitute for Ir'

$$T = \frac{3}{\omega_{ms}} \left[\frac{V^2 R_r'/s}{\left(R_s + \frac{R_r'}{s}\right)^2 + (X_s + X_r')^2} \right] \qquad (10)$$

Comparing eq. 5 and eq.9

$$T = P_g/\omega_{ms} \qquad (11)$$

Differentiating T in eq.10, with respect to s and equating to zero gives the slip for maximum torque

$$s_m = \pm \frac{R_r'}{\sqrt{R_s^2 + (X_s + X_r')^2}} \qquad (12)$$

+ve: Working as IM

-ve: Working as IG

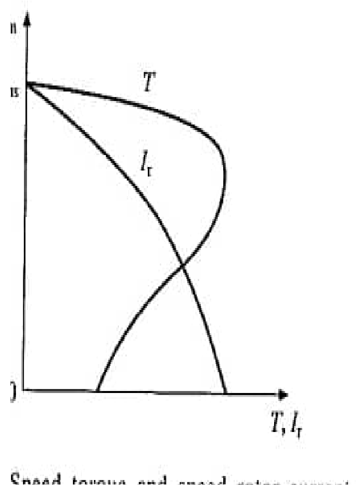
Substitute above Sm in Torque eq.10 to get Tmax

$$T_{max} = \frac{3}{2\omega_{ms}} \left[\frac{V^2}{R_s \pm \sqrt{R_s^2 + (X_s + X_r')^2}} \right] \qquad (13)$$

Maximum torque is also known as breakdown torque. While it is independent of rotor resistance, S_m is directly proportional to rotor resistance.

The natures of speed-torque and speed-rotor current characteristics are shown in Fig.2.

- Both rotor-current and torque are zero at synchronous speed.
- With decrease in speed, both increase.
- While torque reduces after reaching breakdown value, the rotor-current continues to increase, reaching a maximum value at zero speed.



- Dividing Eq. (10) by (13) and then substituting from (12) yields

$$\frac{T}{T_{max}} = \frac{2\left(1 + \frac{R_s}{R'_r} s_m\right)}{\frac{s}{s_m} + \frac{s_m}{s} + 2\frac{R_s}{R'_r s_m}} \qquad (14)$$

- For slips much smaller than s_m, second term of the denominator dominates.
- Therefore, speed-torque relation from 0 to rated torque is approximately represented by a straight line.
- For slips much larger than s_m, first term of the denominator dominates and speed-torque relation takes a hyperbolic shape in this region.
- In the whole region of motor operation, term ($R_s s_m/R'_r$) is small compared to 1 and dominating term in the denominator. Therefore, it can be dropped from Eq. (14). Thus

$$\frac{T}{T_{max}} = \frac{2}{\frac{s}{s_m} + \frac{s_m}{s}} \qquad (15)$$

Induction Motors with Special Designs:

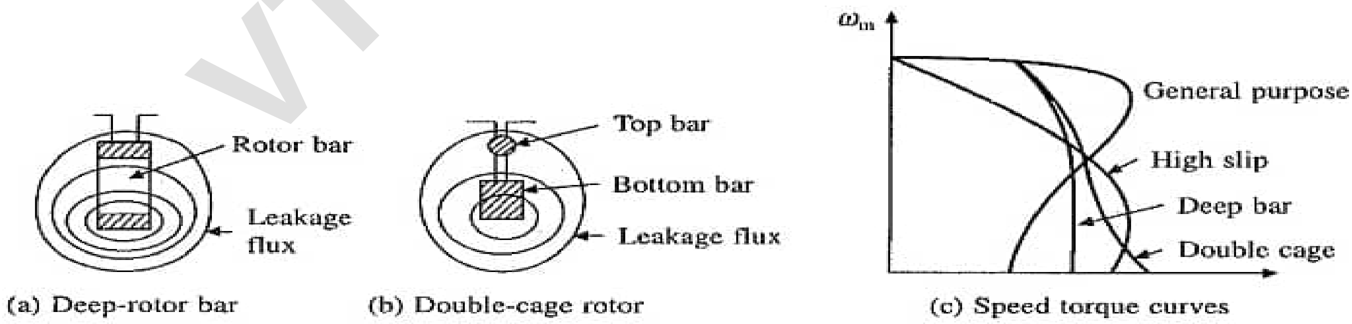


Fig. 3 Induction motors of special designs

- A general purpose induction motor is designed to operate at low slip at full load in order to have good running performance.
- Depending on the rating, full load slip varies from 2 to 7%. Such a motor has high starting current (5-8 times) and low starting torque (full load torque to twice Bill load torque).
- **High Slip Induction Motors** operate at a large slip (between 10 and 40% at full load) they are called high slip motors. High slip motors are also suitable for fan drives where speed is controlled by stator voltage control and are found among both—squirrel-cage and wound rotor

- In squirrel-case induction motors, good starting performance (low starting current and high starting torque) is realized without appreciably affecting full load performance by the use of deep-bar rotor or double-cage rotor motors.
- Rotor frequency changes from 50 Hz to 1-3 Hz as the speed changes from standstill to full load: Variation of rotor frequency is utilized in these motors to vary rotor resistance from a large value at standstill to a very small value at full speed.
- Thus, while starting and low speed performance is improved, full load performance is not appreciably effected.

Operations with Unbalanced Source Voltages and Single phasing

- Supply voltage may sometimes become unbalanced. Further, motor terminal voltage may be unbalanced
- A three-phase Unbalanced Source Voltages: (V_a, V_b and V_c) can be resolved into set of three-phase balanced positive sequence (V_p), negative sequence (V_n) and zero sequence (V_0) voltages, using symmetrical component relations.

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

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

$$V_0 = \frac{1}{3}(V_a + V_b + V_c)$$

- Motor performance can be calculated for positive and negative sequence voltages separately. Zero sequence line voltage is zero due to absence of neutral connection (assumed).
- 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 $s = \frac{\omega_{ms} - \omega_m}{\omega_{ms}}$
- For positive sequence voltages, equivalent circuits are same, 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. (4) and (10). Thus

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

- Interaction between positive sequence air-gap flux wave and positive sequence rotor currents produce positive sequence torque T_p

$$T_p = \frac{3}{\omega_{ms}}\left[\frac{V_p^2 R_r'/s}{\left(R_s + \frac{R_r'}{s}\right)^2 + (X_s + X_r')^2}\right]$$

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

$$s_n = \frac{-\omega_{ms} - \omega_m}{-\omega_{ms}} \qquad s_n = (2 - s)$$

Negative sequence produce a flux opposite to positive sequence

- Equivalent circuits of Fig. 1 are applicable when s is replaced by (2 — s) or s_n, and V are replaced by V_n
- Expressions for rotor current and torque

$$I_{rn}' = \frac{V_n}{\left(R_s + \frac{R_r'}{2-s}\right) + j(X_s + X_r')}$$

$$T_n = -\frac{3}{\omega_{ms}}\left[\frac{V_n^2 R_r'/(2-s)}{\left(R_s + \frac{R_r'}{(2-s)}\right)^2 + (X_s + X_r')^2}\right]$$

- Negative sequence torque T_n is produced due to interaction between negative sequence flux wave and negative sequence rotor currents

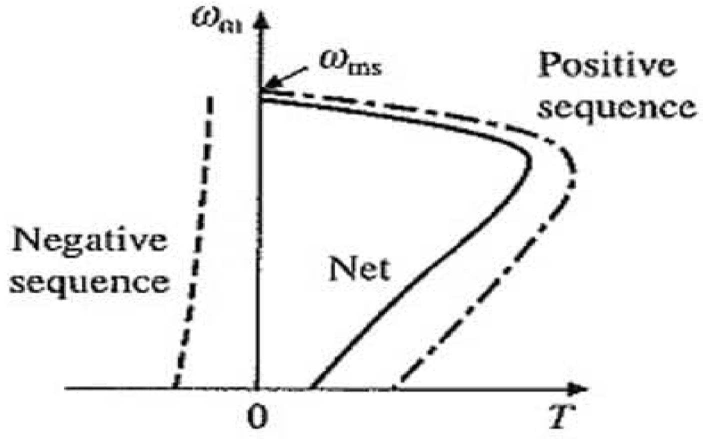
- The rms rotor current and torque are given by

$$I_r' = (I_{rp}'^2 + I_{rn}'^2)^{1/2} \qquad (21)$$

$$T = T_p + T_n$$

$$= \frac{3}{\omega_{ms}}\left[\frac{V_p^2 R_r'/s}{\left(R_s + \frac{R_r'}{s}\right)^2 + (X_s + X_r')^2} - \frac{V_n^2 R_r'/(2-s)}{\left(R_s + \frac{R_r'}{2-s}\right)^2 + (X_s + X_r')^2}\right] \qquad (22)$$

- Positive sequence, negative sequence and the resultant speed-torque characteristics are shown in Fig. 4(a)

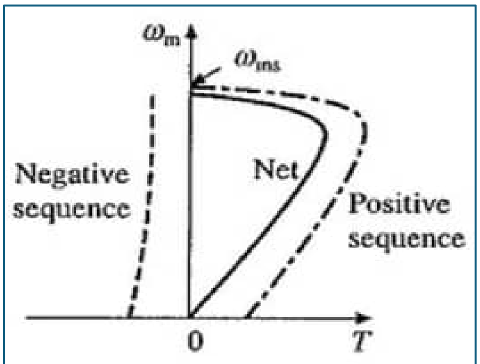


(a) Unbalanced stator voltages

Fig. 4 Speed-torque curves of an induction motor with unbalance stator voltages

Single phasing

- Single phasing (when supply to any one phase fails) is the extreme case of unbalancing, when $V_p = V_n$. At zero speed, s is also equal to s_n, consequently starting torque is zero. Speed-torque curves for single phasing are shown in Fig. 4(b)
- positive sequence torque Tp- is produced by interaction between positive sequence air-gap flux wave and positive sequence rotor currents
- Negative sequence torque Tn- is produced due to interaction between negative sequence flux wave and negative sequence rotor currents.



(b) Single phasing

- Torques-are also produced due to interactions between positive sequence flux wave and negative sequence rotor currents, and negative sequence flux wave and positive sequence rotor currents
- However, these torques are pulsating in nature with zero average values.
- The pulsating torques cause vibrations which reduce the life of motor and produce hum.
- Equations Ir'and T –indicates that while the torque is reduced, copper losses (and also core losses) are increased.
- Thus, the Unbalanced Source Voltages Operations reduces the motor torque capability and efficiency.
- when the unbalance in voltages is more than 5%- Motor is not allowed to run for a prolonged period, to prevent burning of the motor

- For the same reason, motor is disconnected from the source whenever single phasing occurs, unless the single phasing is always accompanied by a light load.

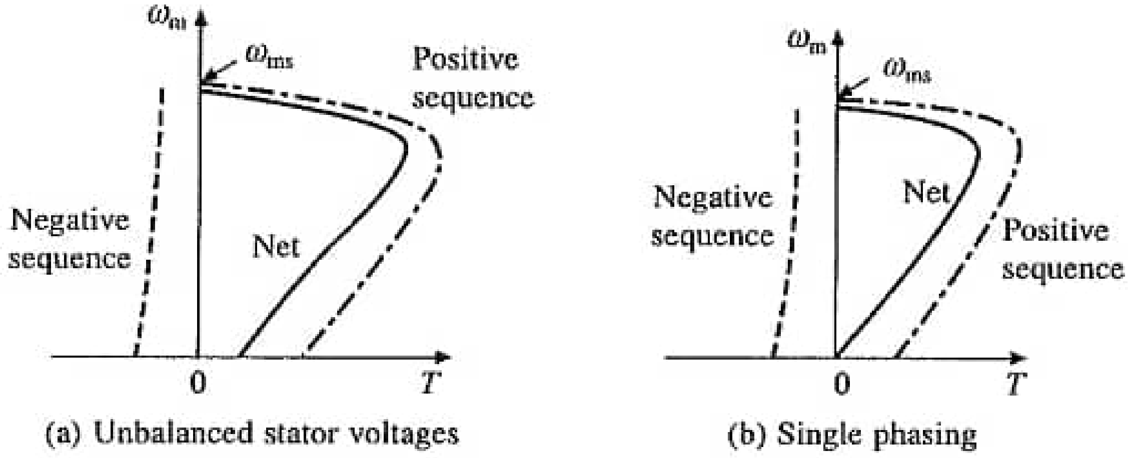
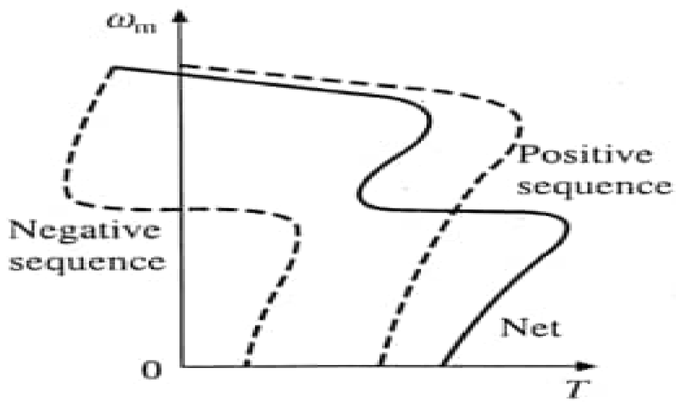


Fig. 4 Speed-torque curves of an induction motor with unbalance stator voltages

Operation with Unbalanced Rotor Impedances

- Unbalanced rotor impedance causes unbalance in rotor currents.
- The unbalanced rotor currents can be resolved into positive and negative sequence components.
- Positive sequence rotor currents produce driving torque similarly as of balanced rotor resistances.
- The negative sequence components produce a rotating field which moves with respect to rotor at a speed ($-S\omega_{ms}$) and in space at a speed of $\omega_s(1- 2S)$
- Interaction between positive and negative sequence components produces pulsating torques with zero average values.
- These sequence components reduces the motor torque, but copper and core losses are increased there by reducing efficiency.
- When single phasing occurs in the rotor, peak value of steady-state voltage is excess of twice normal.
- If one phase of the stator also gets opened at the same time, so that the voltages becomes higher.



Speed-torque curves with unbalanced rotor resistance

Analysis of Induction Motor Fed From Non-Sinusoidal Voltage Supply

- When fed from an Semiconductor Converters (inverter or Cycloconverter), the motor terminal voltage is non-sinusoidal but it has half-wave symmetry.
- A non-sinusoidal waveform can be resolved into fundamental and harmonic components using Fourier analysis. **Because of half-wave symmetry only odd harmonics will be present**.
- The Harmonic can be divided into positive sequence, negative sequence and zero sequence
- The harmonics, which have the same phase sequence as that of fundamental are called positive sequence harmonics.
- The Harmonic having phase sequence opposite to fundamental are called negative sequence harmonics.
- The harmonics which have all three-phase voltages in phase are called zero sequence harmonics.
- The fundamental phase voltage components : *with the phase sequence ABC.*

$$V_{AN} = V_1 \sin \omega t,$$
$$V_{BN} = V_1 \sin (\omega t - 2\pi/3)$$
$$V_{CN} = V_1 \sin (\omega t - 4\pi/3)$$

- The corresponding 5th and 7th harmonic phase voltages are

$$V_{AN} = V_5 \sin 5\omega t \quad \textit{Ps shift=0}$$
$$V_{BN} = V_5 \sin 5(\omega t - 2\pi/3) = V_5 \sin(5\omega t - 4\pi/3) \quad \textit{Ps shift=240}$$
$$V_{CN} = V_5 \sin 5(\omega t - 4\pi/3) = V_5 \sin(5\omega t - 2\pi/3) \quad \textit{Ps=120}$$

*The **5th harmonic has a phase sequence ACB, hence it is a negative sequence harmonic***

$$V_{AN} = V_7 \sin 7\ \omega t \quad \textit{Ps shift=0}$$
$$V_{BN} = V_7 \sin 7(\omega t - 2\pi/3) = V_7 \sin(7\omega t - 2\pi/3) \quad \textit{Ps shift=120}$$
$$V_{CN} = V_7 \sin 7(\omega t - 4\pi/3) = V_7 \sin(7\omega t - 4\pi/3) \quad \textit{Ps=240}$$

***7th harmonic has the phase sequence ABC**, which is the same as that of fundamental.*

Hence it is a positive sequence harmonic

- A positive sequence harmonic 'm' will produce a rotating field, moves in the same direction as the fundamental at a speed m times that of the fundamental field.
- Negative sequence harmonic 'm' will produce rotating field, moves in opposite direction to the fundamental at m times its speed.

- Zero sequence components do not produce a rotating field.
- For fundamental component, the equivalent circuits of Fig.1 will be applicable.

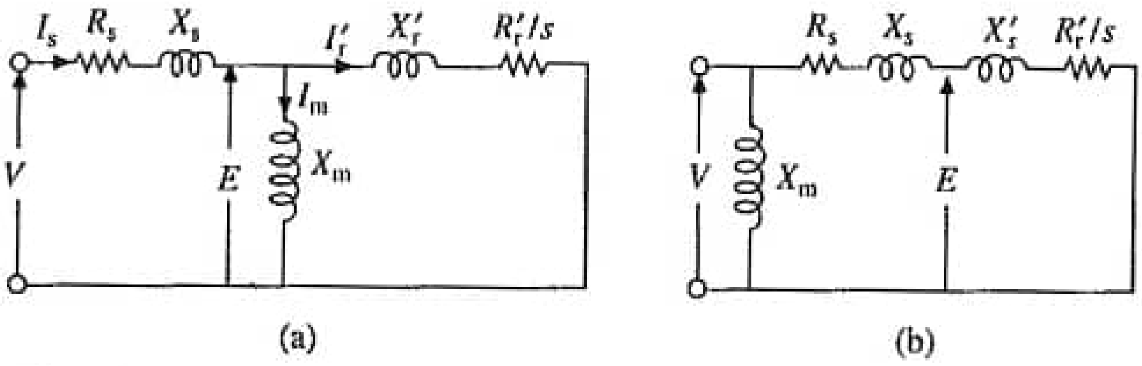


Fig. 1 Per-phase stator referred equivalent circuits of an induction motor

- For any 'm'th harmonic, equivalent circuit is shown in Fig. 2. Each reactance has been increased by a factor 'm'. Due to the skin effect resistances will also be increased several times.

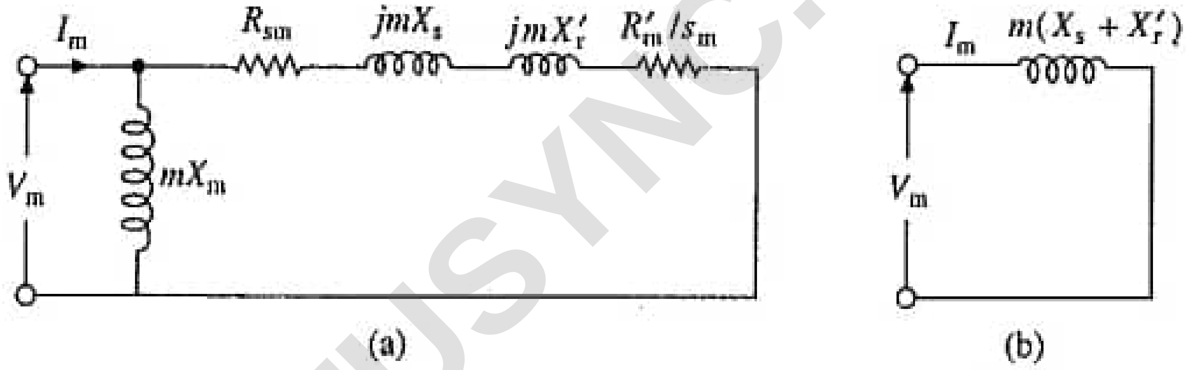


Fig. 2 Harmonic equivalent circuits of an induction motor

Slip s_m for the m^{th} harmonic is given by:

$$s_m = \frac{m\omega_{ms} \mp \omega_m}{m\omega_{ms}}$$

Negative sign -harmonics produce forward rotating fields
positive sign - produce backward rotating fields.

- Since s_m is close to unity, resistance $((R'_m/s_m))$ has a small value. Simplified Eqt ckt is shown in Fig 2b.
- When fed from a semiconductor converter, it can be shown that the net torque produced by harmonics is close to zero.
- The motor torque can be evaluated from equivalent circuits of Fig. 2(b):

$$T = \frac{3}{\omega_{ms}}\left[\frac{V^2 R'_{r/s}}{\left(R_s + \frac{R'_r}{s}\right)^2 + (X_s + X'_r)^2}\right]$$

- Fundamental component of rotor current:

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

- The m_{th} harmonic current is calculated from Fig. 2(b) as

$$I_m = \frac{V_m}{mX}$$

- When stator is star-connected tripplen harmonics (third harmonic and its multiples) will not flow. The rms motor current I_{rms} will then be

$$I_{rms}^2 = I_s^2 + \sum_{m=5,7,11,\ldots} I_m^2$$

- When motor is delta-connected, tripplen harmonics will circulate in delta, but will not flow in the source.
- The source current therefore can be obtained by multiplying I_{rms} given by above Eq. by √3. The rms motor phase current will be obtained by

$$I_{rms}^2 = I_s^2 + \sum_{m=3,5,\ldots} I_m^2$$

Effects of Induction Motor Fed From Non-Sinusoidal Voltage Supply

- For a given motor torque and power, rms current flowing through the motor has a higher value.
- Due to skin effect, harmonic rotor resistance has higher value.
- Harmonics increase the copper loss, core losses, thereby reducing efficiency. Hence motor has to be derated.
- Harmonics produces pulsating torques due to interaction between the rotating field produced by one harmonic and rotor current of another harmonic. Harmonic 5, 7, 11 and 13 are major contributors of torque pulsations.
- When motor supply frequency is not very low, the frequency of torque pulsations is large enough to be filtered out by motor inertia.
- The torque pulsations do not have significant effect on motor speed, although they do increase noise and reduce motor life due to vibrations.
- However, when motor supply frequency is low, these torque pulsations cause pulsations in speed.
- The motor then does not move smoothly but have jerky motion.

Starting of Induction Motor Drives

Starting of IM drives are required to have following features:

- Motor should develop enough starting torque to overcome friction, load torque and inertia of motor-load system, and thus, complete the starting process within a prescribed time limit.
- Starting current magnitude should be such that it does not cause the overheating of the machine and does not cause a dip in the source voltage beyond a permissible value.
- Usually, a motor draws 5 to 7 times rated current during starting.
- When load torque during starting and motor-load-inertia are not large, motor can always be started direct on line.
- For small size motors voltage dip in the supply line is usually below acceptable level.
- When the motor is of large capacity and/or fed from a weak system, some starting arrangement becomes necessary for reducing the starting current.
- When either the load torque during starting is high or load inertia is large, the Starting of Induction Motor Drives process takes long time.
- If motor carries large current during starting, it will get damaged due to overheating. Therefore, motor cannot be started direct on line.
- In these cases, those methods of starting which allow a decrease in starting current without a decrease in starting torque are employed.
- In some applications an increase in starting torque accompanied by a decrease in starting current may be required.
- In a squirrel-cage motor some measures for improvement of starting performance may be taken at design stage, as in case of high slip, deep-bar and double cage squirrel-cage motors.

Types of Starters

1. **Star-delta starter**
2. **Auto-transformer starter**
3. **Reactor starter**
4. **Saturable reactor starter**
5. **Part winding starter**
6. **AC voltage controller starter**
7. **Rotor resistance starter is used for starting of wound-rotor motor**

Starting of Induction Motor

1. Star-Delta Starter:

- In this method, an induction motor designed to operate normally with delta connection is connected in star during starting.
- This allows reduction in stator voltage and current by 1/√3.
- Since motor torque is proportional to the square of stator terminal voltage, starting torque is reduced to one-third.
- A circuit for star-delta starting is shown. Circuit breakers CBm and CBs are closed to start the machine with star connection.
- When steady-state speed is reached CBs is opened and CBr is closed to connect machine in delta.

end

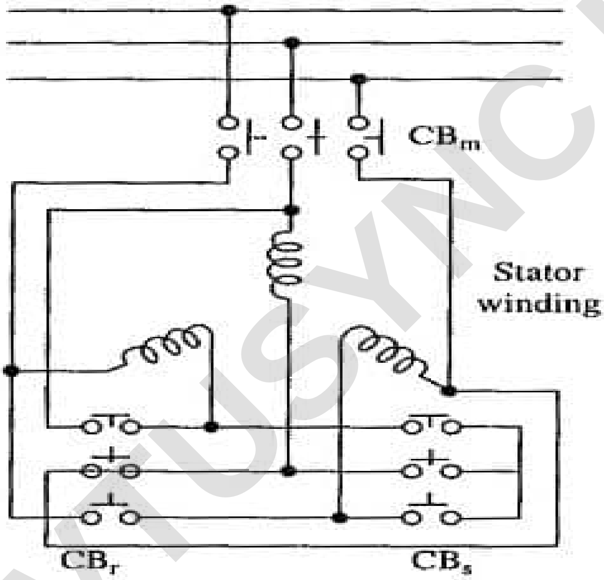


Fig. Start-delta starting

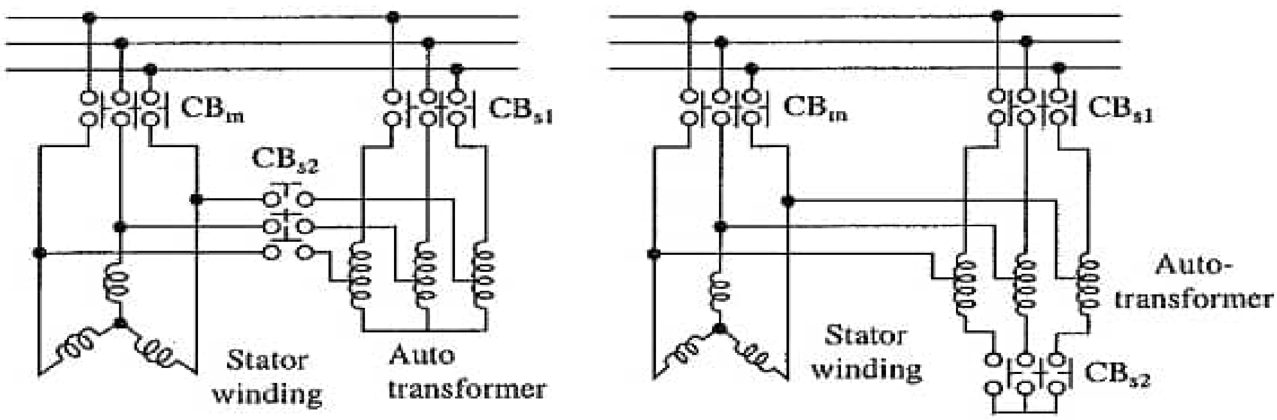
Note:

***CBm**- Supply switch*

***CBs**- closed: Stator RYB terminals are shorted forming Star connection.*

***CBr**- closed: When Motor speed reaches 80%, forming Delta connection (for running)*

2. Auto-transformer Starter:



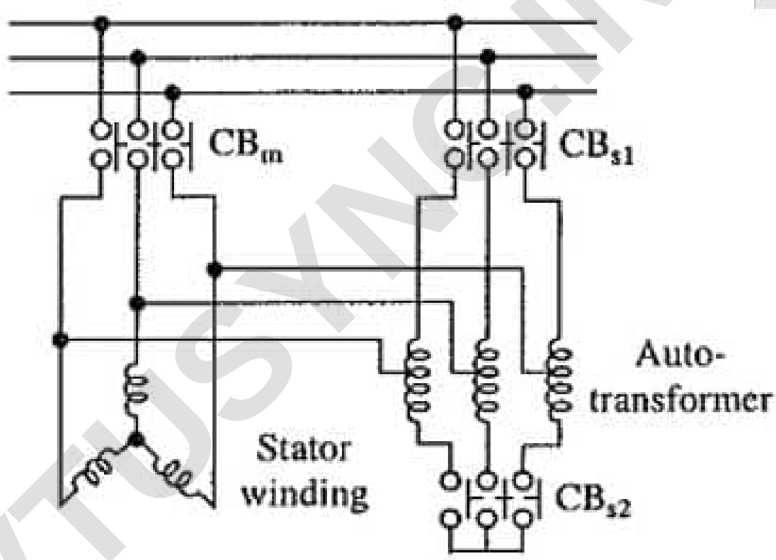
(a) Open circuit transition

(b) Closed circuit transition

Fig. Auto-transformer starting

- Reduced voltage for starting is obtained from an auto-transformer.
- For a secondary to primary turns ratio of a_T, motor terminal voltage and stator current are reduced by a_T. This reduces the current drawn from supply by a^2_T.
- Since torque is proportional to the square of motor terminal voltage, it is also reduced by a^2_T. After the motor has accelerated, it is connected to full supply voltage.
- An auto-transformer starter circuit, with open circuit transition is shown in Fig.(a). First, CB_{s1} is closed followed by CB_{s2}. When motor has accelerated to full speed, CB_{s2} is opened and CB_m closed. Now CB_{s1} is opened to disconnect auto-transformer from switch.

3. Closed-circuit transition



(b) Closed circuit transition

- A large current inrush is produced at the time of reconnection when induced and supply voltages are out of phase. When the current inrush is not acceptable, closed circuit transition is employed.
- A closed-circuit transition scheme for an auto-transformer starter is shown
- It employs three circuit breakers: CBs1, CBs2 and CBm. First CBs2 is closed to close the star point connection of the auto-transformer. CBs1 is closed next. This completes low voltage connection of auto-transformer and the motor starts.
- After steady-state speed is reached, circuit breaker CBs2 is opened. Motor now runs with the upper part of auto-transformer phase windings in series with the stator. Windings simply function as series reactors. Now circuit breaker CBm is closed, which bypasses series reactors and connects motor directly to the supply.

4. Reactor Starter

- Starting current can be reduced by connecting a three-phase reactor in series with stator.
- When motor reaches full speed, the reactor is bypassed.
- Here, CB_m is closed to start the machine.
- After full speed is reached, CB_s is closed to short the reactor.
- It is advantageous to connect reactor at the neutral end of stator winding.
- This minimizes its voltage rating and also maintains its voltage and the voltage of breaker CBs at neutral potential during normal motor operation

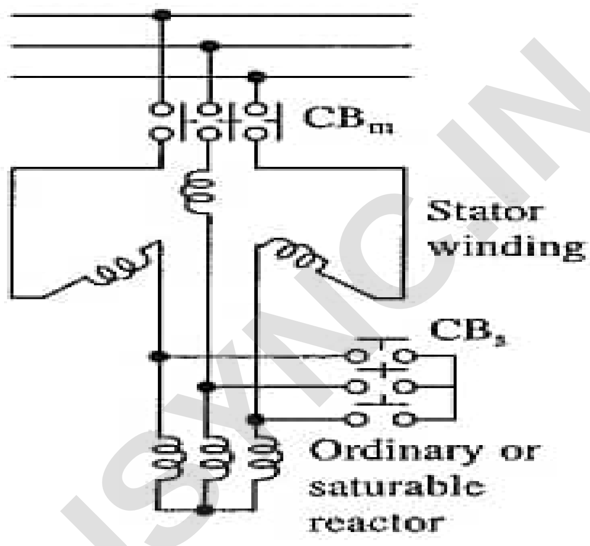


Fig. Reactor starting

5. Soft Start Using Saturable Reactor

- In some applications, starting torque must be controlled steplessly.
- For example in textile machines, it must be varied smoothly, otherwise fibre threads will break during starting. Such a starting arrangement is termed **Soft Start**.
- Thyristor voltage controller scheme is now widely used for soft start.
- A number of existing drives also employ saturable reactor starter is a three-phase saturable reactor is connected in series with the stator.
- Saturable reactor has dc control winding.
- Reactance of saturable reactor can be varied steplessly by changing the control winding current.
- For starting, reactance is initially set at the highest value.
- Starting torque is close to zero.
- Reactance is now reduced smoothly by increasing the control winding current.

- This gives stepless variation of starting torque.
- Consequently, motor starts without any jerk and accelerates smoothly.

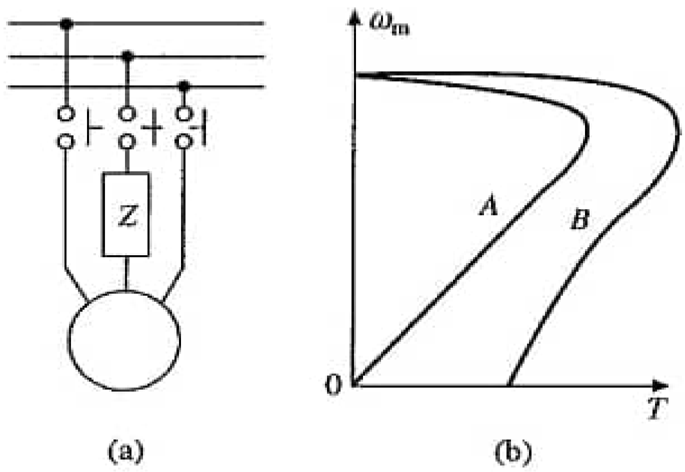


Fig. Starting with a single variable impedance in the stator

6. Part Winding Starting

- Some squirrel-cage motors have two or more stator windings which are connected in parallel during normal operation.
- During starting, only one winding is connected.
- This increase stator impedance and reduces starting current.
- Such a starting scheme is called **Part Winding Starting**.
- Its implementation for a machine with two stator windings is shown in Fig
- Machine starts with winding 1 when CB_m is closed.
- After full speed is reached, CB_s is closed to connect winding 2.

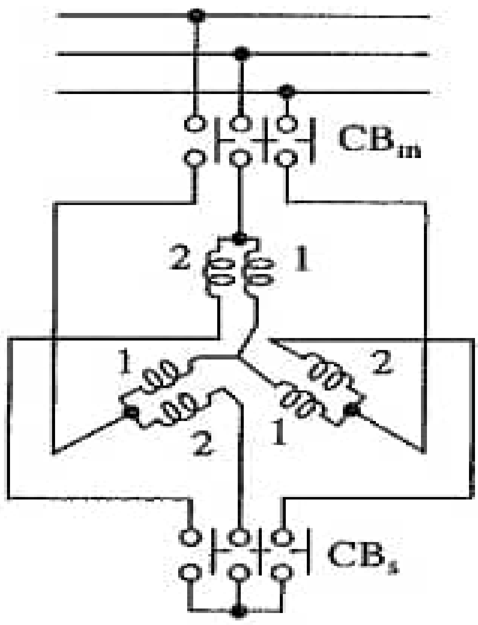


Fig. Part winding starting

7. Rotor Resistance Starter:

- Wound-rotor motors are generally started by connecting external resistors in the rotor circuit (Fig. (a)).
- The highest value of resistance is chosen to limit current at zero speed within the safe value.
- As the motor accelerates, sections in the external resistor are cut out one-by-one by closing contacts.
- As the motor accelerates, sections in the external resistor are cut out one-by-one by closing contacts C_1, C_2 and C_3 so as to limit the rotor current between specified maximum and minimum values Fig b.
- Here, the starting torque and torque-to-current ratio are high.
- It is, therefore, suitable for applications requiring fast acceleration, frequent starts and stops, starting with heavy load, and starting with high inertia load.
- While maximum torque is independent of rotor resistance value, speed at which maximum torque is produced can be controlled by changing the value of external resistors, External resistors can therefore be varied to accelerate the machine at maximum torque.

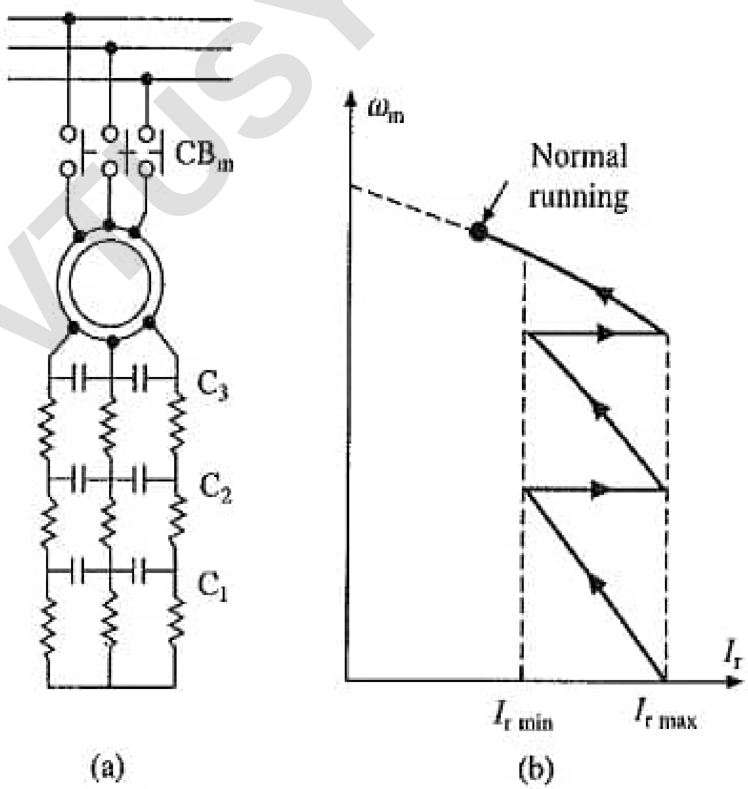


Fig. Rotor resistance starting

Braking of Induction Motor

Following methods are employed for Braking of Induction Motor Drive:

1. **Regenerative braking**
2. **Plugging or reverse voltage braking**
3. **Dynamic (or Rheostatic) braking further categorized as:**
   i. AC dynamic braking
   ii. Self-excited braking using capacitors
   iii. DC dynamic braking
   iv. Zero sequence braking

1. Regenerative Braking:

The power input to an induction motor is given by $P_{in} = 3VI_s \cos \phi_s$

- For motoring operation: $\Phi_s < 90°$
- If N > Ns, The rotor speed becomes greater than synchronous speed, relative speed between the rotor conductors and air-gap rotating field reverses.
- This reverses the rotor induced emf, rotor current and component of stator current which balances the rotor ampere turns.
- Consequently, angle Φ_s becomes greater than 90° and power flow reverses, giving **regenerative braking.**
- Equations (1)-(13) are applicable, except that slip is negative.
- The nature of speed-torque characteristic is shown in Fig.
- When fed from a source of fixed frequency, regenerative braking is possible only for speeds greater than synchronous speed
- With a variable frequency source it can also be obtained for speeds below synchronous speed.
- Main advantage of regenerative braking is that generated power is usefully employed.
- Main drawback being that when fed from a constant frequency source, it cannot be employed below synchronous speed.

$$s = \frac{\omega_{ms} - \omega_m}{\omega_{ms}} \quad (1)$$

$$T_{max} = \frac{3}{2\omega_{ms}} \left[\frac{V^2}{R_s \pm \sqrt{R_s^2 + (X_s + X_r')^2}} \right] \quad (13)$$

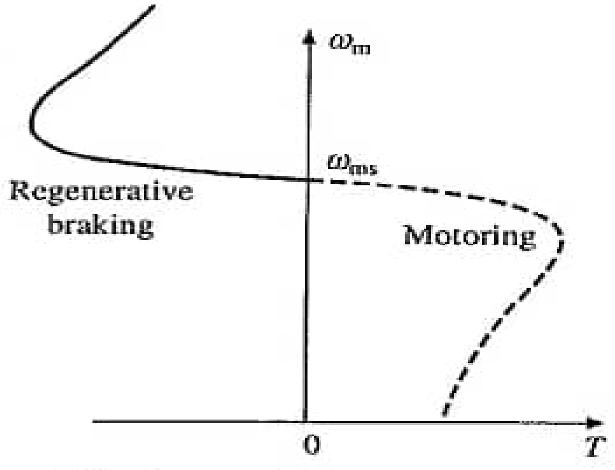
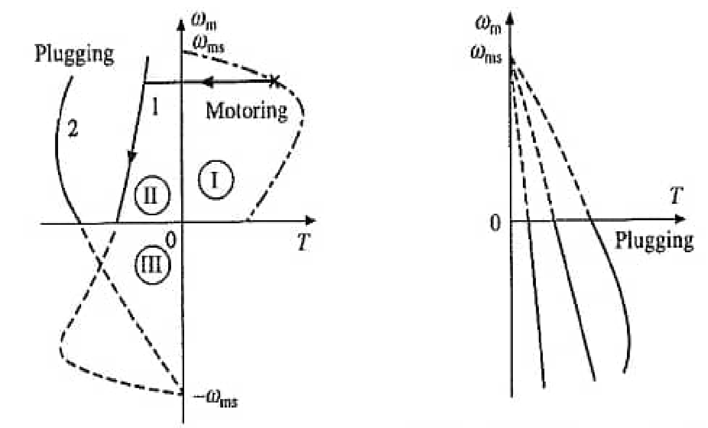


Fig. Regenerative braking

2. Plugging or Reverse Voltage Braking

- When phase sequence of supply of the motor running at a speed is reversed, by interchanging connections of any two phases of stator with respect to supply terminals, **operation shifts from motoring to plugging** as shown in below Fig..
- **Plugging characteristics** are actually extension of motoring characteristics for negative phase sequence from quadrant III to II.
- Reversal of phase sequence reverses the direction of rotating field.
- If the slip for plugging is denoted by s_n, the $s_n = \dfrac{-\omega_{ms} - \omega_m}{-\omega_{ms}} = 2 - s$
- Motor performance can be calculated from Eqs. (4)-(10) when s is replaced by s_n or (2 — s).
- Since at the instant of switchover to plugging, slip can be upto 2, the rotor induced voltage can be twice of its value at zero speed.
- Consequently, motor current is large, although braking torque is low.
- A special case of plugging occurs when an induction motor connected to positive sequence voltages is driven by an active load in the reverse direction (quadrant IV).
- Crane hoist is one such application where large rotor resistance is employed shown in fig.b



(a) 1 : Natural characteristic
2 : With external resistance in rotor

(a) Plugging in IV quadrant with large external resistance in rotor

Fig. Plugging

$$\bar{I}_r' = \frac{V}{\left(R_s + \frac{R_r'}{s}\right) + j(X_s + X_r')} \qquad (4)$$

$$T = \frac{3}{\omega_{ms}}\left[\frac{V^2 R_{r/s}'}{\left(R_s + \frac{R_r'}{s}\right)^2 + (X_s + X_r')^2}\right] \qquad (10)$$

3. Dynamic Braking of Induction Motor(or Rheostatic Braking)

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.b) or connecting it with another machine phase (Fig.c). The two connections of Figs. (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.

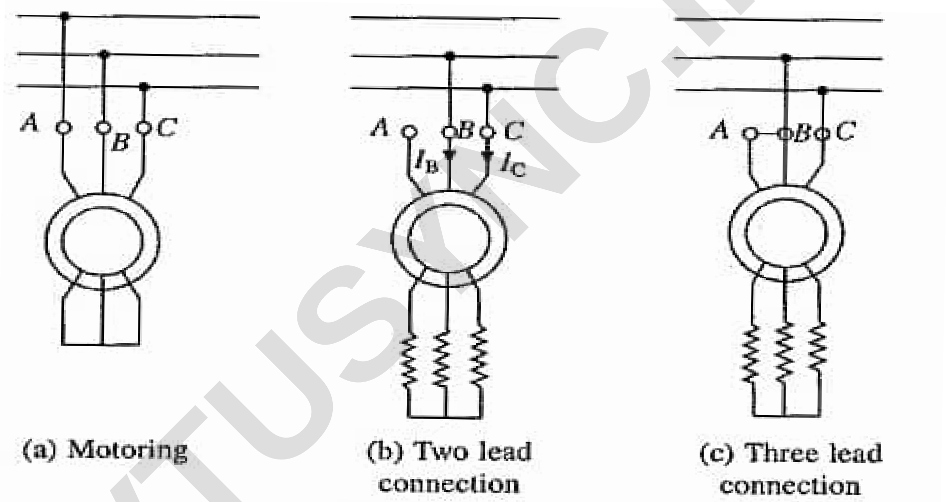


Fig. ac dynamic braking of a wound rotor motor

Two Lead Connection:

Two Lead Connection: Assume that phase A of a Y-connected motor is open circuited. Then IA = 0 and IC = -IB.

- Hence positive and negative sequence components Ip and In, respectively.

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

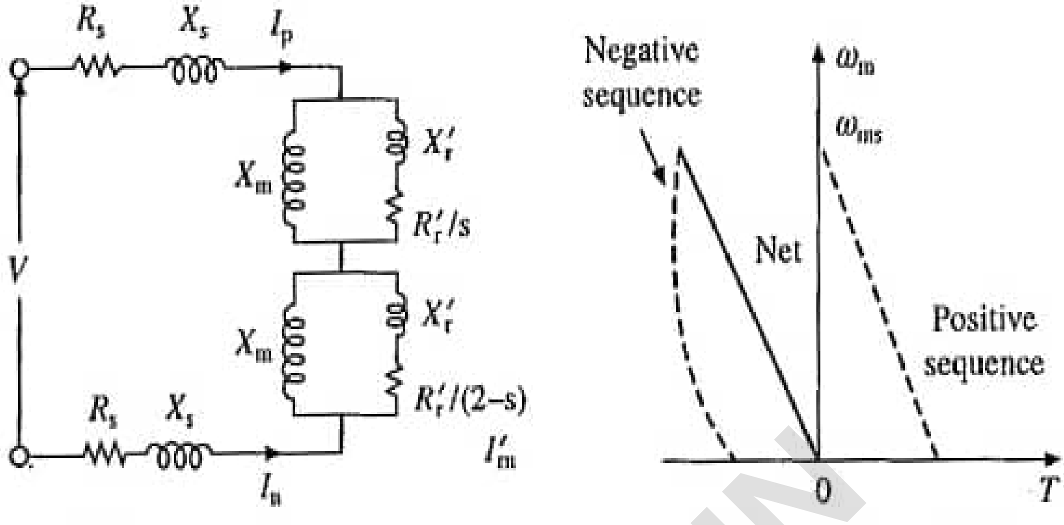
$$\bar{I}_n = \frac{1}{3}(\bar{I}_A + \alpha^2\bar{I}_B + \alpha\bar{I}_C) = \frac{1}{\sqrt{3}}(0 + \alpha^2\bar{I}_B - \alpha\bar{I}_B) = -j\bar{I}_B/\sqrt{3}$$

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

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

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

- The nature of speed-torque curves for positive and negative sequence currents, and net torque are shown in Fig. (b)



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

Fig. ac dynamic braking with two lead connection

Three Lead Connection:

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

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

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

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

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

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

$$V_p\,(\text{phase}) = V_n\,(\text{phase}) = \frac{V}{\sqrt{3}}$$

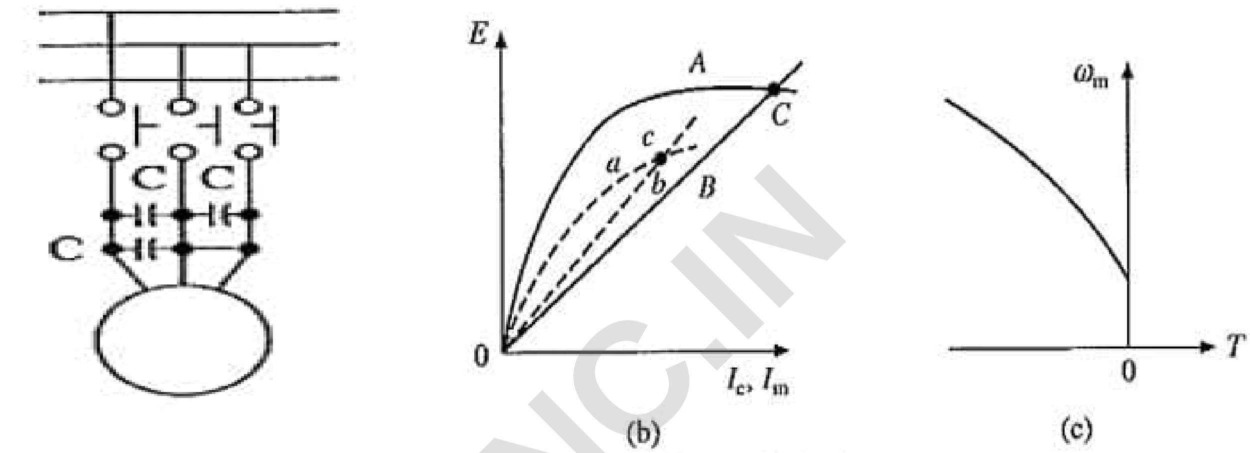
- In contrast to two lead connection, here magnitude of positive and negative sequence components of voltage are equal and not the positive and negative sequence components of currents.

b. Self-Excited Braking Using Capacitors

- In this method three capacitors are kept permanently connected across the motor terminals.

- Values of capacitors is so chosen that when disconnected from the line, motor works as a self-excited induction generator.
- Braking connection is shown in Fig. (a) and self-excitation process is explained in Fig. (b) for no load condition.
- Curve A is no load magnetization curve of the machine at a given speed, and line B represents the current through capacitors, given by

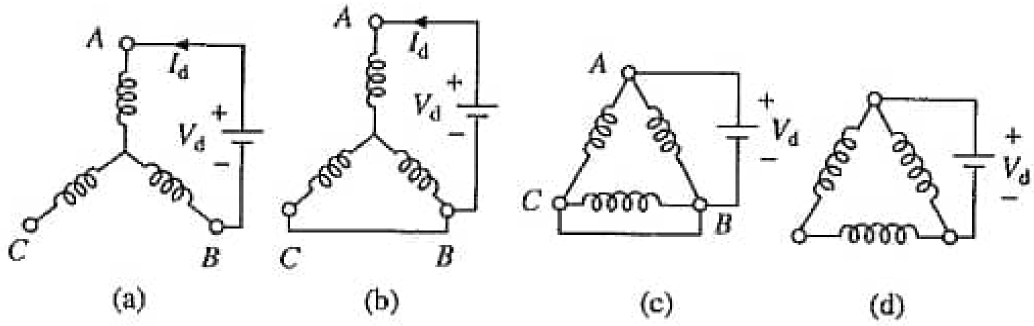
$$I_c = \sqrt{3}\, E \,|\, X_c = \sqrt{3}\, E\omega C$$



(a) Fig. Self-excited braking of induction motor

c. DC Dynamic Braking

- It is obtained when the stator of an induction motor running at a speed is connected to a dc supply.
- Two commonly used connections, two and three lead, for star and delta connected stators are shown in below Fig.1
- A method of getting dc supply with the help of a diode bridge for two lead connection is shown in Fig. 2
- DC current flowing through the stator produces a stationary magnetic field. Motion of rotor in this field induces voltage in the rotor winding.
- So, Machine works as a generator. Generated energy is dissipated in the rotor circuit resistance, thus giving Dynamic Braking of Induction Motor



- Fig. Various stator connections for dc dynamic braking. (a) and (d) are two lead connections and (b) and (c) are three lead connections

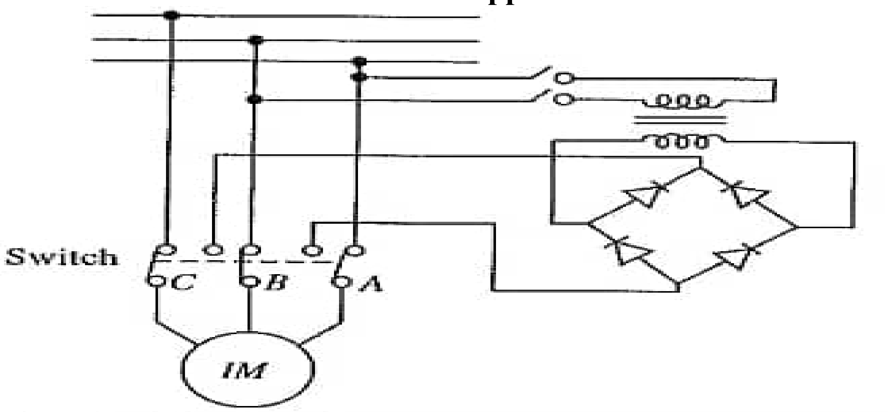


Fig. Details of two lead dc dynamic braking connection

d. Zero Sequence Braking

- In this braking, three stator phases are connected in series across either a single phase ac or a dc source as shown in Fig. (a). Such a connection is known as a Zero Sequence Connection, because currents in all the stator windings are co-phasal.
- The mmf caused zero-sequence currents produces a magnetic field having three times the number of poles for which the machine is actually wound.
- With an ac supply, resultant field is stationary in space and pulsates at the frequency of supply.
- With dc supply, resultant field is stationary in space and is of constant magnitude.
- The nature of speed-torque curves for ac and dc supply is shown in Fig. (b)
- With ac supply, braking could be used only up to one-third of synchronous speed.
- However, braking torques produced by this connection are considerably larger than motoring. Motor essentially works in regenerative braking.
- For motors with low rotor resistance, a significant part of generated energy is recovered.
- It does not require large rotor resistance, can be used both—with squirrel-cage and would-rotor motors.

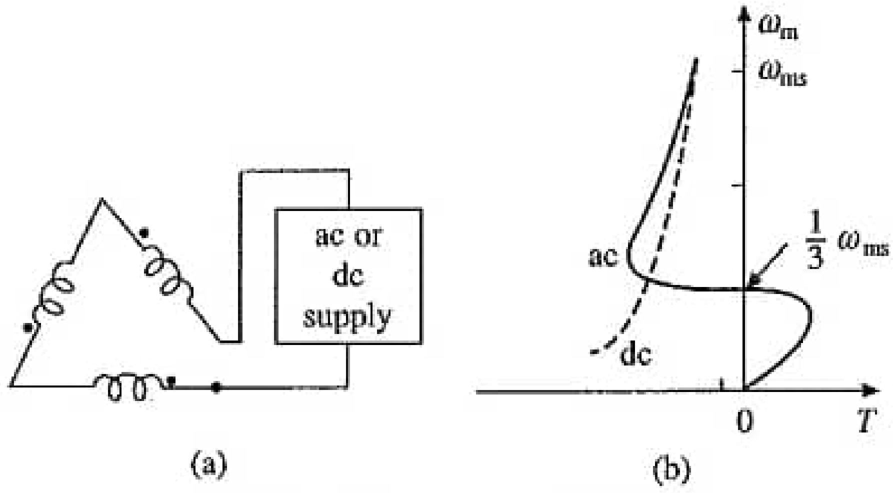


Fig. Zero-sequence braking

Transient Analysis of Induction Motor

For starting and plugging operation of machine, torque is given by Eq. $$\frac{T}{T_{max}} = \frac{2}{\frac{s}{s_m} + \frac{s_m}{s}}$$

$$J = \frac{d\omega_m}{dt} = T(\omega_m) - T_l(\omega_m)$$

yields $$J\frac{d\omega_m}{dt} = \frac{2T_{max}}{s/s_m + s_m/s} - T_l(\omega_m)$$

In some cases, Eq. will be in integrable form, and therefore, can be solved analytically.

It is useful to examine the transients for starting and plugging operations when operating on no load. Thus, from Eq. for no load operation

Starting and Plugging

Differentiating Eq. $\omega_m = \omega_{ms}(1 - s)$

$$\frac{d\omega_m}{dt} = -\omega_{ms}\frac{ds}{dt}$$

$$J\frac{d\omega_m}{dt} = \frac{2T_{max}}{s/s_m + s_m/s}$$

$$dt = -\frac{\tau_m}{2}\left(\frac{s_m}{s} + \frac{s}{s_m}\right)ds$$

$$\tau_m = \frac{J\omega_{ms}}{T_{max}}$$

τ_m is the mechanical time constant of motor. It is defined as the time taken by motor to reach its synchronous speed from standstill under constant accelerating torque equal to the maximum torque of the motor.

time required to start an induction motor on no load is $$t_s = -\frac{\tau_m}{2}\int_1^{0.05}\left(\frac{s}{s_m} + \frac{s_m}{s}\right)ds$$

- When operating on no load, steady-state is reached when s = 0. Thus during starting slip changes from 1 to 0. However, if eq is integrated for s = 1 to s = 0 an infinite value is obtained for starting time.
- When final speed is the steady-state equilibrium speed, transients are considered to be over when 95% range of speed is covered. Therefore, in Eq. integration is done from s = 1 to s = 0.05. Solving gives

$$t_s = \tau_m\left[\frac{1}{4s_m} + 1.5\, s_m\right]$$

- Thus starting time is a function of sm. Starting time has a minimum value of 1.22τm at sm = 0.4. From Eq. ,

$$s_m = \pm \frac{R_r'}{\sqrt{R_s^2 + (X_s + X_r')^2}}$$

- when Rs is negligible, rotor resistance required to start the motor in minimum time is

$$(R_{rm}')_s = 0.4\,(X_s + X_r')$$

- Time required for stopping by plugging, when initially running at synchronous speed, can be expressed as

$$t_b = -\frac{\tau_m}{2}\int_2^1 \left(\frac{s}{s_m} + \frac{s_m}{s}\right) ds = \tau_m\left[0.345\, s_m + \frac{0.75}{s_m}\right]$$

- Stopping time is again a function of s_m. It has a minimum value of $1.027\tau_m$ at s_m = 1.47. Corresponding value of rotor resistance is

$$(R_{rm}')_b = 1.47\,(X_s + X_r')$$

- Time required for speed reversal by plugging when running on no load is given by

$$t_r = -\frac{\tau_m}{2}\int_2^{0.05} \left(\frac{s}{s_m} + \frac{s_m}{s}\right) ds = \tau_m\left[3.69\, s_m + \frac{1}{s_m}\right]$$

- Minimum time for reversal is thus $2.88\tau_m$ and corresponding value of s_m is 0.52. Rotor resistance required for speed reversal by plugging in minimum time is

$$(R_{rm}')_r = 0.52\,(X_s + X_r')$$

Calculation of Energy Losses

Let us next obtain expressions for energy loss in motor windings for starting and plugging operations. The rotor winding loss for starting can be written as

$$E_{sr} = \int_0^{t_s} 3 I_r'^2 R_r' dt$$

As the machine is operating under no load

$$J\frac{d\omega_m}{dt} = T$$

$$E_{sr} = \int_0^{t_s} \omega_{ms} T s dt$$

$$-J\omega_{ms}\frac{ds}{dt} = T$$

$$Tdt = -J\omega_{ms}ds$$

$$E_{sr} = -\int_1^0 J\omega_{ms}^2 s ds = \frac{1}{2}J\omega_{ms}^2$$

- Rotor winding energy loss is equal to the kinetic energy stored in moving parts at completion of the starting process, and it is independent of the starting time or rotor resistance.
- Energy loss in stator winding, neglecting magnetizing current is
- Total winding loss during starting under no load is

$$E_{ss} = \int_0^{t_s} I_r'^2 R_s dt$$

$$= \frac{1}{2}J\omega_{ms}^2\left(\frac{R_s}{R_r'}\right)$$

$$E_s = \frac{1}{2}J\omega_{ms}^2\left(1 + \frac{R_s}{R_r'}\right)$$

- Rotor winding loss during stopping by plugging under no load can be written as

$$E_{sr} = \int_2^1 J\omega_{ms}^2 s\, ds = \frac{3}{2}J\omega_{ms}^2$$

- Rotor winding loss can be reduced when started by using methods based on the variation of synchronous speed.
- As an example let us consider a motor with an arrangement for doubling the pole number.
- Let it be started with higher pole number for which the synchronous speed is ωms/2.
- Then, from eq, rotor copper loss for change of speed from 0 to ωms/2 will be Jω2ms/8.
- Now the pole number is lowered. Consequently, rotor copper loss for speed range ωms/2 to ωms will be

$$E_{sr}' = \int_{0.5}^0 J\omega_{ms}^2 s\, ds = \frac{J\omega_{ms}^2}{8}$$

- Thus, total rotor winding loss is $J\omega^2_{ms}/4$, which is one-half of the copper loss when there is no provision for doubling the pole number.

Speed control of Induction Motor

The conventional methods of speed control of induction motors are,

Stator Side

- **Stator voltage control**
- **Variable frequency control**
- Stator current control
- V/f control
- Changing the number of poles on stator

Rotor Side

- Rotor resistance control
- Injecting emf in the rotor

Stator Voltage Control of Induction Motor

- Speed of induction motor can be varied by varying the voltage applied to the stator winding.
- Torque developed by 3 phase induction motor is directly proportional to the square of the stator voltage as given by the equation

$$T_m = \frac{3}{2\pi N_s} \times \frac{S.E_2^2.R_2}{R_2^2 + (S.X_2)^2} \text{-------} 1 \quad \longrightarrow \quad N_s = \frac{3}{2\pi T_m} \times \frac{S.E_2^2.R_2}{R_2^2 + (S.X_2)^2} \text{------} 2$$

(S.X2)² is very small as compared to R2

$$T_m \propto \frac{S.E_2^2}{R_2}$$

R2 is constant

$$T_m \propto S.E_2^2$$

E2 is proportional to the supply voltage V1

$$T_m \propto S.V_1^2 \text{-------} 3$$

Current is proportional to voltage

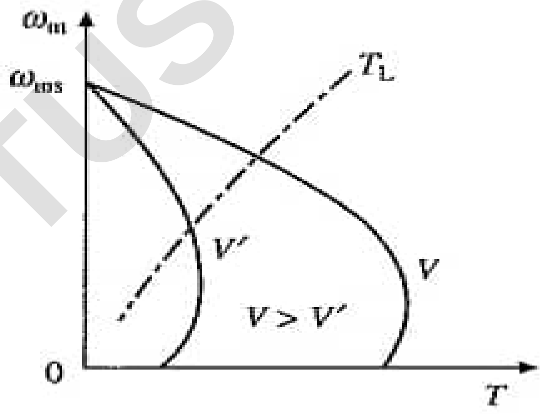
$$\bar{I}_r' = \frac{V}{\left(R_s + \frac{R_r'}{s}\right) + j(X_s + X_r')}$$

- From eqn. 2, it is clear that any reduction in supply voltage will reduce the motor speed.
- But from equation 3, it is seen that any reduction in supply voltage will reduce the torque also.

- Therefore, as voltage is reduced to reduce speed, for the same current motor develops lower torque.
- This method is suitable for applications where torque demand reduces with speed, such as for fan and pump drives.
- Hence this method is used in applications where torque demand reduces with reduction in voltage.
- Here the slip increases at low speeds. Hence the efficiency of the drive reduces
- If stator copper loss, core loss, and friction and windage loss are ignored, then from eqns , motor efficiency η is given by

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

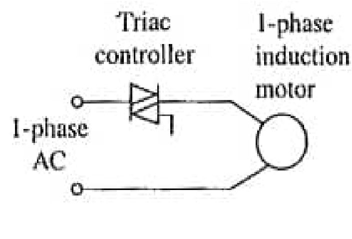
- The equation shows that the efficiency falls with decrease in speed
- The speed control is essentially obtained by dissipating a portion of rotor input power in rotor resistance.
- Thus, not only the efficiency is low the power dissipation occurs in the rotor itself, which may overheat the rotor.
-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



Control by AC Voltage Controllers and Soft Start

Single-phase

Domestic fan motors, which are always single-phase, are controlled by a single-phase Triac Voltage Controller shown in Fig. a

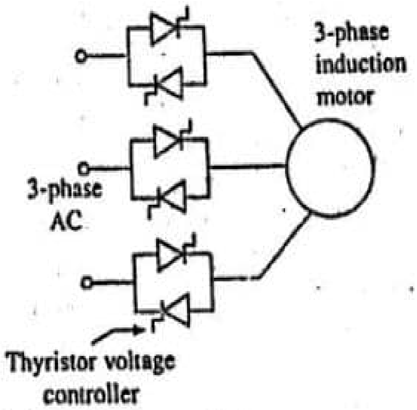


(a)

- Speed control is obtained by varying firing angle of the Triac.
- These controllers, commonly known as solid state fan regulators, are now preferred over conventional variable resistance regulators because of higher efficiency.

Three-phase motors.

Fig. Stator voltage control by semiconductor voltage Controller



(b)

- Industrial fans and pumps are usually driven by Three-phase motors.
- Fig.b shows thyristor voltage controller for speed control of 3-phase motors.
- Motor may be connected in star or delta. In delta connection, third harmonic voltage produced by motor back emf causes circulating current through the windings which increases losses and thermal loading of motor.
- Speed control is obtained by varying conduction period of thyristors.
- For low power ratings, anti-paralleled thyristor pair in each phase can be replaced by a triac.

Variable Frequency Control From Voltage sources

i. **Variable Frequency Control of an Induction Motor**

ii. **Slip Speed Control**

iii. **Torque and Power Limitations, and Modes of Operation**

i. Variable Frequency Control of an Induction Motor

- 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.
- Increase in flux will saturate the motor, which increases the magnetizing current, distort the line current and voltage, increase the core loss and the stator copper loss, and produce a high-pitch acoustic noise.
- Increase in flux beyond the rated value is undesirable from the consideration of saturation effects, a decrease in flux is also avoided to retain the torque capability of the motor.
- Therefore, the **variable frequency control** below the rated frequency is carried out at rated air-gap flux by varying terminal voltage with frequency so as to maintain (V/f) ratio constant at the rated value.
- From Torque Equation

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

- The maximum torque in an induction motor is given by,

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

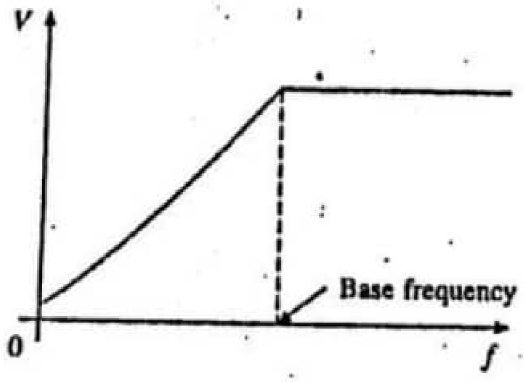
K is a constant and Ls & Lr' are the stator and stator referred rotor inductances.
+ve: For Motoring
-ve: Braking

- At high frequencies, the value of (Rs/f) will be very much less than 2π (Ls+ Lr').
- So (Rs / f) can be neglected and hence the torque equation becomes

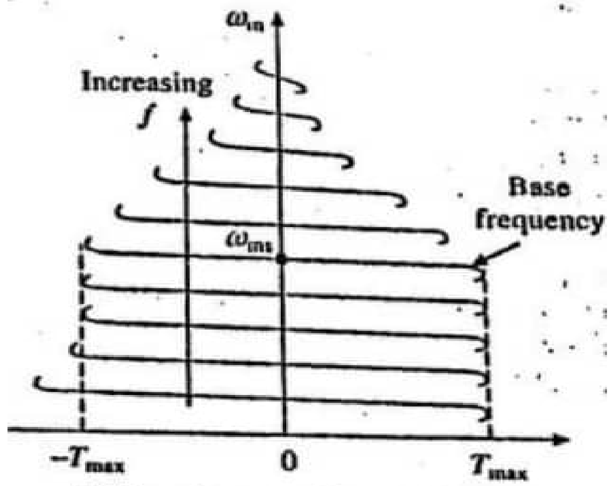
$$T_{max} = \pm \frac{K(V/f)^2}{\sqrt{[4\pi^2(L_s + L_r')^2]}}$$

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

- From above equation, if the ratio (V / f) is kept constant, the motor can produce a constant maximum torque, Tmax. i.e constant torque operation.
- Hence if maximum torque needs to be maintained constant at low speeds, then (V / f) ratio must be increased.
- Near to base speed (or rated speed), the supply voltage will be maximum and it cannot be increased further.
- Therefore, above base speed, the frequency is changed by keeping supply voltage constant.
- But this will decrease the maximum torque produced by the motor as per the equation
- Variation in terminal voltage with frequency is shown in Fig.a.
- (V/f) ratio is increased at low frequency to keep maximum torque constant, which leads to increase in maximum braking torque.
- Above base speed, frequency is changed with V kept constant.
- up to base frequency- (V/f) ratio is kept constant.
- above base frequency- V is kept constant and frequency is varied
- At low frequencies - (V/f) ratio is Increased to keep maximum torque constant.
- Corresponding speed torque curves are shown in Fig. 6.33(b) both for motoring and braking operations.
- The curves suggest that speed control and braking operation are available from nearly zero speed to above synchronous speed.



(a) V-f relation



(b) Speed-torque characteristics

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

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

(b) During transients(starting, braking and speed reversal) the operation can be-carried out at the maximum torque with reduced current giving good dynamic response.

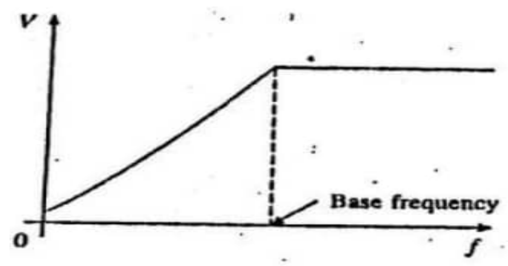
(c) Copper losses are low, and efficiency and power factor are high as the operation is restricted between synchronous speed and maximum torque point at all frequencies.

(d) Drop in speed from no load to full load is small.

Variable Frequency Variable Voltage Source (VFVS).

Block diagram of variable frequency speed control scheme is shown in Fig. The motor is fed from a variable frequency variable voltage source (VFVS).

- V* and f* are voltage and frequency commands for VFVS.
- Flux control block produces a voltage command V* for VFVS in order to maintain the relation between V* and f* as per the v-f Graph.
- Reference frequency f* is changed to control speed.
- A delay circuit is introduced between f* and f', so that even when is changed by a large amount, f* will change only slowly so that motor speed can track changes in f*.
- Thus restricting the motor operation for each frequency between synchronous speed and the maximum torque point.
- VFVS can be a voltage source inverter or a cycloconverter.



(a) V-f relation

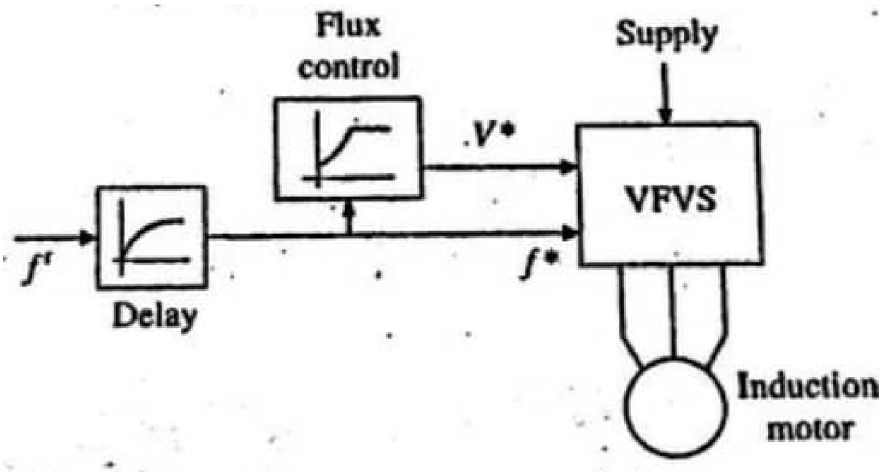


Fig. 6.34 Variable frequency control

ii. Slip Speed Control

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

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

- If (ks) is maintained constant as k is varied, then rotor current I′r and torque T will remain constant.
- Since the slip is small I′r will be in phase with voltage. Since flux is constant Im will also be constant. Now

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

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

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

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

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

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

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

Where ω_{s1} is the slip speed, which is the difference in the rotating field speed $k\omega_{ms}$ and rotor speed ω_m.

- It is also the drop in motor speed from its no load speed, when the machine is loaded.
- Operation of the machine at a constant slip speed also implies the operation at a constant rotor frequency as shown below

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

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

For $s < s_m$, $(R'_r/ks) >> (X_s + X'_r)$,

$$T = \frac{3}{\omega_{ms}}\left[\frac{V^2 R'_r/ks}{(R'_r/ks)^2 + (X_s + X'_r)^2}\right] \Rightarrow T = \frac{3V^2}{R'_r\omega_{ms}}(ks) = \text{constant} \cdot \omega_{sl}$$

For $s < s_m$, the speed torque curves are nearly straight lines. Since they are also parallel, the speed-torque curves are approximately parallel straight lines for $s < s_m$.

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

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

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

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

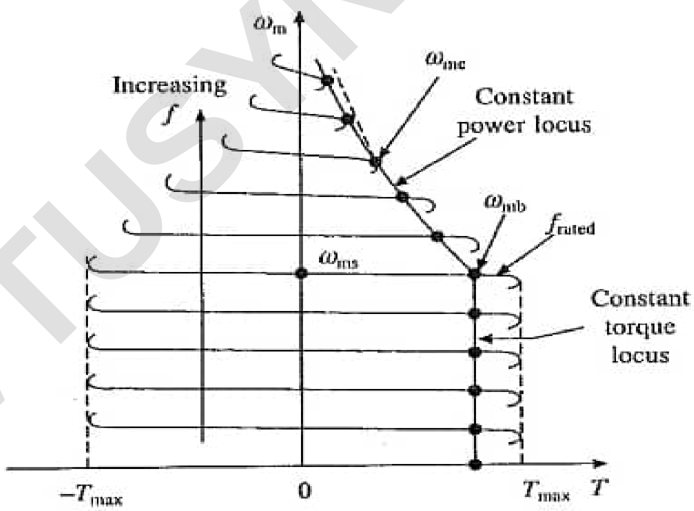
$$(k\omega_{ms} - \omega_m) = \omega_{sl} = \frac{R'_r}{V}\omega_{ms}(kI'_r)$$

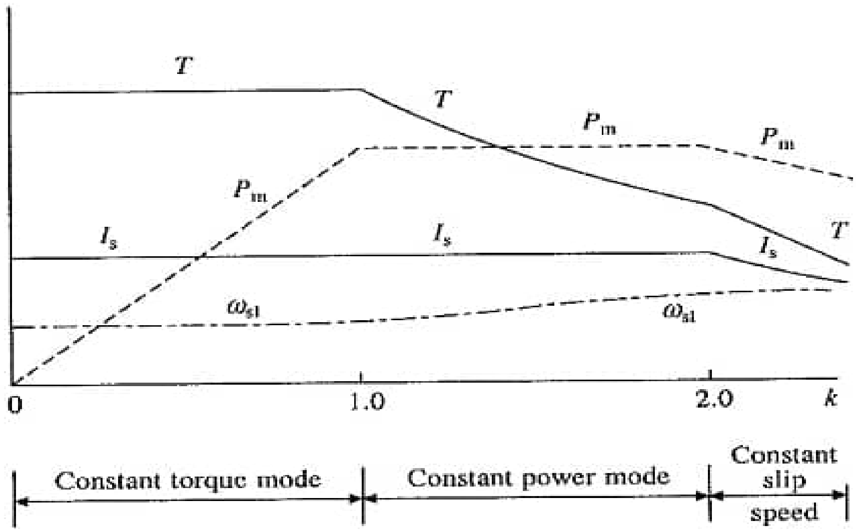
- Since the slip is small, I'_r is in phase with V. If the machine copper loss is neglected, the developed power P_m is given by

$$P_m = 3VI'_r$$

iii. Torque and Power Limitations, and Modes of Operation

- When the stator current has the maximum permissible value, these will represent the maximum torque and power capabilities of the motor in Variable Frequency Control of Induction Motor Drive.
- Zero to base speed ω_{mb} : The motor has a constant maximum torque, hence the drive operates in constant torque mode.
- Beyond the speed ω_{mc} :The machine is operated at a constant slip speed and the maximum permissible current and maximum power are allowed to decrease.
- Now the motor current reduces inversely with speed and torque decreases inversely as the speed squared.
- The operation in this region is required in drives requiring wide speed range but low torque at high speeds.
- For example in traction applications the drive operates in this region when running at full speed because the torque required in steady state at high speeds is very small compared to its value during acceleration.





Module-4

Induction Motor Drives cntd.

Synchronous Motors

Syllabus

Induction Motor Drives (continued):

- Voltage Source Inverter (VSI) Control
- Cycloconverter Control
- Closed Loop Speed Control Converter Rating for VSI Cycloconverter Induction Motor Drives
- Variable Frequency Control from a Current Source
- Current Source Inverter (CSI) Control
- Current regulated voltage source inverter control
- Speed control of single phase induction motors.

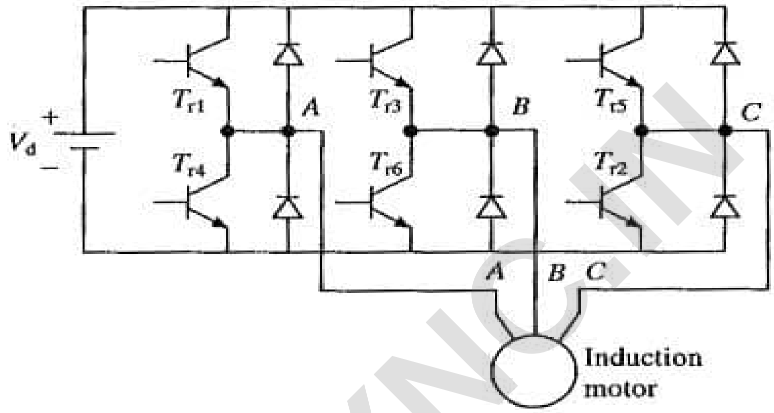
Synchronous Motor Drives:

- Operation from fixed frequency supply-starting
- Synchronous motor variable speed drives
- Variable frequency control of multiple synchronous motors

Induction Motor Drives cntd.

Voltage Source Inverter Control (VSI)

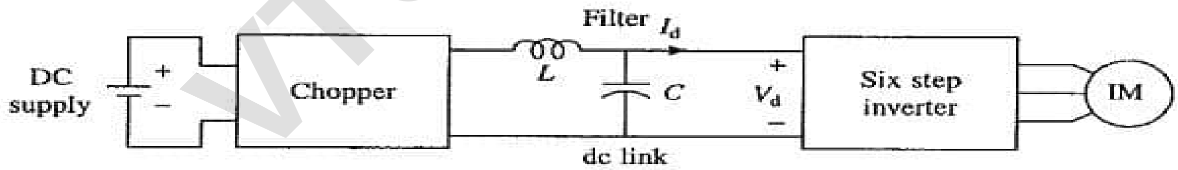
- A VSI converts the input dc voltage into an variable frequency ac voltage.
- VSI using normal transistors is shown in below Fig.
- In voltage source inverters, the input voltage is kept constant.
- The magnitude of output voltage of VSI is independent of the load.
- But the magnitude of output current depends on the type of load.



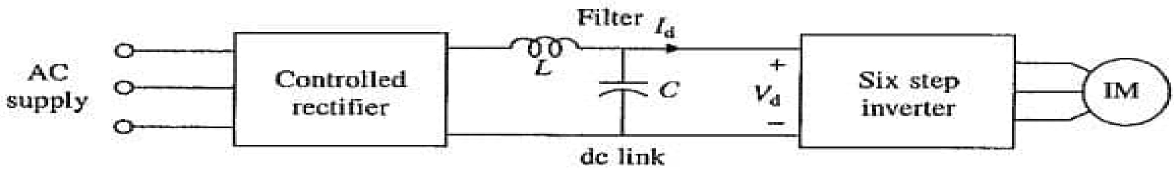
(a) Transistor inverter-fed induction motor drive

Any other self commutated device can be used in place of transistors such as

- ✓ MOSFET is used in low voltage and low power inverters.
- ✓ IGBTs and power transistors are used up to medium power levels.
- ✓ GTO and IGCT are used for high power levels.

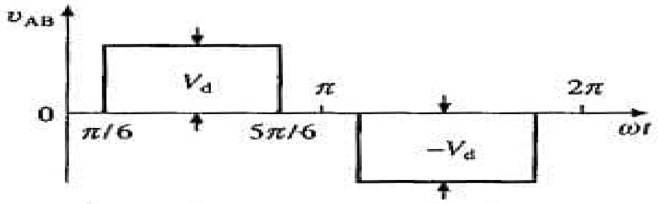


(a)



(b)

The output voltage waveform of a six step inverter is shown in below Fig.



(b) Stepped wave inverter line voltage waveform

VSI can be operated as a **stepped wave inverter** or a **PWM inverter.**

Stepped wave inverter:

- When VSI is operated as a **six step inverter**, the transistors are turned ON in the sequence of their numbers with a time interval of T/6 seconds if T is the total time period of one output cycle.
- Frequency of the inverter output is varied by varying the time period (T) of one cycle .
- If the **supply is dc**, then a variable dc voltage is obtained by connecting a **chopper** between input dc and the inverter as shown in below Fig. a
- If the input **supply is ac**, then a variable dc is obtained by connecting a controlled **rectifier** between the input ac and the inverter as shown in below Fig. b.
- A large electrotytic 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.

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

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

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

The rms value of the fundamental phase voltage

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

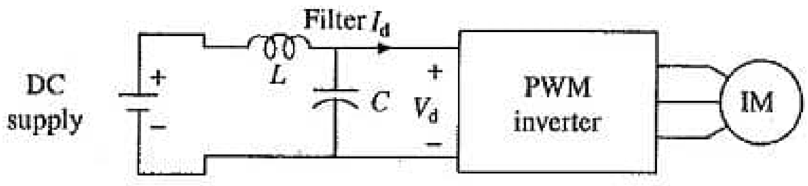
Disadvantages of six step inverter

- Low frequency harmonics are more and hence the motor losses are increased at all speeds.
- Motor develops pulsating torques due to 5th, 7th, 11th and 13th harmonics.
- Harmonic content increases at low speeds. This will overheat the machine.

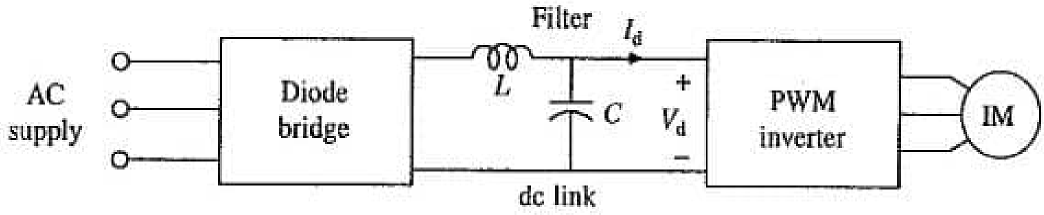
PWM inverter:

The above said problems are rectified when a PWM inverter is used.

- If a PWM inverter is used as VSI as shown in below Fig c & d, Where the harmonics are reduced, low frequency harmonics are eliminated, losses are reduced and smooth motion is obtained at low speeds
- when inverter is operated as a pulse width, then the input voltage may be a constant dc which is obtained from a simple diode rectifier.
- The output of a PWM inverter is a variable voltage and variable frequency.



(c)



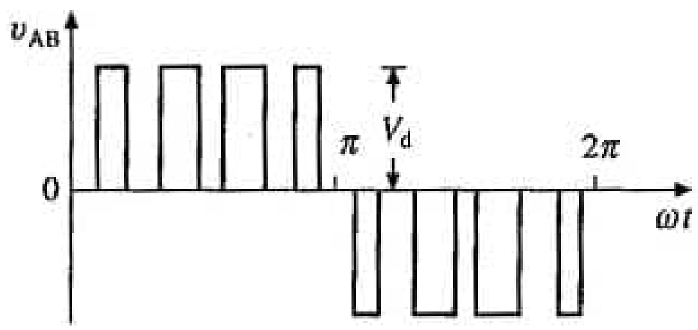
(d)

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

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

Where m- modulation index

- When supply is dc: Inverter can be directly connected
- When supply is ac: Inverter is connected through Diode rectifier.
- The harmonics in the motor current produce torque pulsation and derate the motor.
- For a given harmonic content in motor terminal voltage, the current harmonics are reduced when the motor has higher leakage inductance, this reduces derating and torque pulsations.
- Therefore, when fed from VSI, Induction Motor with **large** (compared to when fed from sinusoidal supply) **leakage inductance are used**



(c) PWM inverter line voltage waveform

Braking and Multi-quadrant Operation of VSI Induction Motor Drives

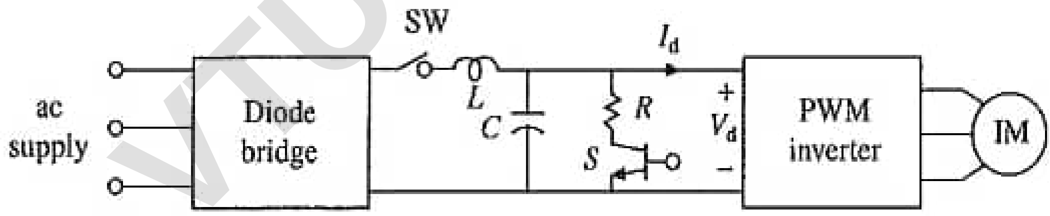
- The power input into the motor is given by $P_{in} = 3VI_s \cos\phi$

Where,

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

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

Dynamic Braking



- Generated energy flowing into the dc link charges the capacitor and its voltages rises.
- When it crosses a set value, switch S is closed, connecting the resistance across the link.
- The generated power and a part of energy stored in the capacitor flow into the resistance, and dc link voltage reduces.
- When it falls to its nominal value, S is opened.
- Thus by closing and opening switch S based on the value of dc link voltage, generated energy is dissipated in the resistance, giving **dynamic braking**.

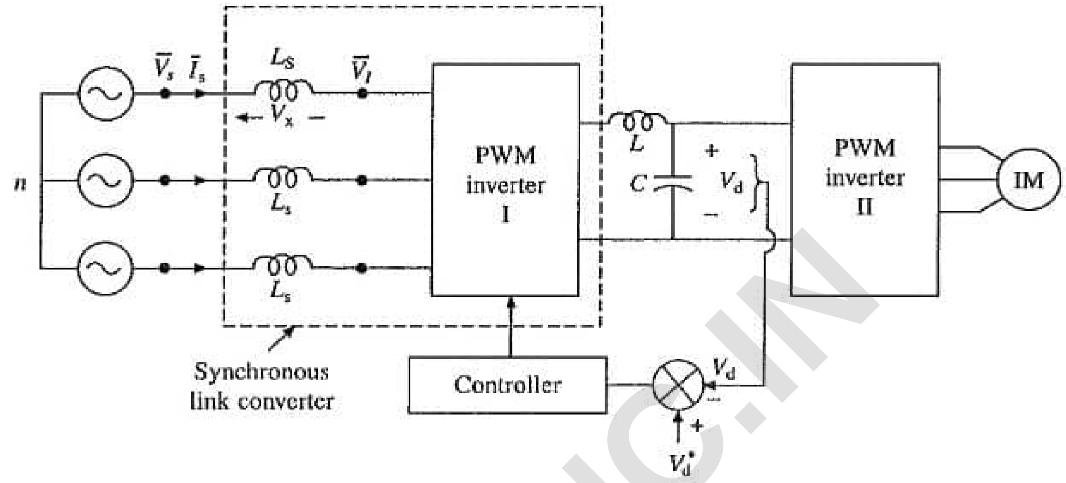
Regenerative Braking

When the operation shifts from motoring to braking I_d reverses but V_d remains in the same direction.

For regenerative braking, a converter with dc voltage of one polarity and dc current of either direction is required.

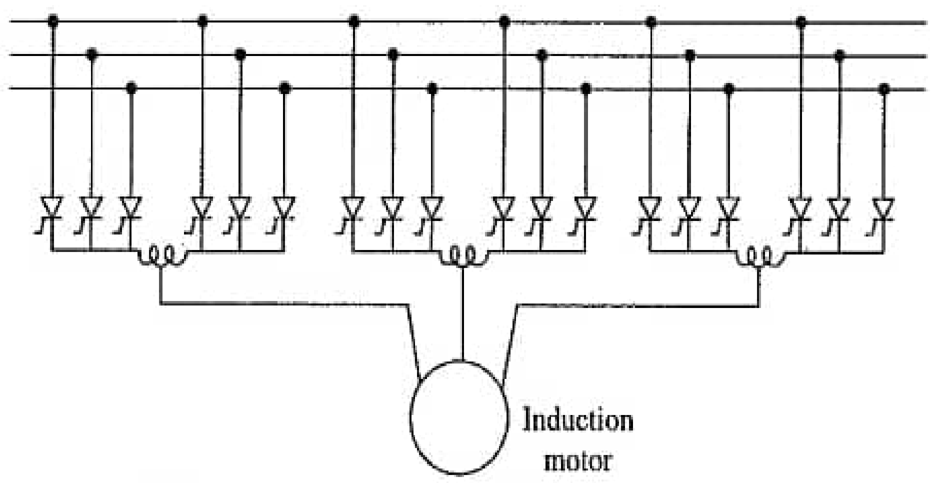
A dual converter with this feature is conventionally used.

The recent drives use synchronous link converter (SLC) because it takes sinusoidal current at unity power factor from the ac source, both during motoring and braking operations.



- A regenerative drive with a SLC and PWM inverter is shown in Fig.
- The inductors Ls and PWM inverter I constitute a SLC.
- PWM inverter I is operated to produce voltage VI of required magnitude and phase and with a low harmonic content, so that source current Is is nearly sinusoidal and in phase with Vs for motoring and 180° out of phase for braking, thus giving unity power factor.

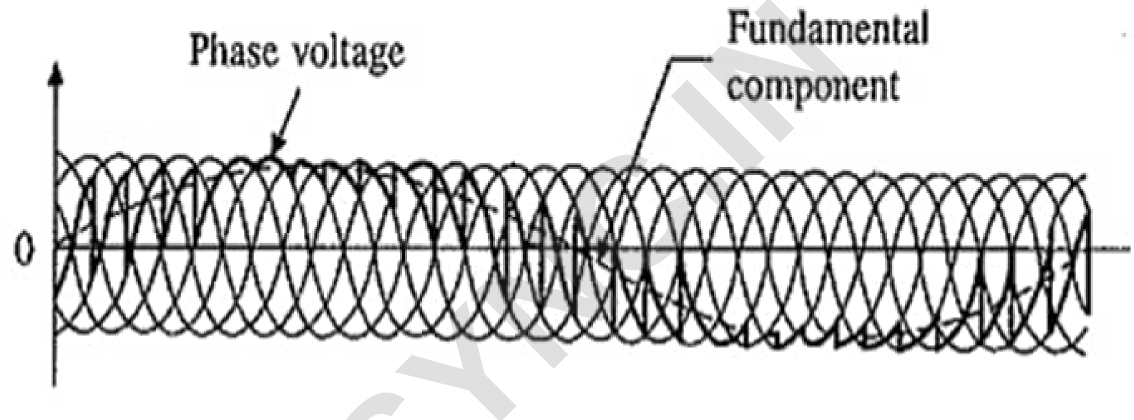
Cycloconverter Control of Induction Motor



(a) Half wave cycloconverter-fed induction motor

- Cycloconverter Control of Induction Motor allows variable frequency and variable voltage supply to be obtained from a fixed voltage and frequency ac supply.

- Half-wave Cycloconverter Control of Induction Motor and its output voltage waveform is shown in Fig.
- Because of low harmonic content when operating at low frequencies, smooth motion is obtained at low speeds.
- Harmonic content increases with 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.



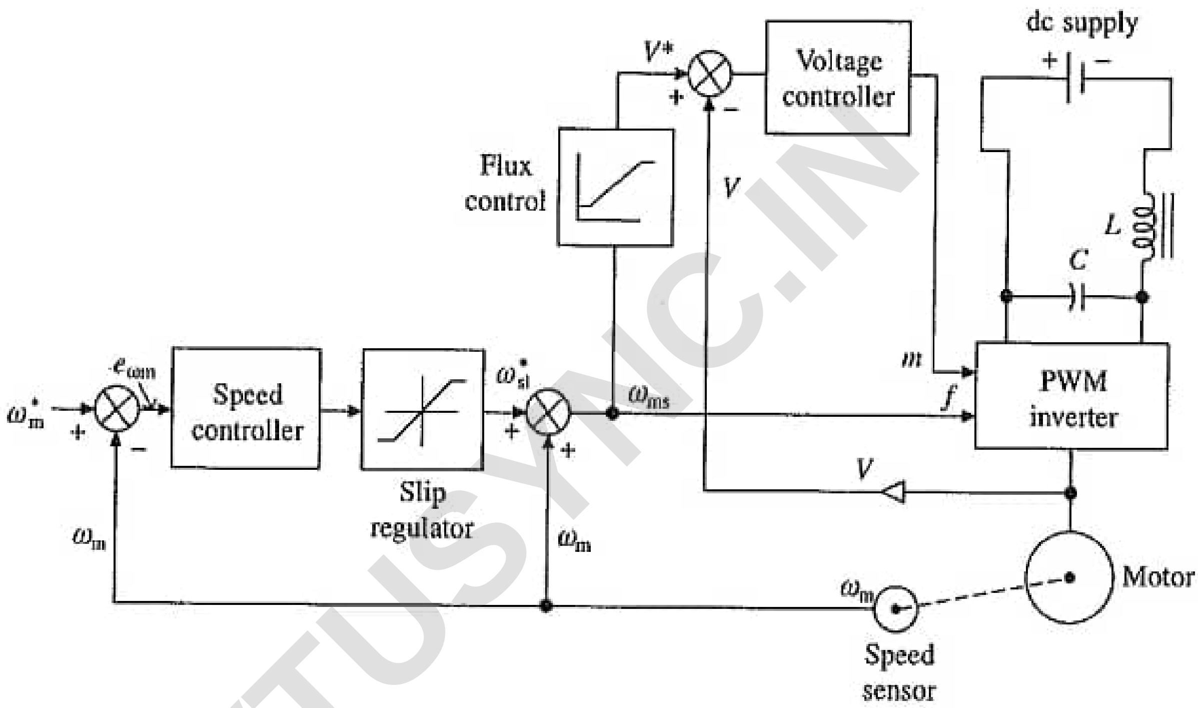
(b) Phase voltage waveform

- Since cycloconverter employs large number of thyristors, economically suitable only for large power drives, requiring good dynamic response but only low speed operation.
- The low speed operation is obtained by feeding a motor with large number of poles from a Cycloconverter Control of Induction Motor operating at low frequencies.
- These drives are called gearless drives because, the low speed operation of load is obtained without a reduction gear, thus eliminating the associated cost, space and maintenance.

Closed Loop Speed Control of Induction Motor Drives

- A Closed Loop Speed Control of Induction Motor Drives is shown in Fig. It employs inner slip-speed loop with a slip limiter and outer speed loop.
- Here, the Slip speed has a fixed value, the slip speed loop also functions as an inner current loop.

- Here, the motor operation always occurs on the portion of speed-torque curve between synchronous speed and the speed at the maximum torque for all frequencies, resulting in high torque to current ratio.
- The drive uses a PWM inverter fed from a dc source, which has capability for regenerative braking and four-quadrant operation.
- The drive scheme is applicable to any VSI or cycloconverter drive having regenerative or dynamic braking capability.



- The speed error is processed through a PI controller and a slip regulator.
- PI controller is used to get good steady-state accuracy, and to attenuate noise.
- The slip regulator sets the slip speed command ωs1*, whose maximum value is limited to limit the inverter current to a permissible value.
- The synchronous speed, obtained by adding actual speed ωm and slip speed ωs1*, determines the inverter frequency.
- The reference signal for the Closed Loop Speed Control of Induction Motor Drives of the machine terminal voltage V* is generated from frequency f using a function generator.
- It gives constant flux - up to base speed ; constant terminal voltage - above base speed.
- A step increase in speed command ωm* produces a positive speed error. The slip speed command ωs1* is set at the maximum value.
- The drive accelerates at the maximum inverter current, producing maximum torque, until the speed error is reduced to a small value.

- The drive finally settles at a slip speed for which the motor torque balances the load torque.
- The drive decelerates under regenerative braking, at the maximum current and the maximum braking torque, until the speed error is reduced to a small value.
- Now the operation shifts to motoring and the drive settles at the slip speed for which the motor torque equals the load torque.

Variable Frequency Control From Current Source

- Consider the motor control by **Variable Frequency Control From Current Source (VFCS).**
- An equivalent circuit for motor fed from a current source is obtained when voltage source V is replaced by a current source Is.

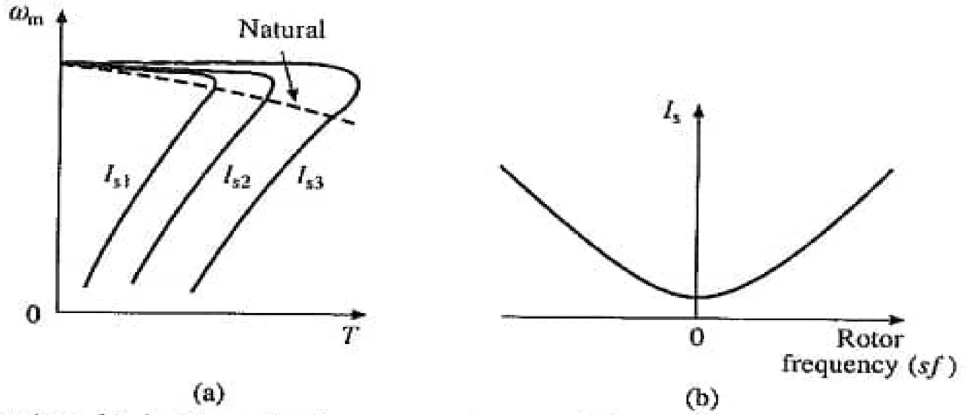
$$I_r' = \frac{X_m I_s}{\sqrt{(R_r'/s)^2 + (X_m + X_r')^2}}$$

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

$$I_m^2 = \left[\frac{(R_r'/s)^2 + X_r'^2}{(R_r'/s)^2 + (X_m + X_r')^2} \right] I_s^2$$

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

- Motor speed-torque curves for various values of Is and natural speed-torque curve, at rated constant flux is shown.
- For a given Is, motor operates above the natural characteristic- for a flux higher than rated ; motor operates below the natural characteristic – at less than rated flux.
- Since rated flux operation is preferred, the natural characteristic is locus of preferred, operating points.
- Fig (b) shows stator current Is and rotor frequency (sf), when frequency is changed to control the speed.
- When operating at a constant flux, the operating points are located mostly on the part of speed torque curve, which gives unstable operation with most loads.

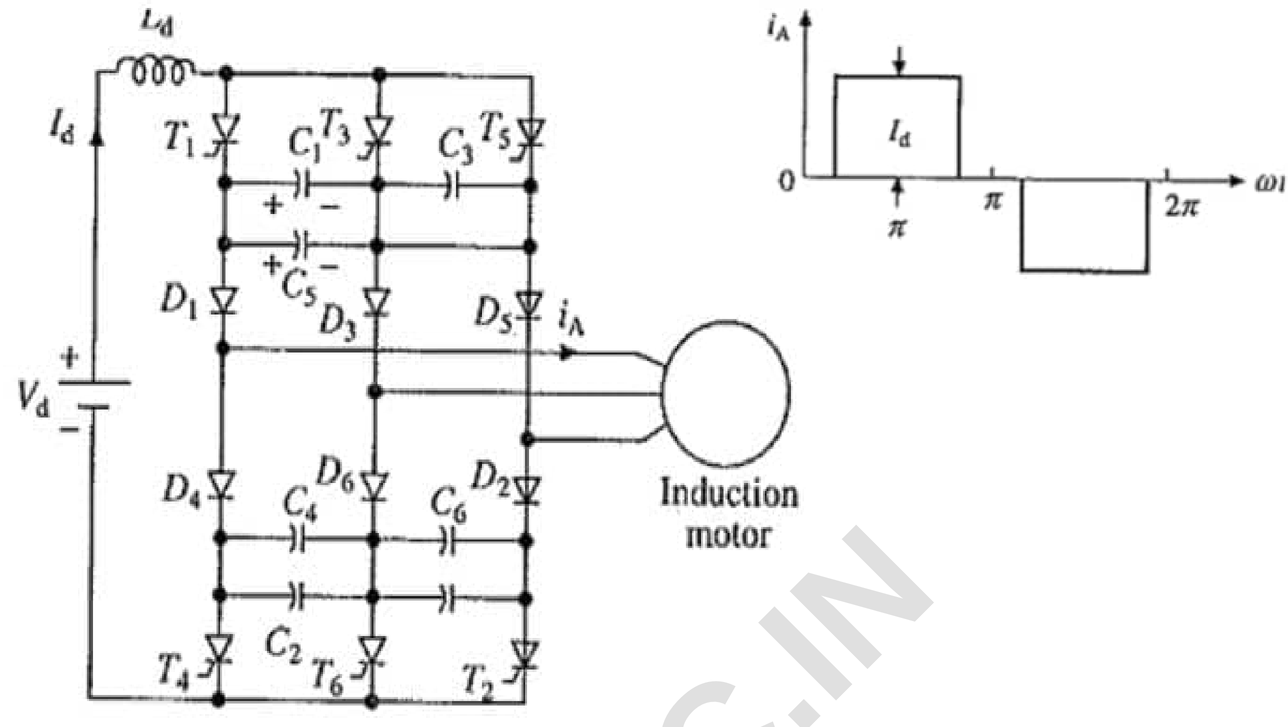


Operation of induction motor from a current source: (a) speed torque curves; (b) I_s vs sf curves

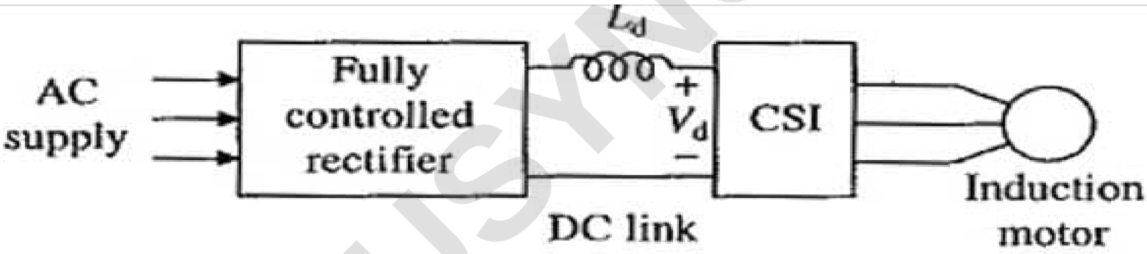
- Hence, closed loop control is mandatory. Since motor is constraint to operate at constant flux, its steady-state behavior is identical to that with VFVS.
- Thus at a given slip speed (or rotor frequency), the motor draws a constant current and develops a constant torque at all frequency.
- The motor, therefore, operates in constant torque mode from zero to base speed. At base speed, either rated machine voltage is reached or VFCS voltage saturates.
- In either case machine operates at a constant terminal voltage above base speed, providing constant power mode.
- Variable frequency current supply is provided by a Variable Frequency Control From Current Source inverter.

Current Source Inverter Control of Induction Motor

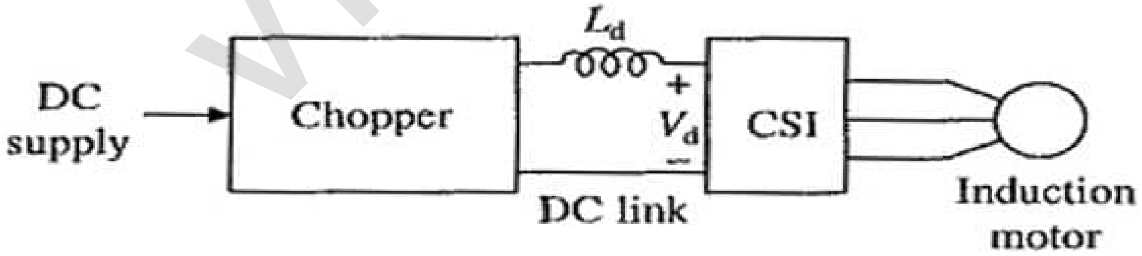
- A thyristor Current Source Inverter Control of Induction Motor (CSI) is shown in Fig.
- Diodes D1-D6 and capacitors C1-C6 provide commutation of thyristors T1-T6, which are fired with a phase difference of 60° in sequence of their numbers.
- It also shows the nature of output current waveforms.
- Inverter behaves as a current source due to the presence of large inductance Ld in dc link.
- The fundamental component of motor phase current from Fig. is
- For a given speed, torque is controlled by varying dc link current I_d by changing the value of V_d.
- Therefore, when supply is ac, a controlled rectifier is connected between the supply and inverter and when supply is dc, a chopper is interposed between the supply and inverter.
- The maximum value of dc output voltage of fully-controlled rectifier and chopper are chosen so that the motor terminal voltage saturates at rated value.



(a)



(a)



(b)

- The major advantage of Current Source Inverter Control of Induction Motor is its reliability.
- In **case of VSI** , a commutation failure will cause two devices in the same leg (e.g. T_{r1} and T_{r4}) to conduct. This connects conducting devices directly across the source. So, current through devices suddenly rises to dangerous values. Hence, Expensive high speed semiconductor fuses are required to protect the devices.
- In **case of CSI,** conduction of two devices in the same leg does not lead to sudden rise of current through them due to the presence of a large inductance L_d.

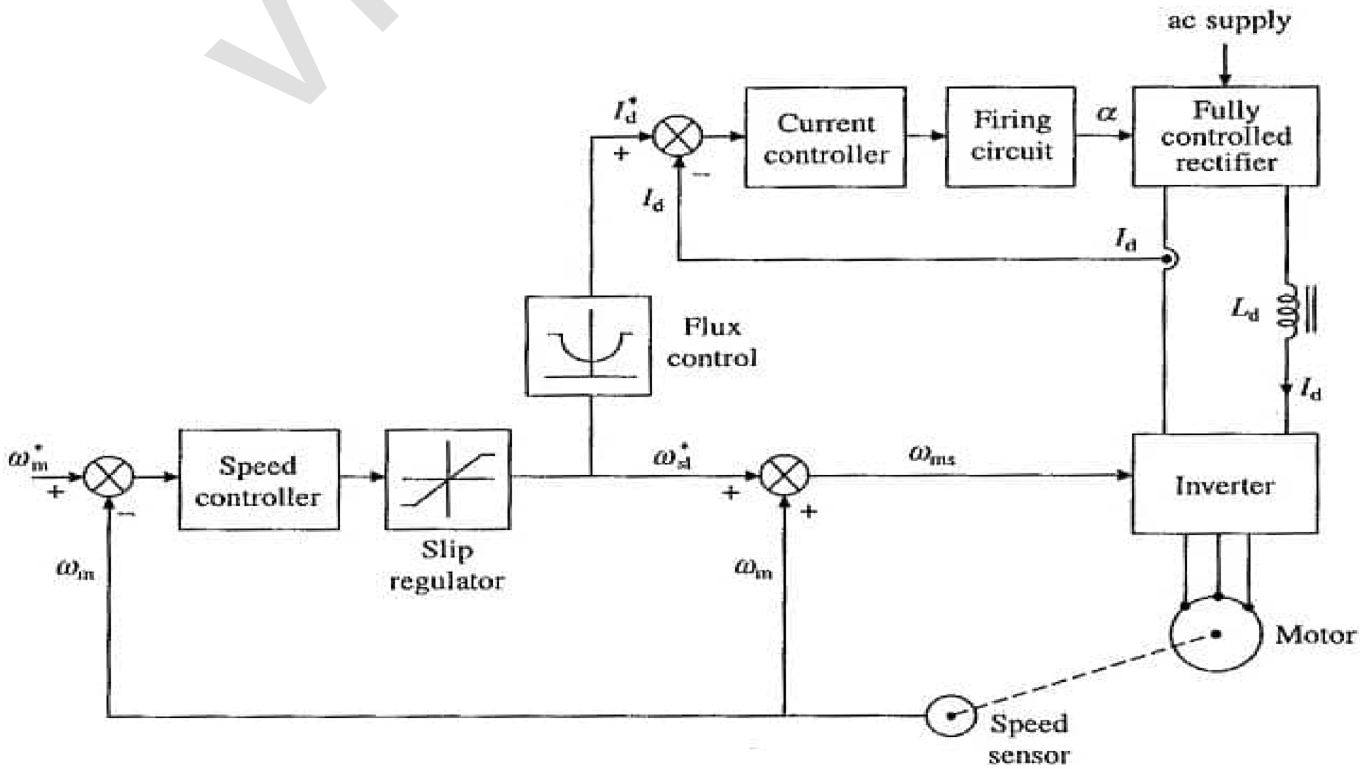
- This allows time for commutation to take place and normal operation to get restored in subsequent cycles. Further, less expensive HRC fuses are good enough for protection of thyristors.

Regenerative Braking and Multiquadrant Operation:

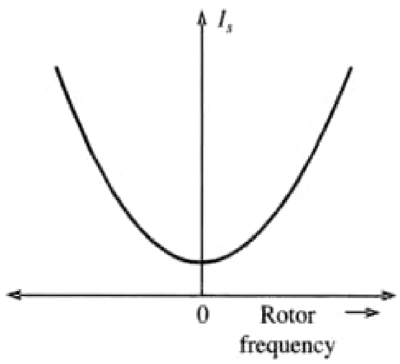
Refer the same fig a and b:

- When inverter frequency is reduced to make synchronous speed less than motor speed, machine works as a generator.
- Power flows from machine to dc link and dc link voltage Vd (Fig.) reverses.
- If fully-controlled converter of Fig. (a) is made to work as an inverter, the power supplied to dc link will be transferred to ac supply and regenerative braking will take place.
- Thus, no additional equipment is required for regenerative braking of CSI drive of Fig. (a).
- Change of phase sequence of Current Source Inverter Control of Induction Motor will provide motoring and braking operations in the reverse direction.
- The drive of Fig.(b) can have regenerative braking capability and four-quadrant operation if a two quadrant chopper providing current in one direction but voltage in either direction is used

Closed Loop Speed Control of CSI Drives



- A closed loop Current Source Inverter Control of Induction Motor drive is shown in Fig a)
- Actual speed ω_m is compared with the reference speed ω^*_m.
- The speed error is processed through a PI controller and slip regulator.
- The slip regulator sets the slip speed command ω^*_{s1}.
- The synchronous speed obtained by adding ω_m to ω^*_{s1}, determines the inverter frequency. Constant flux operation is obtained when slip speed ω_{s1} (or rotor frequency) and I_s have relationship as in fig b).
- Since Id is proportional to Is, as per eq. $I_s = \frac{\sqrt{6}}{\pi} I_d$
- A relation similar to Fig b) exists between ωs1 and Id for constant flux operation.
- Based on the value of ω^*_{s1}, the flux control block produces a reference current I^*_d, which through a closed-loop current control adjusts the dc link current Id to maintain a constant flux.
- The limit imposed on the output of the slip regulator, limits Id at the inverter rating.
- Therefore, any correction in speed error is carried out at the maximum permissible inverter current and maximum available torque, giving fast transient response and current protection.
- Beyond base speed, machine terminal voltage saturates .
- Flux control and closed-loop control of Id are made ineffective.
- To operate the drive up to rated inverter current, the slip speed limit of the slip regulator must increase linearly with frequency.
- This is realized by adding to the slip regulator output a signal proportional to frequency.

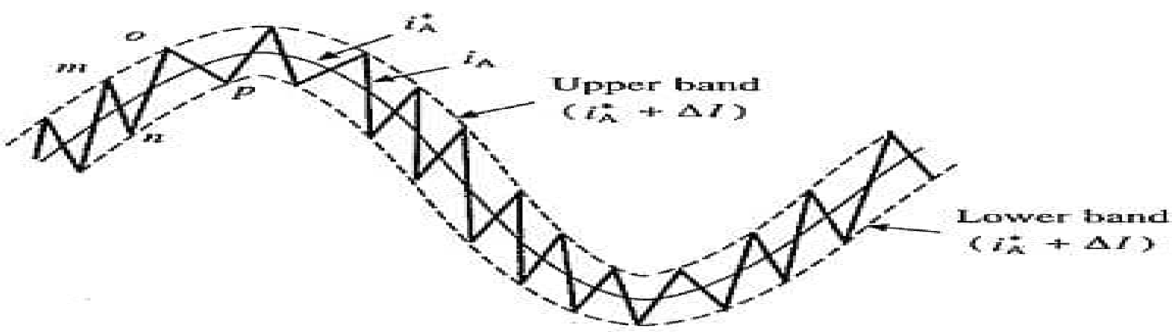


b)
Is Vs sf curve

Comparison of CSI (current source inverter)and VSI (drives voltage source inverter)

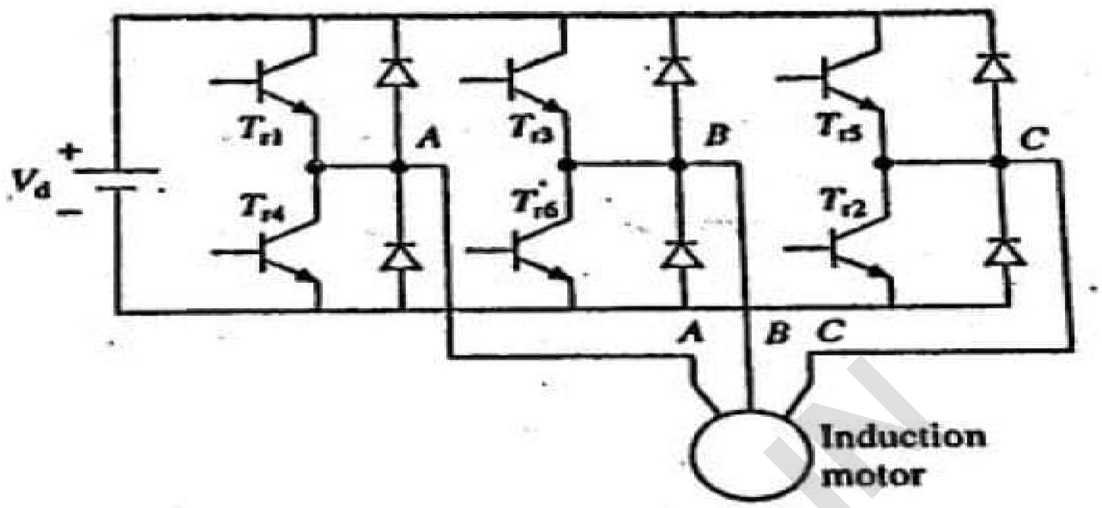
Current Source Inverter (CSI) drives	Voltage Source Inverter (VSI) drives
CSI is more reliable because conduction of two devices in the same leg does not short circuit the input supply.	Conduction of two devices in the same leg due to commutation failure causes short circuit of the input supply. This may raise the current through the devices and damage them.
Raise of current is prevented because of the presence of large inductance in the current source.	It requires expensive high speed semiconductor fuses for controlling the current due to short circuit.
Motor current rise and fall are very fast and that creates high voltage across windings.	No such problem arises here in case of VSI.
These high voltage spikes are controlled by having large values of commutating capacitors which may increase the cost and size of the inverter.	Less costly than CSI.
Slow response due to large value of input inductance.	Fast dynamic response is possible if VSI uses PWM inverter. If a six step inverter is used, then response becomes slower like CSI drives.
Frequency range of CSI is lower than VSI. Hence CSI drive has lower speed range.	Frequency range is wide and hence the speed range is also wide.
CSI requires a separate rectifier and inverter combination. Hence it is not suitable for multi motor drives.	A single rectifier can be used to feed many VSIs. Hence VSI is suitable for multi motor drives.
Regenerative braking is naturally possible in CSI.	An additional full converter is required to achieve regenerative braking.
If input AC supply fails, electric braking is not possible in CSI.	But VSI can use dynamic braking in case input AC supply fails.

Current Regulated Voltage Source Inverter



(a)

- 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



(a) Transistor inverter-fed induction motor drive

Above Fig. (a) shows a sinusoidal reference current $i^*_A = I_m \sin \omega t$.

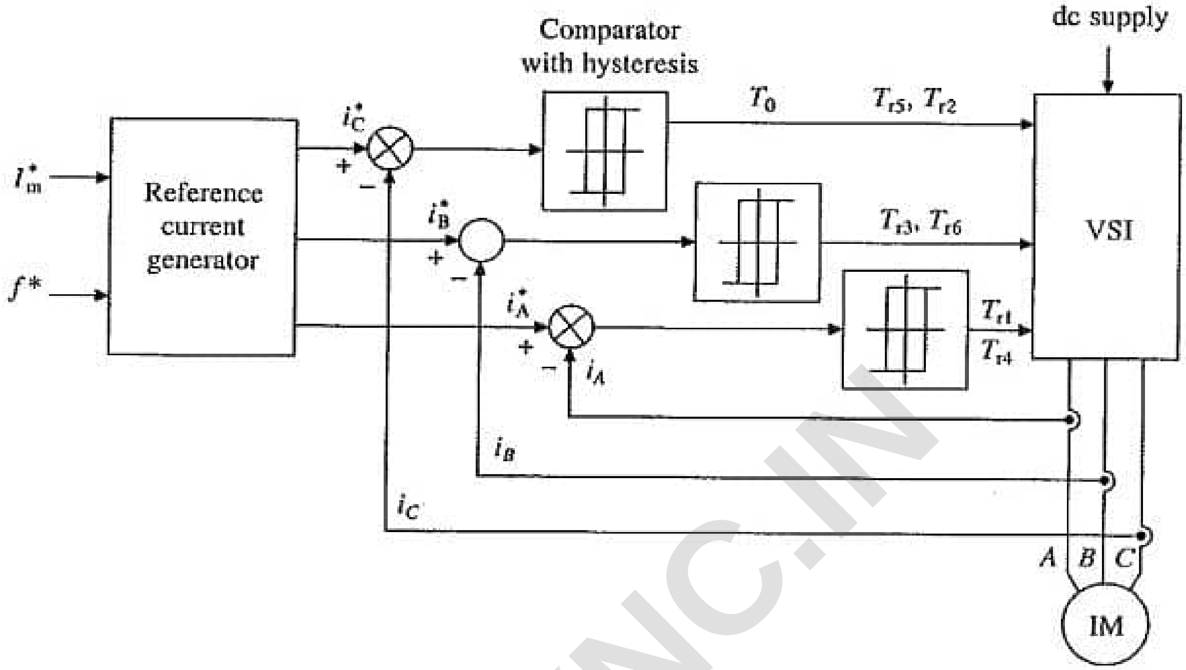
Here, two bands, separated from i^*_A by an amount ΔI.

- Switching in the inverter is carried out such that the actual motor current iA remains within these two bands.
- For this voltage source inverter Fig. (a1) is employed. In this inverter phase A current iA is shaped by transistors Tr1 and Tr4.
- When **<u>Tr1 is on</u>** (Tr4 is off), phase A is connected to the positive terminal of dc source, hence the rate of change of current iA will be positive
- When **<u>Tr4 is on</u>** (Tr1 is Off), phase A is connected, to negative terminal of the dc source, hence rate of change of current iA will be negative.

In Fig. (a):

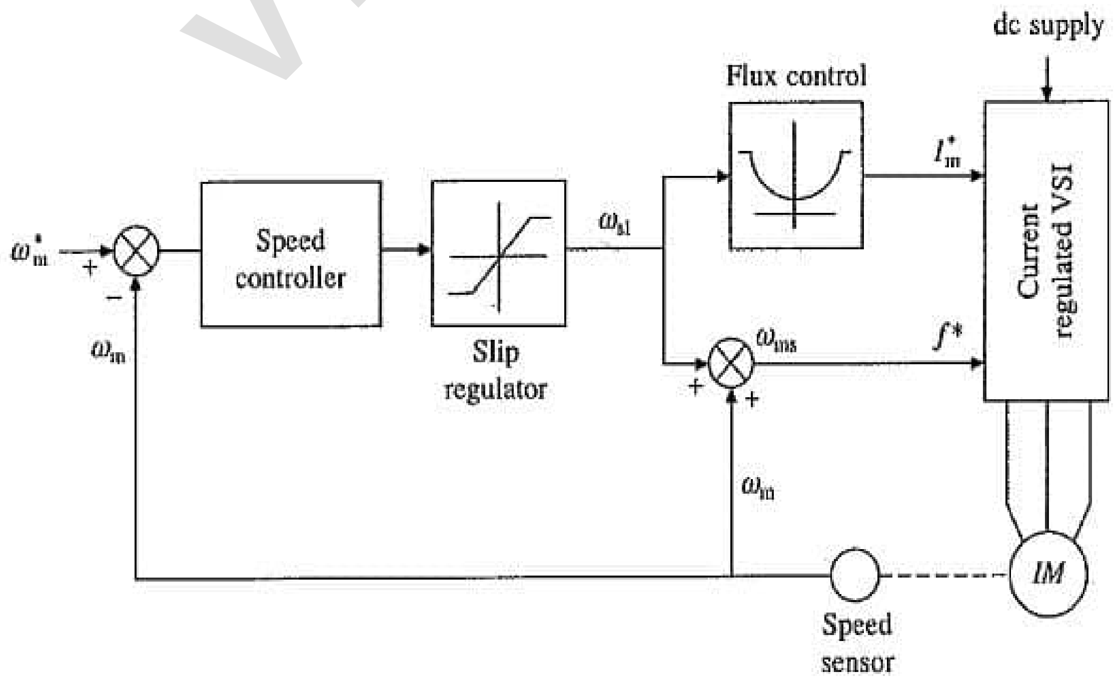
- current iA is falling along the path ‘mn’ when Tr4 is on.
- When iA reaches the lower band at ‘n’, Tr4 is turned off and Tr1 is turned on.
- This makes rate of change of IA to be **<u>positive</u>** and it rises along the path ‘no’.
- When iA reaches the upper band at ‘o’ , Tr1 is turned off and Tr4 is turned on.
- This makes rate of change of iA to be **<u>negative</u>** and it falls along ‘op’.
- This way actual current iA is constraint to remain within two hysteresis bands.
- Reference current for phases B and C are **: $i^*_B = I_m \sin(\omega t - 120°)$, $i^*_C = I_m \sin(\omega t - 240°)$** and by controlling respective transistors i_B and i_C are made to follow i^*_B and i^*_C within hysteresis bands.
- When the band is small, motor currents will be nearly sinusoidal.

- As the band reduces, harmonic content in phase currents reduces but switching frequency increases.
- Thus, inverter with fast switching devices will have lower harmonic content.



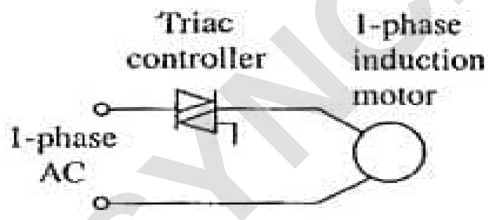
(b)

- Fig. (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.



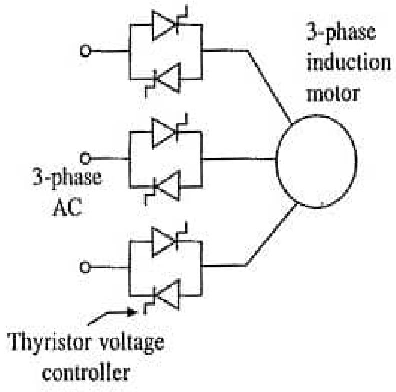
- Since the magnitude and waveforms of motor currents are independent of changes in motor impedance and source voltage, the **inverter operates as a current source inverter.**
- The closed-loop speed control scheme of CSI drive is used for Current Regulated Voltage Source Inverter drive, is shown in Fig.c)
- A servo drive for closed-loop position control is obtained by adding a position loop around the speed loop in below Fig.
- Although Current Regulated Voltage Source Inverter operates as a CSI, it does not use large dc inductor and filter capacitors, hence it has lower weight, volume and cost and faster dynamic response.
- This drive has applications in servo control systems.

Speed control of Single- Phase Induction Motor



(a)

- Speed of a single-phase induction motor is generally controlled by controlling its stator voltage which can be controlled by connecting a variable resistance in series with the stator. Because of poor efficiency the resistance control is now rarely used.
- Stator voltage can be controlled by the use of ac voltage controllers.
- By reducing Stator Voltage, speed of a high-slip induction motor can be reduced, suitable for the speed control of some fan and pump drives method where torque demand reduces with speed.
- Domestic fan motors, which are always single-phase, are controlled by a single-phase triac voltage controller shown in Fig. (a).
- Speed control is obtained by varying firing angle of the triac.
- These controllers, commonly known as solid state fan regulators, are now preferred over conventional variable resistance regulators because of higher efficiency.
- Industrial fans and pumps are usually driven by three-phase motors.



(b)

- Fig. (b) shows a commonly used thyristor voltage controller for speed control of 3-phase motors.
- Motor may be connected in star or delta.
- In delta connection, third harmonic voltage produced by motor back emf causes circulating current through the windings which increases losses and thermal loading of motor.
- Speed control is obtained by varying conduction period of thyristors.
- For low power ratings, anti-paralleled thyristor pair in each phase can be replaced by a triac.
- The speed of the motor can also be controlled by variable frequency control.
- However, it is rarely used because for most of the variable speed applications of single-phase motors, the stator voltage control is good enough.

Synchronous Motor Drives

Operations from Fixed Frequency Supply

- For any speed other than synchronous speed, the relative speed between air gap flux wave and the rotor is not zero.
- δ varies from 0 to 360°, and torque fluctuates between positive and negative values, but its average value remains zero.
- Frequency of torque fluctuations depends on the relative speed between air-gap flux wave, which rotates at synchronous speed, and the rotor.
- When rotor is at stand-still, the frequency is too high for the rotor inertia to allow any change in speed. The motor is not self starting.
- If rotor is brought close to synchronous speed by some starting method and then dc field excited, the synchronous torque assisted by the damper winding torque is able to pull the rotor into step with the rotating field after a short duration of hunting, and the machine then works as a synchronous motor.
- The process of pulling rotor into step with the rotating field is called pull-in or synchronisation.

Starting

- The purpose of starting method is to bring rotor speed close to synchronous speed.
- One widely used method is to start the synchronous motor as an induction motor with field unexcited and damper winding serving as a squirrel-cage rotor.

Consider the following methods of starting

- **Method-1 :** The starting torque and current can be increased and reduced respectively, by increasing the damper winding resistance. For successful pull-in, the motor speed while running as an induction motor must be close to synchronous speed. For this the damper winding resistance must be as low as possible.
- **Method-2 :** During acceleration as an induction motor, because of large number of turns in field winding, the induced voltage in the field winding may reach several thousand volts, thus overstressing the insulation of the winding and increasing the voltage rating of the field supply converter. Here, the field circuit is closed through small discharge resistance before dc excitation is applied. So the actual potential difference between the turns is reduced to safe value.
- **Method-3 :** DC excitation should not be applied during acceleration as an induction motor because while it produces no net motoring torque, it does produce braking torque. So, dc field should be applied only after the motor has reached close to full speed.

Method-4 : When rotor has salient pole construction, the damper winding can have conductors only over Pole arc. This leads to a dip in the speed-torque curve at half of synchronous speed.

Method-5 : When started with full supply voltage, the starting current can be 7 to 10 times of full load value. In small size motors- It leads to fluctuations in supply voltage. In case of large size motors- cause a large drop in the terminal voltage, thus reducing low starting torque further. Starting current can be reduced by employing the reduced voltage starting methods. When started at a reduced voltage, the transition to full voltage can be made before or after the pull-in. Pull-in can be achieved faster and with larger motor loads.

Method-6: It uses a low power auxiliary motor coupled to the synchronous motor shaft. With the help of auxiliary motor, the rotor speed is brought near, synchronous speed and then dc field is switched-in. This method has a very low starting torque.

Pull-in (Synchronism)

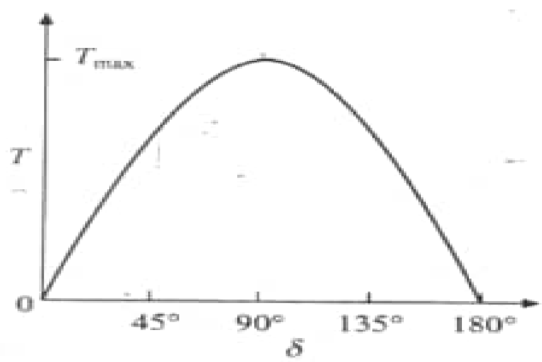
- Pull-in process begins when the field supply is switched-in.
- When pull-in takes place at no load or at light loads, field supply can be switched-in without regard to the value of torque angle at the instant of switching.
- This may give rise to considerable disturbance in line currents during the pull-in process, with their magnitudes going well above the rated value.
- However, this would occur without regard to polarity of the rotor poles.
- If polarity is right, the pull-in will take place with minimum disturbance.
- If wrong, the rotor may slip several poles before pull-in is completed.
- Torque is negative: for δ from 0 to 180° leading, so the synchronous torque will decelerate the rotor
- Torque is positive: for δ from 0 to 180° lagging, hence synchronous torque will accelerate the rotor.
- Rotor will be subjected to the accelerating torque of longest duration : when the field is excited at $\delta = 0$. Hence, it is the most favourable angle for exciting dc field.

Transients Due to Load Disturbance

Steady – State Stability Limit

$$T = T_{max} \sin \delta$$

$$T_{max} = \frac{3VE}{X_s \omega_{ms}}$$



$$T = \frac{3VE'}{\omega_{ms} X_s'} \sin \delta \qquad = T'_{max} \sin \delta$$

$$T'_{max} = \frac{3VE'}{\omega_{max} X_s'}$$

Torque balance equation of the synchronous motor is [7]

$$T = T_a + T_d + T_L$$

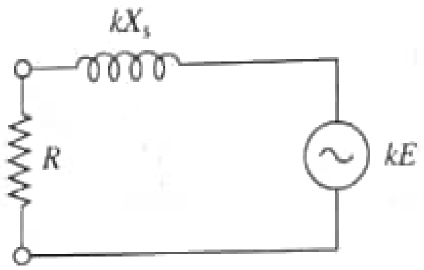
where $T_a = K_j \frac{d^2\delta}{dt^2}$ is the acceleration torque and $T_d = K_d \frac{d\delta}{dt}$ is the damping torque

$$K_j \frac{d^2\delta}{dt^2} + K_d \frac{d\delta}{dt} - T'_{max} \sin \delta + T_L = 0$$

Braking

The per unit speed k is given by

$$k = \frac{\omega_m}{\omega_{ms}}$$



Dynamic braking equivalent circuit

braking current $I_{sb} = \frac{kE}{\sqrt{R_B^2 + (kX_s)^2}}$

braking power $P_B = 3I_s^2 R_B$

braking torque $T_B = \frac{P_B}{k\omega_{ms}}$

$$T_B = \frac{3R_B kE^2}{\omega_{ms}(R_B^2 + k^2 X_s^2)}$$

Synchronous Motor Variable Speed Drives

Variable Frequency Control

- The synchronous speed is given by, $N_s = \frac{120.f}{P}$
- From the above equation, it is clear that the speed of a synchronous motor can be controlled by varying the frequency of the supply.
- Here, the stator flux is maintained constant by keeping the (v/f) ratio constant as that of induction motors, . Constant flux operation ensures that the maximum torque at all frequencies is same.
- v/f ratio is increased at low frequencies to increase the torque producing capability of motor.
- Above rated speed, the stator voltage is kept constant and the frequency alone is increased. In this case, the torque produced by the motor may be reduced.

Modes of Variable Frequency Control

Variable frequency control may be achieved by any one of the methods listed below.

1. True synchronous mode (or) separate controlled mode.

2. Self synchronous mode (or) self controlled mode.

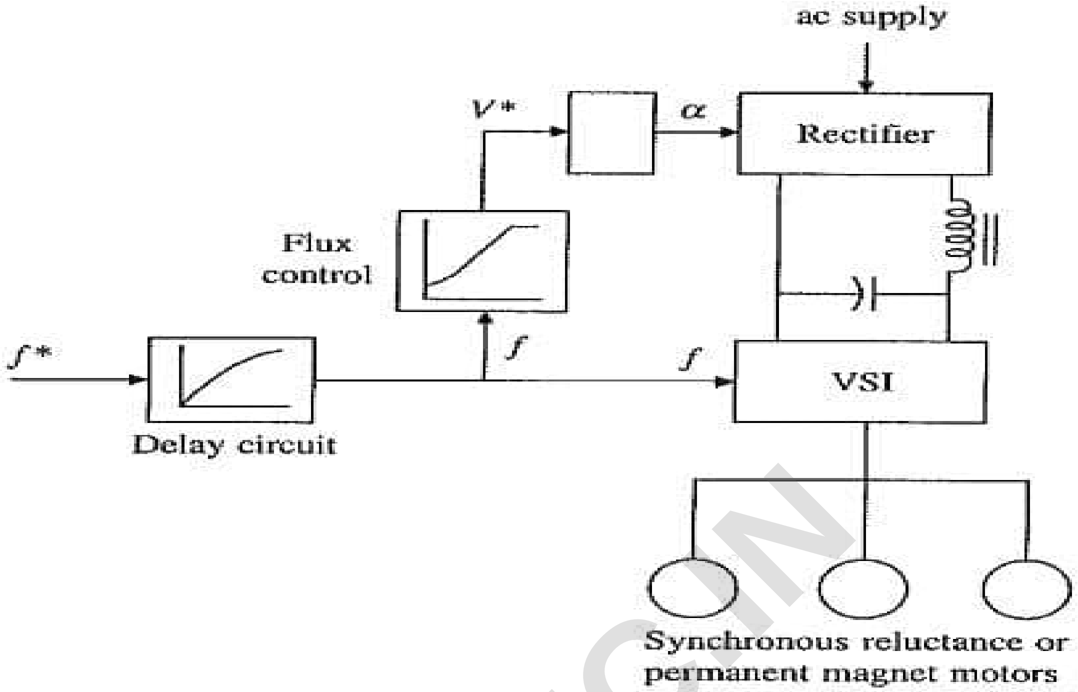
1. True synchronous mode (or) Separate controlled mode

- In this mode of speed control, the stator supply frequency is controlled from outside by using a separate oscillator.
- The frequency is changed gradually so that the difference between synchronous speed and rotor speed is small during any speed change.
- This gradual change in frequency helps the rotor to follow the stator speed properly at all operating points.
- When the desired speed is reached, the rotor gets locked with the stator flux speed (rotor pulls into step) after hunting oscillations

2. Self control mode of synchronous motor drive

- In self control, the stator supply frequency is changed proportional to the rotor speed.
- Hence the stator rmf rotates at the same speed as the rotor speed.
- This ensures that the rotor moves in synchronism with stator at all operating points.
- Consequently a self controlled motor will never come out of synchronism or step.
- It does not suffer from hunting oscillations

Variable Frequency Control of Multiple Synchronous Motors



Variable frequency control of multiple synchronous motors

- A drive operating in true Variable Frequency Control of Multiple Synchronous Motors
- 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.

Module 5

Synchronous Motors cntd
Stepper Motor Drives
Industrial Drives

Syllabus:

Synchronous Motor Drives (continued):

Self-controlled synchronous motor drive employing load commutated thryrister inverter,

Starting Large Synchronous Machines,

Permanent Magnet ac (PMAC) Motor Drives,

Sinusoidal PMAC Motor Drives, Brushless dc Motor Drives.

Stepper Motor Drives:

Variable Reluctance

Permanent Magnet

Important Features of Stepper Motors,

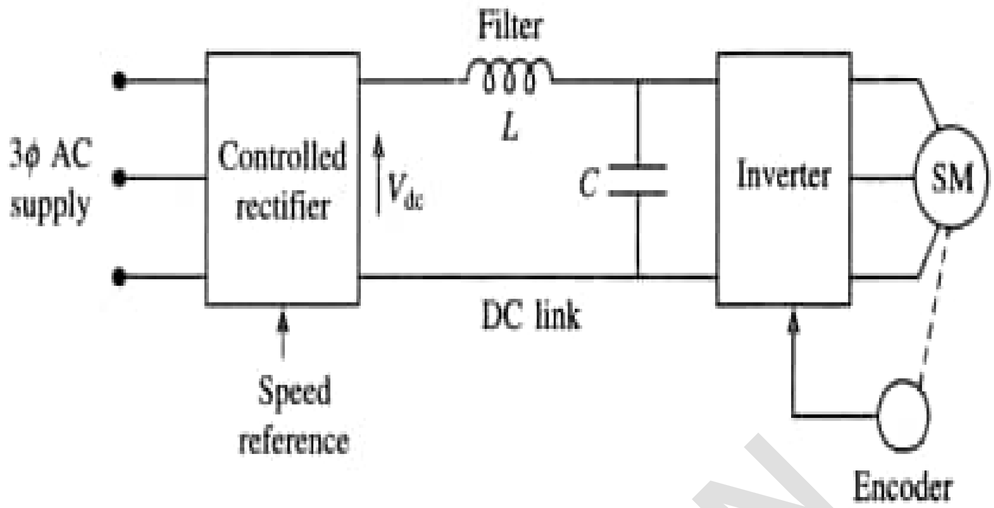
Torque Versus Stepping rate Characteristics,

Drive Circuits for Stepper Motor.

Industrial Drives:

Textile Mills, Steel Rolling Mills, Cranes and Hoists, Machine Tools

Self Controlled Synchronous Motor



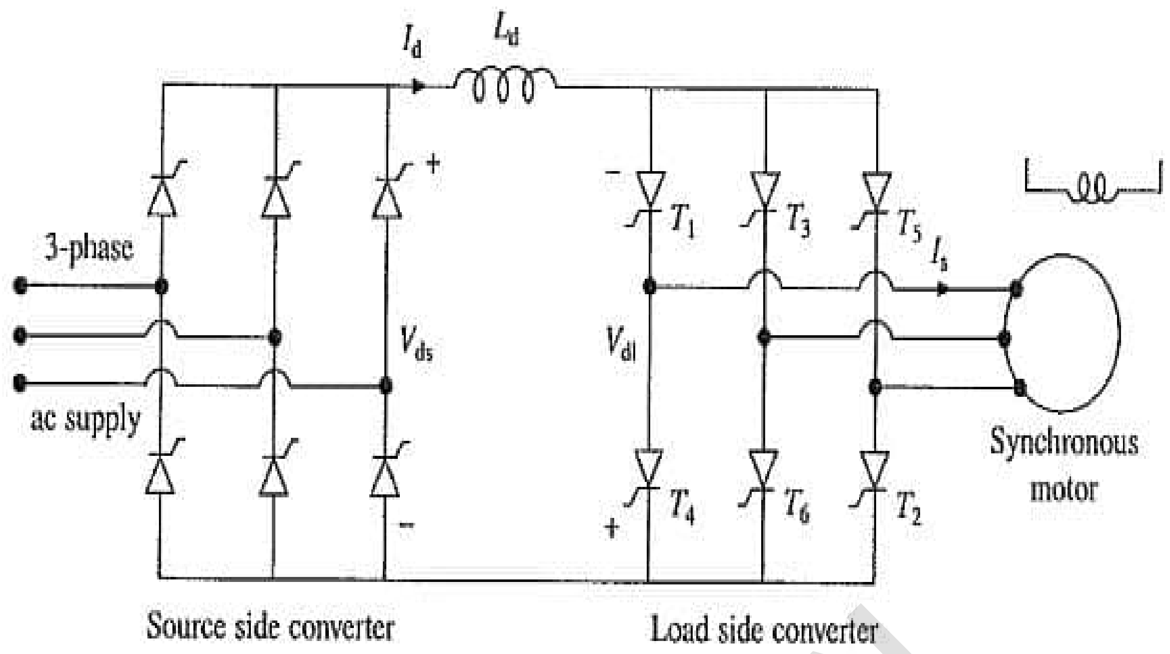
- The block diagram of a self controlled motor fed from a 3 phase inverter is shown in below Fig.
- The inverter may be a CSI or VSI. Depending on the type of inverter, the input dc source may be a controllable current source or controllable voltage source
- The inverter output frequency is determined by the rotor speed.
- The accurate speed of the rotor is tracked by using rotor position sensors, where the switching devices operate to turn the stator windings ON and OFF. The switches are fired at a frequency proportional to the motor speed.
- With the increase of load if the rotor slows down, then the stator supply frequency automatically changes so that the rotor remains synchronized with the rotating field.
- When the motor starts from rest, the motor current will be large at first and then will decrease with increase of speed.
- The speed of the motor is controlled by varying the dc link voltage to the inverter, by varying the firing pulses of the controlled rectifier.
- Four quadrant operation is possible if the inverter is fed from a full converter.

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.

The drive employs two converters.

1. **Source side converter**
2. **Load side converter**



Self-controlled synchronous motor drive employing load commutated inverter

1. Source side converter

- The source side converter-is a 6-pulse line-commutated thyristor converter.
- For a firing angle range $0 \leq \alpha_s \leq 90^\circ$, it works as a line-commutated fully controlled rectifier delivering positive V_{ds} and positive I_d,
- For firing angle range $90^\circ \leq \alpha_s \leq 180^\circ$, it works as a line-commutated inverter delivering negative V_{ds} and positive I_d.
- 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

2. Load Side Converter

- For $0 \leq \alpha_l \leq 90^\circ$ it works as a rectifier giving positive V_{dl}.
- For, $90^\circ \leq \alpha_l \leq 180^\circ$, Converter operates as an inverter producing negative V_{dl} and carrying positive I_d

$0 \leq \alpha_s \leq 90^\circ$, $90^\circ \leq \alpha_l \leq 180^\circ$ and with $V_{ds} > V_{dl}$	source side converter works as a rectifier and load side converter as an inverter	power flow from ac source to the motor, thus giving motoring operation
$90^\circ \leq \alpha_s \leq 180^\circ$ and $0^\circ \leq \alpha_l \leq 90^\circ$,	the load side converter operates as a rectifier and the source side as an inverter.	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.
- Commutation lead angle for load side converter as $\beta_l = 180° - \alpha_l$
- Converter working as an inverter with Fixed value of commutation lead angle= β_{lc}
- When working as a rectifier: $\beta_l = 180°$ (or $\alpha_l = 0°$)

Constant Margin Angle Control:

- To minimize converter rating, with good power factor , the load side converter when working as an inverter is operated with **Constant Margin Angle Control**.
- The duration for thyristor under commutation is subjected to reverse bias after current through it has fallen to zero is given by $\gamma = \beta_l - u$

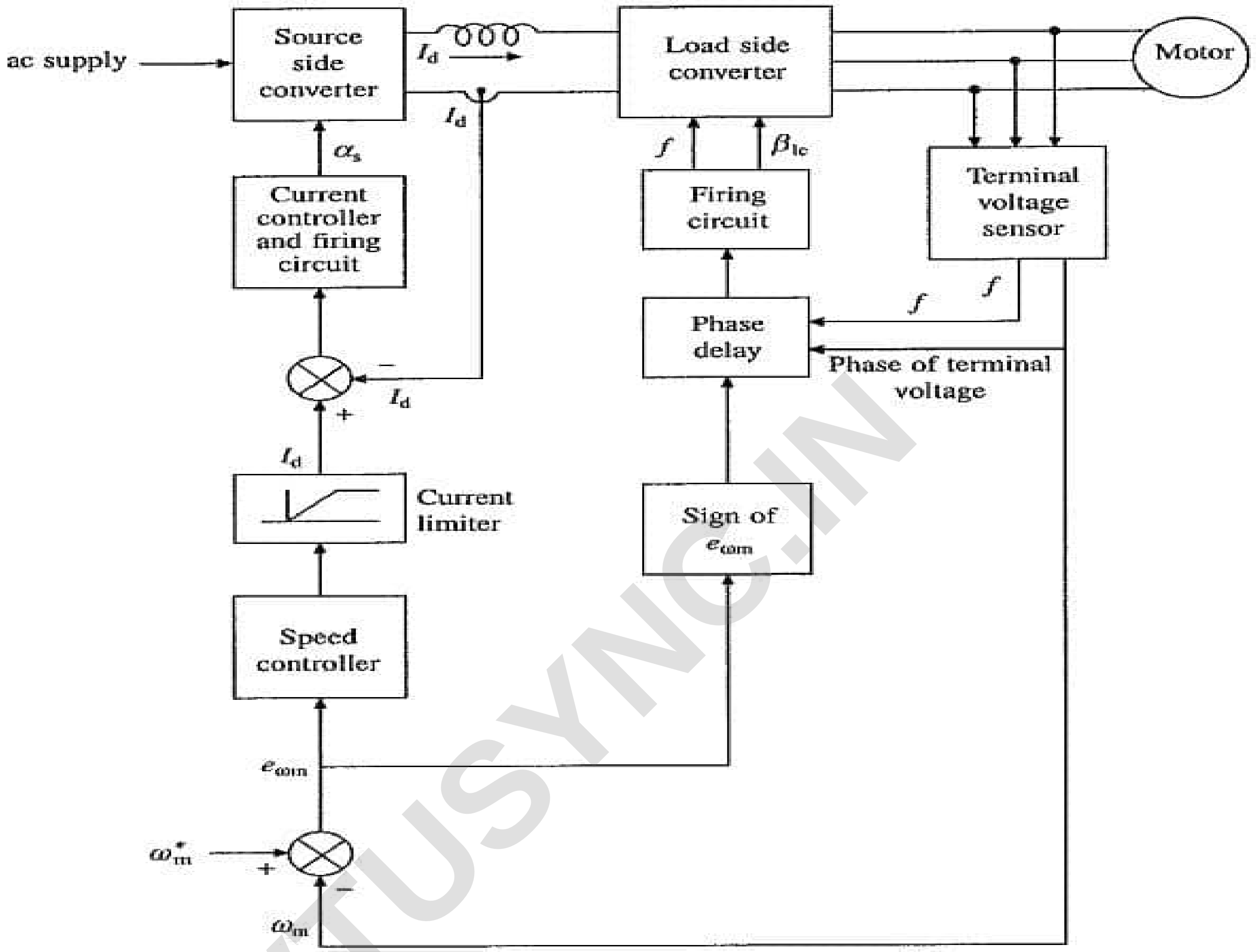
  Where, u-commutation overlap of the thyristor under commutation
- For successful commutation of thyristor: $\gamma > \omega t_q$

  where t_q is the turn-off time of thyristors and ω the frequency of motor voltage in radians/sec.
- Since u α I_d ; βl can be calculated such that the thyristor under commutation is reverse biased for a duration γ_{min} for commutation.
- This in turn minimizes βl 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 - prevents the two converters from interfering with each other's operation.
- Fundamental component of motor phase current I_s is: $I_s = \frac{\sqrt{6}}{\pi} I_d$

Load commutation has a number of advantages over forced commutation:

- ✓ **it does not require commutation circuits**
- ✓ **frequency of operation can be higher and**
- ✓ **it can operate at power levels beyond the capability of forced commutation.**
- Load side converter performs somewhat similar function as commutator in a dc machine.
- The load side converter and Self Controlled Synchronous Motor Drive combination functions similar to a dc machine.
- The drive consisting of load side converter and synchronous motor is known as **Commutator Less DC Motor.**

Closed-loop speed control scheme of load commutated inverter synchronous motor drive



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

- It employs <u>outer speed control loop</u> and <u>inner current control loop</u> with a limiter, like a dc motor .
- The terminal voltage sensor generates reference pulses of the same frequency as the machine-induced voltages.
- The phase delay circuit shifts the reference pulses to obtain control at a constant commutation lead angle β_{lc}.
- Depending on the sign 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} 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, 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.

Advantages of the drive:

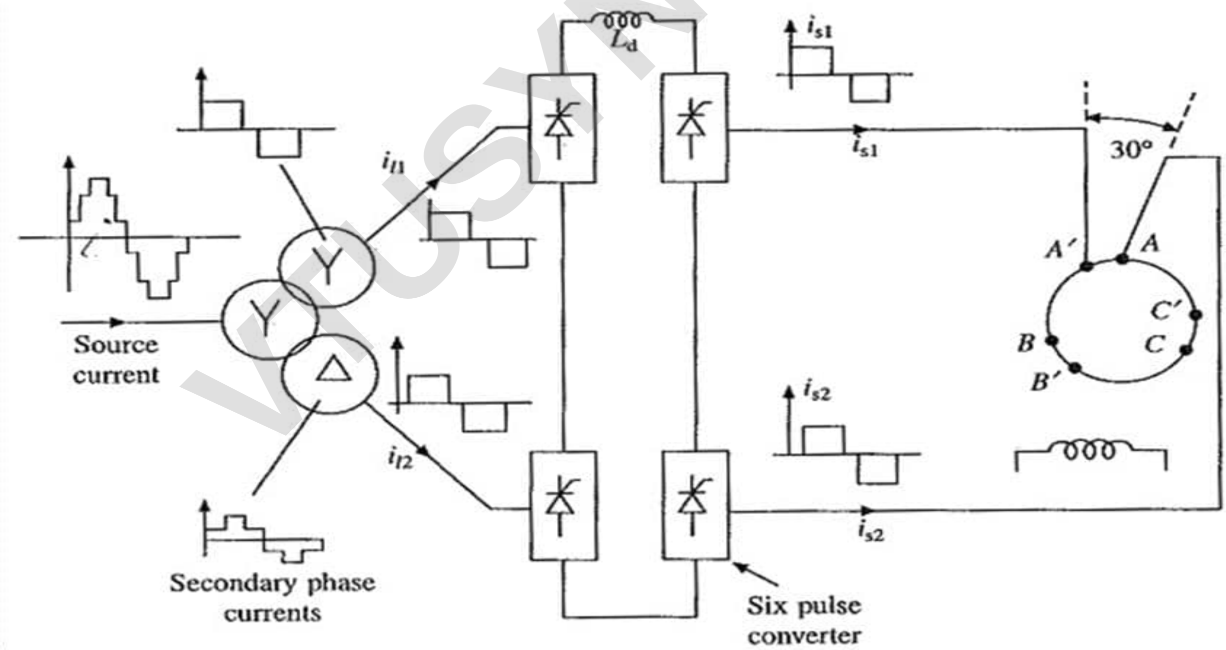
- ✓ High efficiency
- ✓ four-quadrant operation with regenerative braking,
- ✓ high power ratings (up to 100 MW)
- ✓ ability to run at high speeds (6000 rpm)

Applications:

High speed and high power drives for compressors, blowers, fans, pumps, conveyers, steel rolling mills, main line traction, ship propulsion and aircraft test facilities.

Single line diagram of a high power drive

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.



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

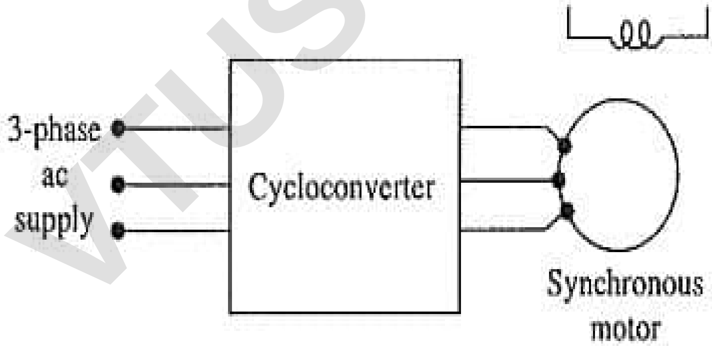
- The source side harmonics are reduced by using a 12-pulse converter.
- For this two six-pulse converters are connected in series.
- The supply for the converters is obtained through a transformer with primary-star and two secondary windings- one star connected feeds one six pulse converter and another delta connected 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.
- 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
- These effects are minimized by using a Self Controlled Synchronous Motor Drive
- The resultant stator mmf has twelve pulse waveform.
- Therefore, torque pulsations and rotor and damper winding losses are reduced.

Starting large Synchronous Motor

- When operating with self control, the starting current is low & starting torque is high compared to DOL starting as in case of IM.
- To start large synchronous motor in gas turbines and pumped storage power plants, self-control is employed.
- From standstill to 10% base speed, inverter operate in pulse mode and above 10% speed synchronous speed the inverted operated with load commutation.

Self Synchronous Motor Drive Employing a Cycloconverter

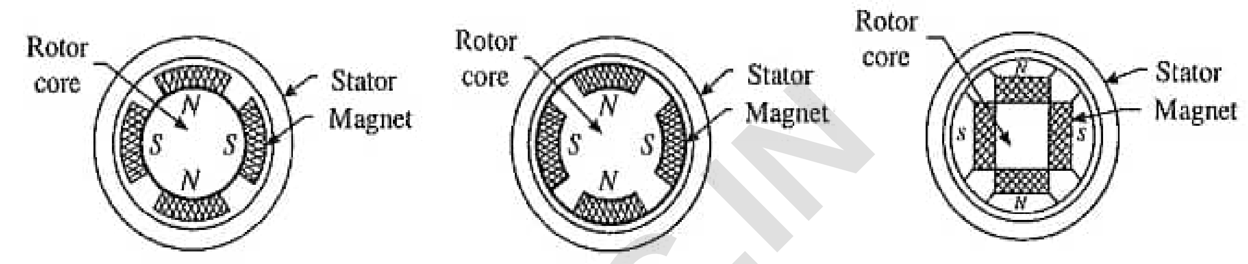


Self-controlled synchronous motor drive employing a cycloconverter

- Self Controlled Synchronous Motor Drive Employing a Cycloconverter as shown in Fig.
- Firing pulses are generated either by comparison of the motor terminal voltages or by rotor position sensors as in the case of drive.
- Cycloconverter control has the advantages of smooth low speed operation, four-quadrant operation with regenerative braking and good dynamic response.
- 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.
- 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 Self Controlled Synchronous Motor Drive Employing a Cycloconverter.
- 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 cycloconverter is ideally suitable for such a low frequency supply. Earlier gears were employed to get low speed operation

Permanent Magnet AC Motor Drives



(a) Projecting surface mounting (b) Inset magnet (a) Interior magnet

- Permanent magnet synchronous motors are now commonly known as permanent magnet ac (PMAC) motors.
- Classified based on the nature of voltage induced in the stator as

✓ **Sinusoidally Excited-** induced voltage has a sinusoidal waveform- Known as **Sinusoidal PMAC** Motors

✓ **Trapezoidally Excited-** induced voltage has trapezoidal waveform-known as **Trapezoidal PMAC** motors.

Sinusoidal PMAC motor

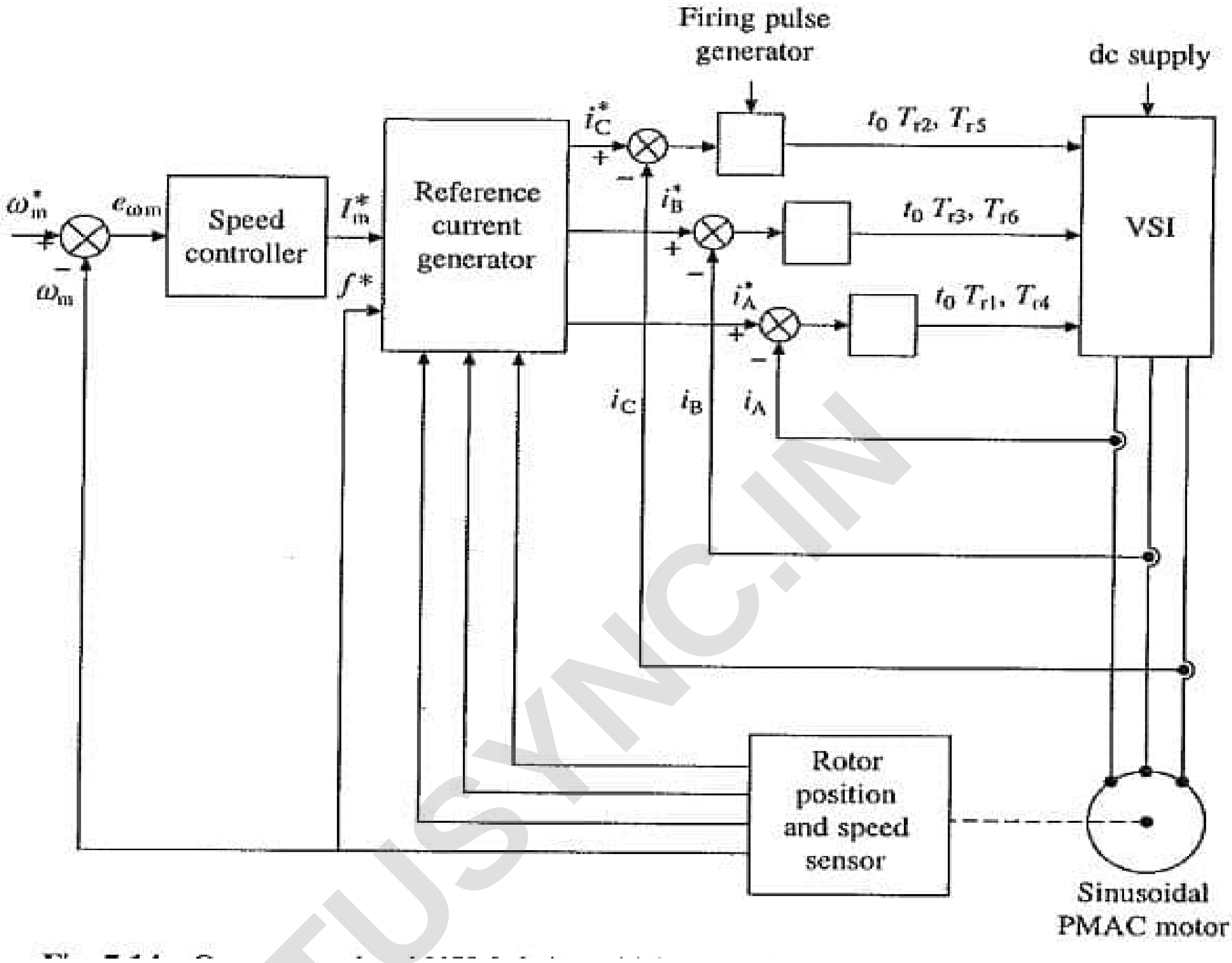
✓ has distributed winding in the stator.
✓ rotor geometries includes inset or interior shown in Fig.
✓ Rotor poles are so shaped that the voltage induced in a stator phase has a sinusoidal waveform.

Trapezoidal PMAC motors.

✓ The stator has concentrated windings
✓ rotor with a wide pole arc.
✓ The voltage induced in the stator phase has a trapezoidal waveform.
✓ The self-controlled variable frequency drives employing a trapezoidal PMAC motor are now called brushless dc motor drives

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.

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



- Reference currents i^*_A, i^*_B and i^*_C - generated by a reference current generator.
- 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.

Brushless DC Motor Drives (Trapezoidal PMAC)

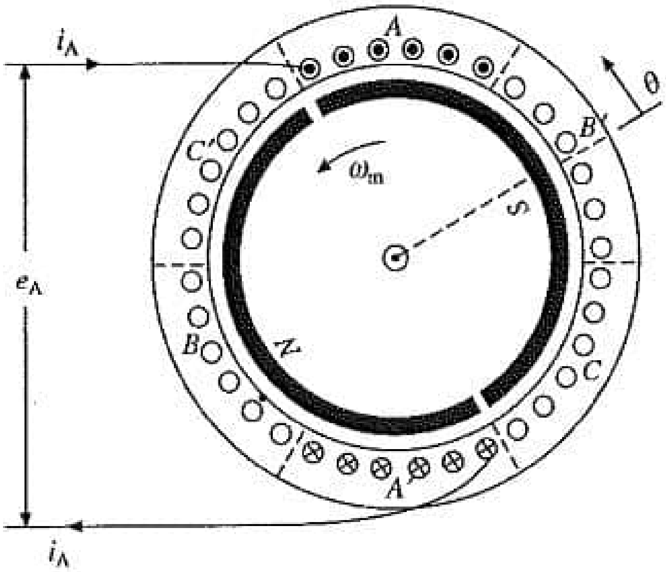


Fig 1 Cross Section of Trapezoidal PMAC Motor

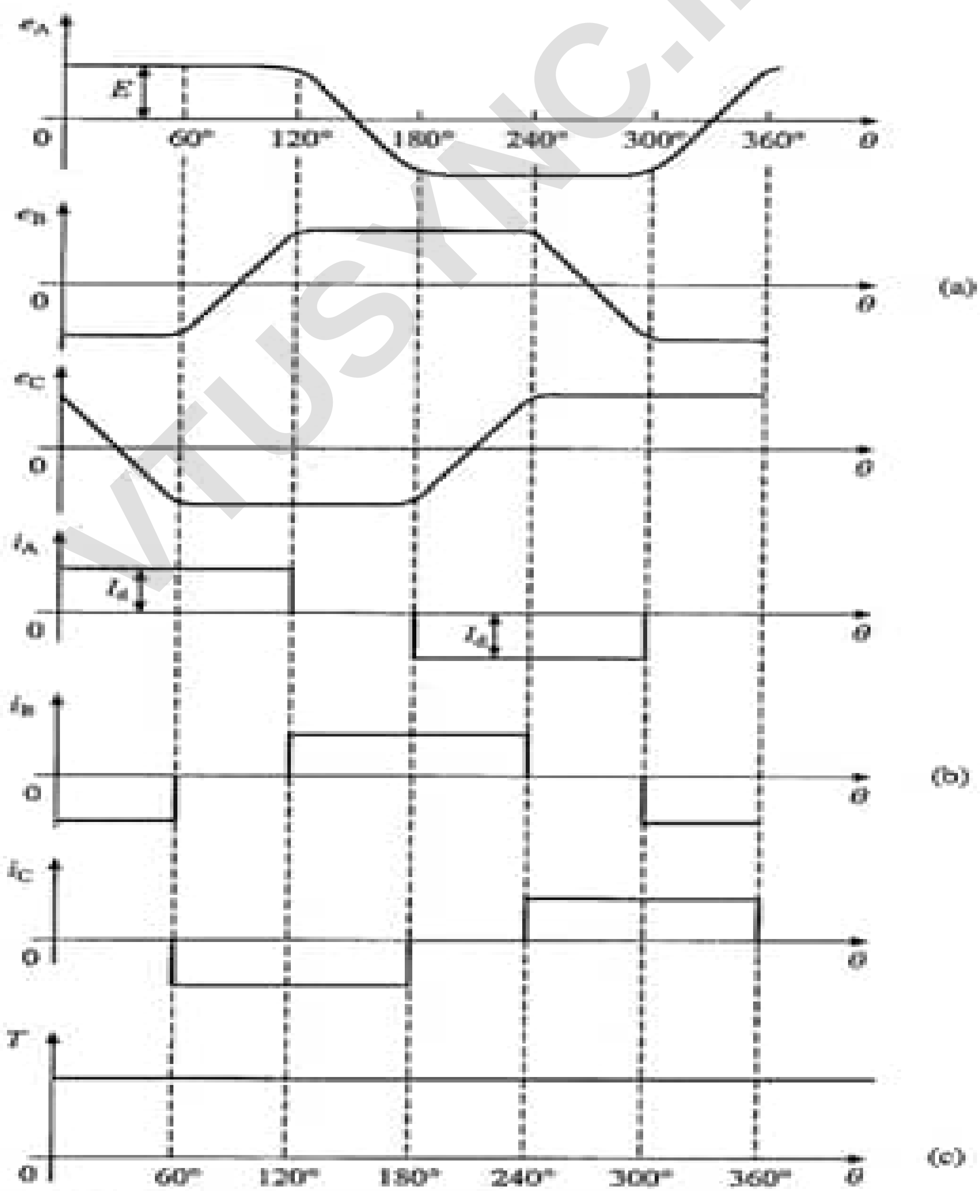


Fig. 2 Induced voltage, phase current and torque wavefors of a brushless dc motor

- The cross section of a 3-phase 2 pole Brushless DC Motor Drives is shown in Fig.1.
- An inverter fed trapezoidal PMAC motor drive operating in self-controlled mode is called a brushless dc motor
- 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. 2

Reason for getting trapezoidal waveform:

- When revolving in the counter-clockwise direction, up to 120^0 rotation from the position shown in Fig. 1, 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 120^0 rotation as in fig2.
- Beyond 120^0, 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 60^0 rotation.
- Rest of the waveform of phase A and waveforms of phases B and C can be similarly explained.

Brushless DC Motor Drive for Servo Applications

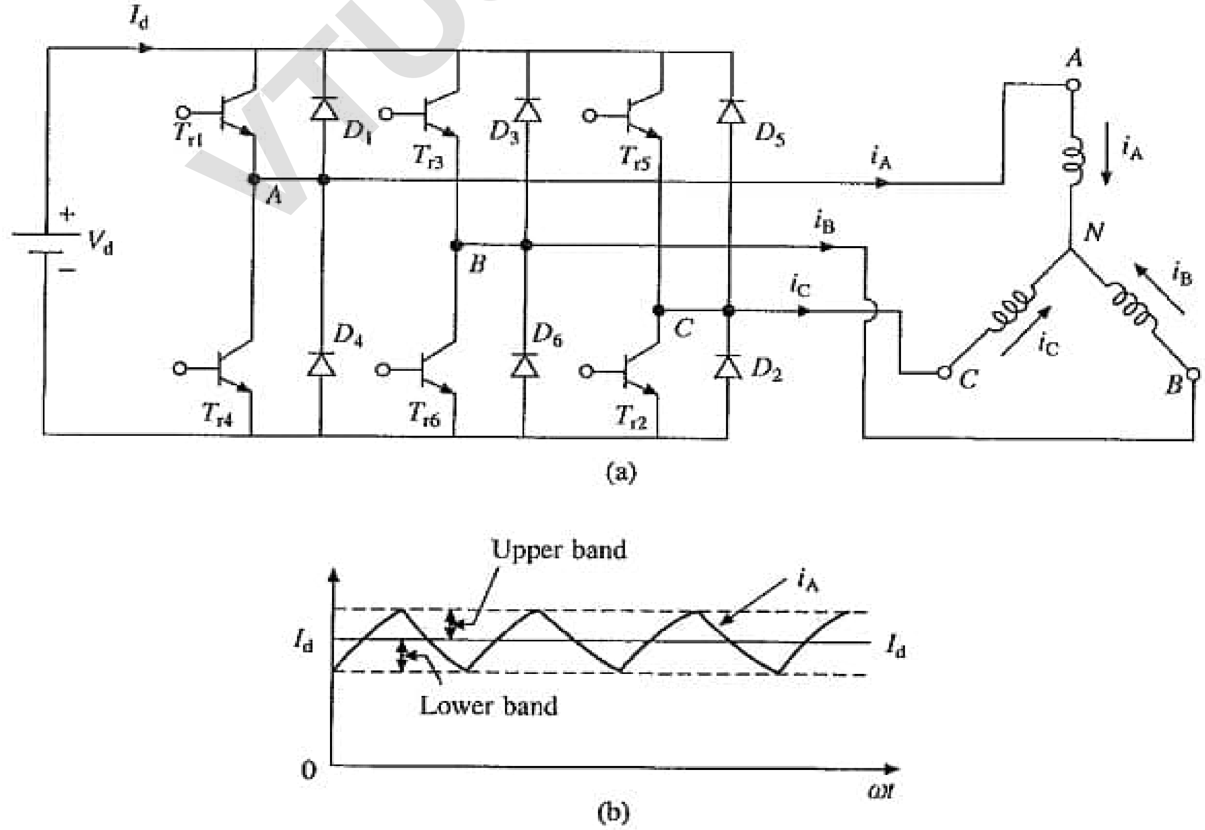


Fig. 3 Trapezoidal PMAC motor fed from a current regulated voltage source inverter

- A Brushless DC Motor Drives employing a voltage source inverter (VSI) and a trapezoidal PMAC motor is shown in Fig. 3(a) the stator windings be fed with current pulses shown in Fig. 3(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.

$$E = K_e \omega_m$$

- During each 60° interval in Fig.4, current enters one phase and comes out of another phase, therefore, power supplied to the motor in each such interval

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

The waveform of torque is shown in fig.below

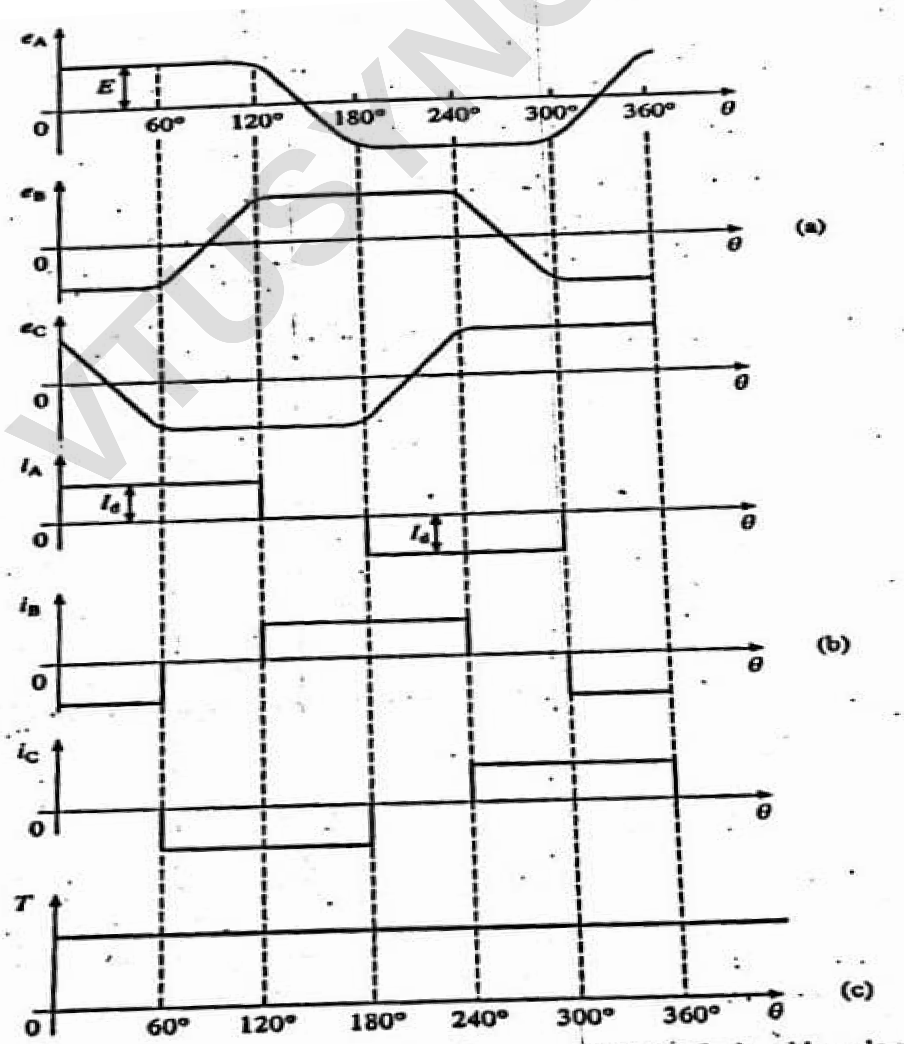


Fig. 7.17 Induced voltage, phase current and torque wavefors of a brushless dc motor

Torque developed by the motor $T = \frac{P}{\omega_m} = 2K_e I_d = K_T I_d$

- 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. Rate of change of i_A will be negative.
- A current can be made to follow the reference current I_d within a hysteresis band as shown in Fig. 3(b).
- By reducing the band sufficiently nearly a dc current of desired value can be produced.
- The sensors are mounted at 60^0 interval and aligned suitably with the stator winding,
- Sensors used with trapezoidal PMAC motor are cheaper compared to those required with sinusoid PMAC motor. Hence the drive has much lower cost.

Important Features and Applications

- Due to the absence of brushes and commutator, Brushless DC Motor Drives 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 Drives 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.

Stepper Motor

Defn: Stepper Motor is a brushless electromechanical device which converts the train of electric pulses applied at their excitation windings into precisely defined step-by-step mechanical shaft rotation. The shaft of the motor rotates through a fixed angle for each discrete pulse. This rotation can be linear or angular. It gets one step movement for a single pulse input

Large Varieties of Stepper Motor can be divide into three categories based on the rotor arrangements. They are as follows

1. **Variable Reluctance (VR) Stepper Motor** : It is of two types.
    i. Single stack variable reluctance motor
    ii. Multi-stack variable reluctance motor.
2. **Permanent Magnet (PM) Stepper Motor**
3. **Hybrid Stepper Motor (combination of VR and PM type)**

Important Features of Stepper Motors

Stepper motors have following advantages and disadvantages:

Advantages of stepper Motor

- Compatibility with digital systems and do not require digital to analog conversion at the input.
- 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 system.
- A wide range of step angles is available in the range of 1.8 to 90º. The range of torque is from 1μNm(tiny wrist watch) to 50Nm(Machine Tool applications)
- Bidirectional control is available
- Maximum Torque occurs at low pulse rates. The stepper motor can accelerate its load easily.
- Low Speed are possible without reduction gear.
- Moment of Inertia is usually Low.
- Multiple stepper motors driven from the same source can maintain perfect synchronization.
- The starting current is Low
- Low Cost, Compact Size

Disadvantages of Stepper Motor

- Proper Matching between Load, motor and its drive is required.

- At the higher speed, the value of torque reduces.
- Lower efficiency.
- The Resonance condition arises and requires micro stepping.
- At the high speed, the control is not possible

Applications of stepper Motor

- Machine tools
- Process Control system
- X-Y Recorder
- Robotics
- Textile industry
- Integrated circuit fabrication
- Electric Watches

Step Angle in Stepper Motor

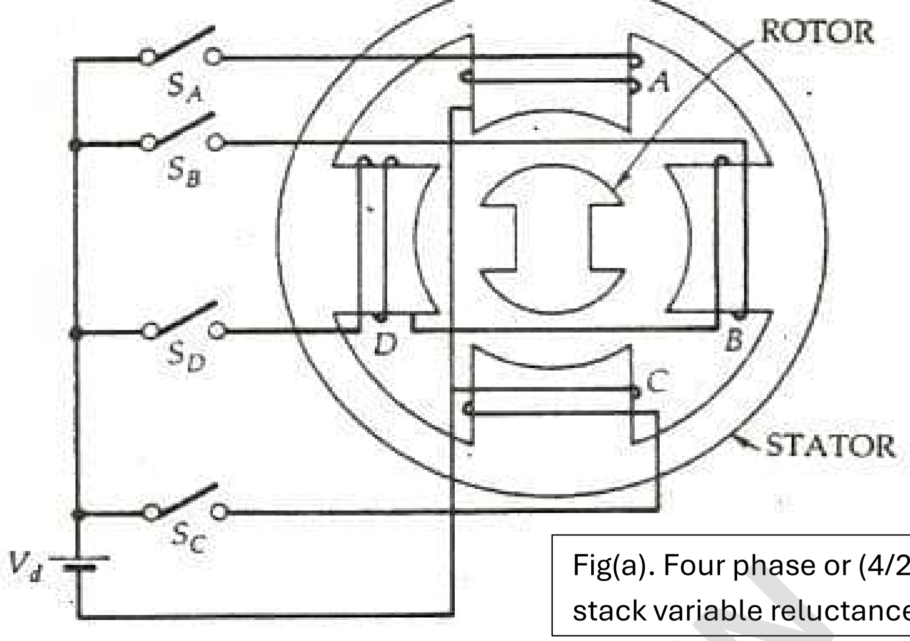
- **Definition: Step angle** is defined as the angle which the rotor of a stepper motor moves when one pulse is applied to the input of the stator.
- The positioning of a motor is decided by the step angle and is expressed in degrees.
- The resolution or the step number of a motor is the number of steps it makes in one revolution of the rotor.
- Smaller the step angle higher the resolution of the positioning of the stepper motor

$$\text{Resolution} = \frac{\text{number of steps}}{\text{number of revolutions of the rotor}}$$

Variable reluctance stepper motor

1. Single stack variable reluctance stepper motor

- A variable reluctance stepper motor has salient pole (or tooth) stator and rotor.
- Rotor has no windings, stator has concentrated coils placed over the stator poles (teeth).
- Number of phases in Stator winding depends on the connection of stator coils.
- A four phase, 4/2 pole (4 stator poles & 2 rotor poles), single stack variable reluctance stepper motor is shown in fig.



Fig(a). Four phase or (4/2 pole), single stack variable reluctance stepper

- The four phases A, B, C and D are connected to the DC source with the help of a semiconductor, switches SA, SB, SC and SD respectively as shown in the above figure (a).
- The phase windings of the stator are energized in the sequence A, B, C, D, A.
- The rotor aligns itself with the axis of phase A as the winding A is energized. The rotor is stable in this position and cannot move until phase A is de-energized.
- Now, the phase B is excited and phase A is disconnected.
- The rotor moves 90 degrees in the clockwise direction to align itself with the axis of the phase.
- Similarly the phase C is energized, and the phase B is disconnected, and the rotor moves again in 90 degrees to align itself with the axis of the phase.
- Thus, as the Phases are excited in the order as A, B, C, D, A, the rotor moves 90 degrees at each transition step in the clockwise direction.
- Direction of rotation can be reversed by reversing the sequence of switching the phases, that is A, D, C, B, A.
- The step-angle can be reduced from 90 to 45^0 by exciting phases in sequence A, A + B, B, B + C, C, C + D, D, D +A, A.
- When phase A is excited, the rotor aligns with the axis of A.
- When, both phases A and B are excited, the resultant air-gap field axis, and therefore, rotor turns by 45^0 in the clockwise direction.
- Rotor can be turned in anticlockwise direction with a step of 45^0 by switching phases in sequence of A, A + D, D, D + C, C, C + B, B, B + A, A.
- This technique of gradually shifting excitation from one phase to another (e.g. from A to B with an intermediate step of A + B) is known as **microstepping** and is used to realise smaller steps.

Example: A four-phase, 8/6 pole, single-stack variable reluctance motor

- A four-phase, 8/6 pole, single-stack variable reluctance motor is shown in Fig. 8.2.
- The rotor turns with a step angle of 15^0
- For clockwise rotation, phases are switched in the sequence of A, B, C, D, A
- For anticlockwise rotation, they are switched in the reverse sequence of A, D, C. B, A.

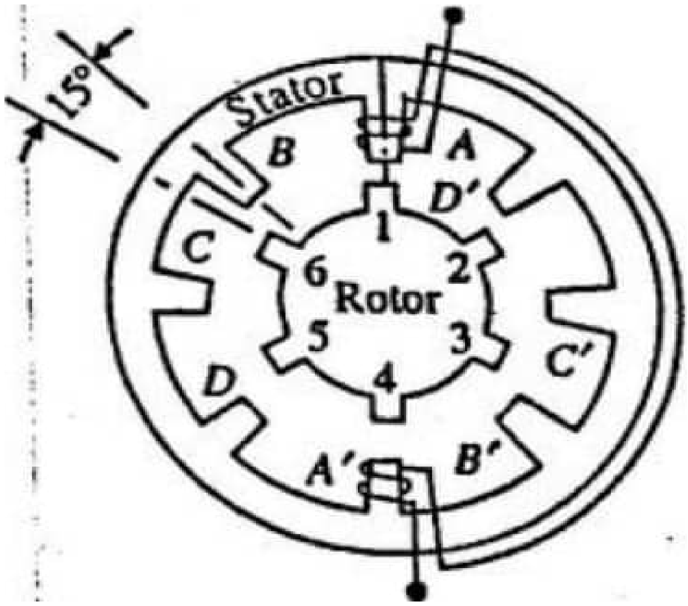


Fig. 8.2 Four-phase 8/6-pole variable reluctance motor

- When phase A is energised, the rotor turns until a pair of its poles (1 and 4 here) align with the axis of phase A (Fig. 8.2).
- If B is excited, the rotor turns by 15^0 in the clockwise direction until rotor poles 3 and 6 are aligned with the; axis of phase B. Here also, the microsteeping can be adapted to reduce the step size.
- For clockwise rotation with a Step size of 7.5^0 the sequence A, A + B, B, B + C, C, C+D,D, D +A, A can be used.
- In order to have self starting capability and bidirectional rotation, the stator and rotor pole numbers have to be different.

2. Multi Stack or m stack variable reluctance stepper motor

- A Multi Stack or m stack variable reluctance stepper motor is made up of m identical single stack variable reluctance motor.
- These are used to obtain smaller step sizes of range of 2 to 15^0.
- The rotor is mounted on the single shaft.
- Here stator and rotor, have the same number of poles and hence, the same pole pitch.
- All the stator poles are aligned in a Multi-Stack motor. But the rotor poles are displaced by 1/m of the pole pitch angle from each other.
- The stator windings of each stack forms one phase as the stator pole windings are excited simultaneously.
- Thus, the number of phases and the number of stacks are same.
- There are 12 stator and rotor poles in each stack.
- The pole pitch for the 12 pole rotor is 30 degrees and the step angle or the rotor pole teeth are displaced by 10 degrees from each other.

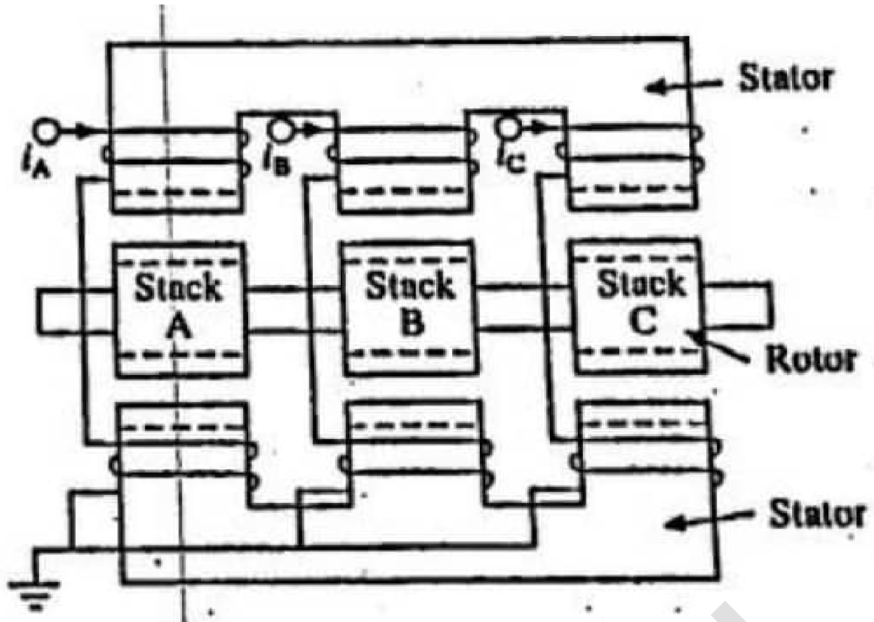


Fig. 8.3 Cross section of a three stack variable reluctance motor parallel to the shaft.

- Rotor poles of stack A are aligned with the stator poles.
- If phase A is de-excited and B excited, rotor poles of stack B will get aligned with the stator poles.
- Thus, rotor will move by 1/3rd of the pole pitch in anticlockwise direction as shown in fig b)
- If phase B is de-excited and C excited, rotor will move by another 1/3rd of pole pitch in the anticlockwise direction.
- If phase C is de-excited and A excited, rotor will have moved by one pole pitch compared to its position in Fig. 8.4(a).

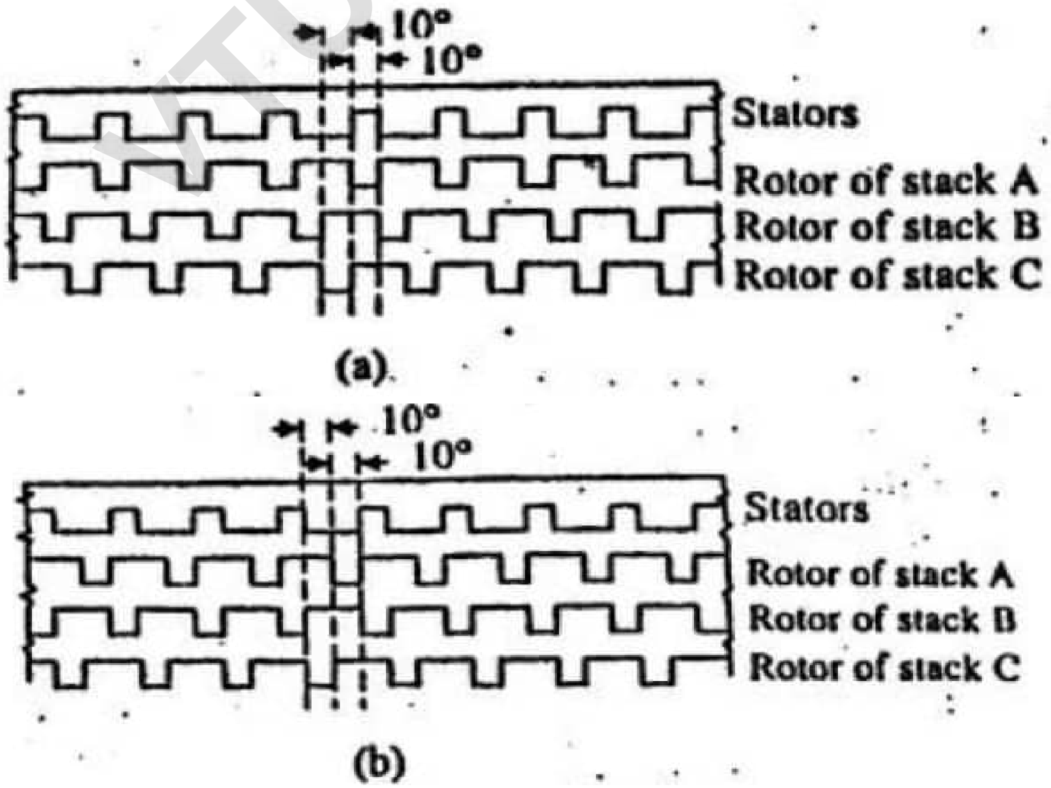


Fig. 8.4 Position of stator and rotor poles in a 3-stack variable reluctance motor: (a) Phase A is excited. Stator and rotor poles in stack A are aligned, (b) Phase B is excited. Stator and rotor poles in stack B are aligned.

Let,
N -number of rotor poles (or teeth)
m-number of stacks or phases.

$$\text{Pole (or tooth) pitch} = \frac{360^\circ}{N}$$

$$\text{Step angle} = \frac{360^\circ}{m \times N}$$

• The variable reluctance motors, both single and m- stack types. have high torque to inertia ratio, giving high rates of acceleration and fast response.

Permanent Magnet Stepper Motor

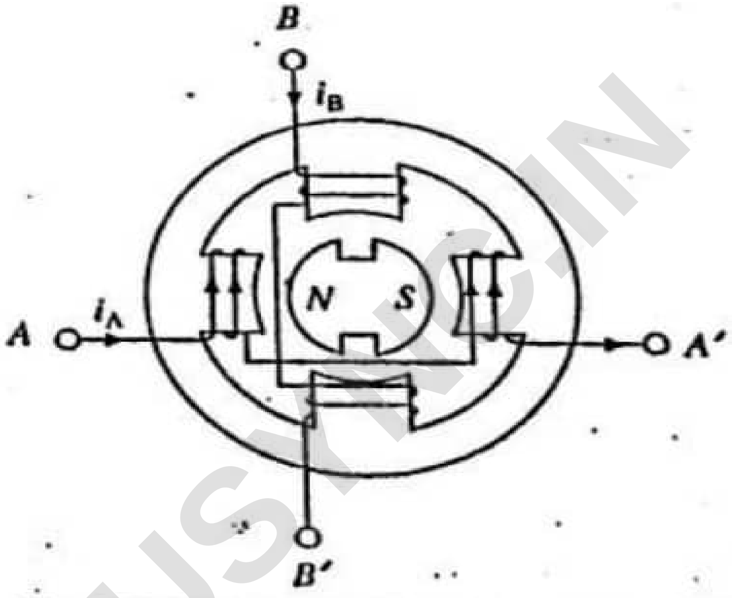


Fig. 8.5 Two-phase 4/2-pole permanent magnet stepper motor.

- The stator of a permanent magnet stepper motor is simitar to that of a single-stack variable reluctance motor.
- Rotor is cylindrical and consists of radially magnetised permanent magnets.
- Fig. shows a two-pole permanent magnet stepper motor.
- When phase A is exited with the direction of current i_A as shown, north pole of rotor aligns with the phase A pole on the left.
- The rotor turns through 90^0 when excitation is switched from phase A to B.
- The direction of rotation depends on the direction of current in phase B.
- When i_B is positive, the rotor turns clockwise
- when i_B is negative, rotor turns anticlockwise.
- Thus, polarities of winding currents determine the direction of rotation and for bidirectional operation, provision has to be made for supply of current in either direction.

i. Comparison with Variable Reluctance Motor

- Due to permanent magnet rotor, the motor has:

✓ high Detent (residual) torque

✓ produces higher torque per ampere of stator current

- ✓ because of higher rotor volume it has higher inertia
- ✓ lower torque-to-inertia ratio.
- ✓ Slower acceleration and response.

- The maximum stepping rate for permanent magnet stepper motors is around 300 pulses/sec. It can be as high as 1200 pulses/sec for variable reluctance motors.
- Due to manufacturing difficulty of small permanent magnet rotor with large number of poles, the permanent magnet stepper motor are restricted to larger step sizes in the range of 30-90^0.
- Disk-type of permanent magnet stepper motor has overcome the above limitations.

ii. Disk-type of permanent magnet stepper motor

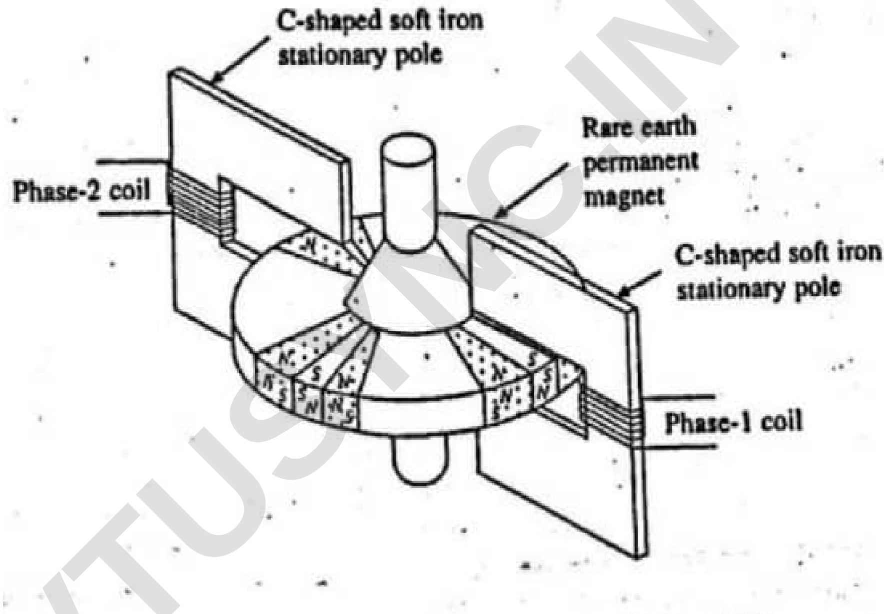


Fig. 8.6 Disk-type permanent magnet stepper motor.

- The disk is magnetised with alternating north and south poles.
- Due to thin disk, it can be magnetised up to around 100 individual tiny magnets.
- Simple C shaped two stationary field-poles, offset by half a rotor pole pitch form two phases.
- When one of the phase is energised, the rotor will align itself with its field-pole.
- When excitation is shifted to another phase, the rotor will turn by half the rotor pole pitch, to align with field-pole of the second phase.
- To keep the rotor turning in the same direction, second phase is turned-off and first phase turned-on with its direction reversed

iii. Hybrid Stepper Motor

It combines the important features Of variable reluctance and permanent magnet motors. This is achieved by incorporating an axial permanent magnet in the middle of the rotor, whose construction is somewhat similar to the rotor of a variable reluctance motor.

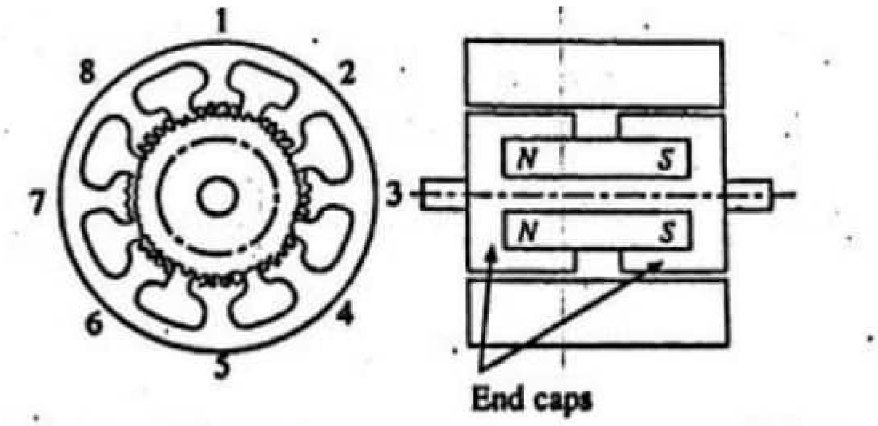


Fig. 8.7 Hybrid stepping motor with 200 steps per revolution

Advantages of Hybrid Stepper Motor

- The length of the step is smaller.
- It has greater torque.
- Provides Detent Torque with the de-energized windings.
- Higher efficiency at lower speed.
- Lower stepping rate.

Disadvantages of Hybrid Stepper Motor

- Higher inertia.
- The weight of the motor is more because of the presence of the rotor magnet.
- If the magnetic strength is varied, the performance of the motor is effected.
- The cost of the Hybrid motor is more as compared to the Variable Reluctance Motor.

Torque Vs Stepping(or Pulsing) rate Characteristics of a Stepper Motor

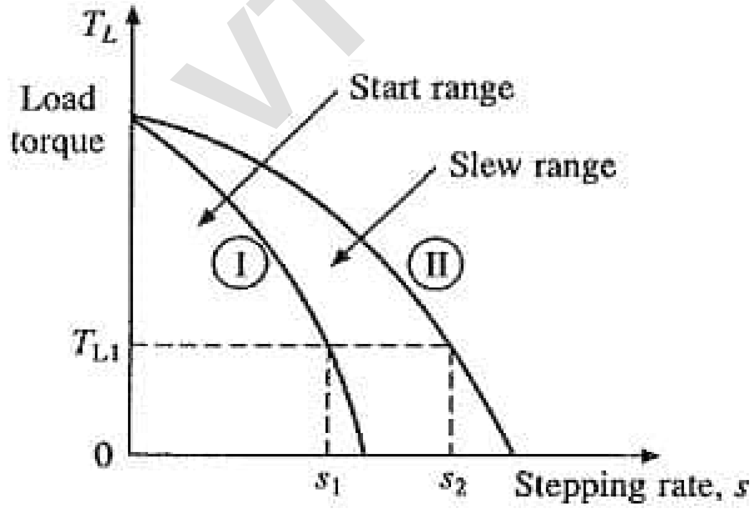


Fig. 8.8 Torque-stepping rate characteristics

- The **Torque pulse rate Characteristics** of a Stepper Motor gives the variation of an electromagnetic torque as a function of stepping rate in pulse per second (PPS).
- There are two characteristic curves 1 and 2 shown in the figure below.
- **Curve I -** known as the **Pull-in torque**.
- It shows the maximum stepping rate for the various values of the load torque at which the motor can start, synchronise, stop or reverse.

- **Curve II-** known as **pullout torque characteristics.**

- If the pulse rate is less than S_1: The motor can start, synchronise and stop or reverse for the load torque TL1
- The stepping rate can be increased for the same load as the rotor started the rotation and synchronized.
- The stepping rate can be increased up to S2: synchronising, without losing the synchronism, for the load TL1.
- If the stepping rate is increased beyond S2: the motor will lose synchronism.
- Thus, the area between curves 1 and 2 represents the various torque values, the range of stepping rate, which the motors follow without losing the synchronism.
- This is known as **Slew Range** and motor operate in slewing mode.

Drive Circuits for Stepper Motor

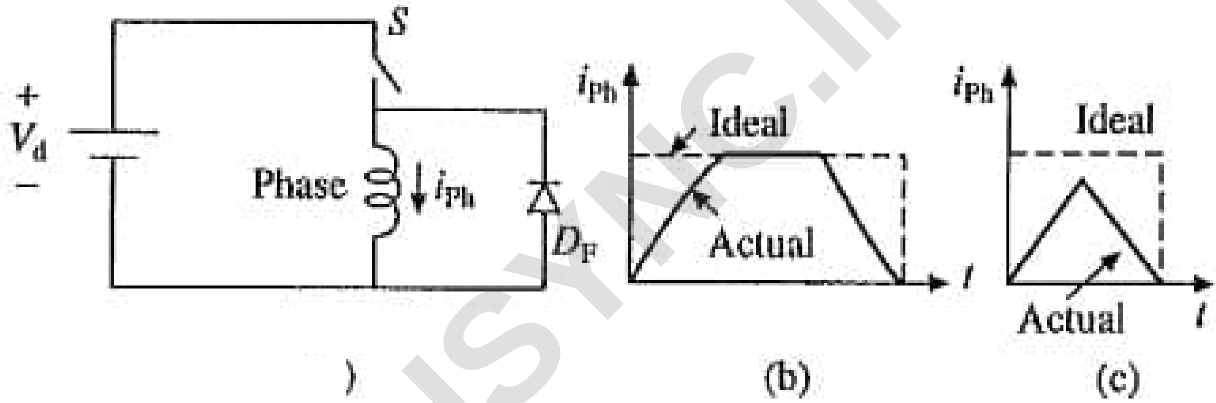
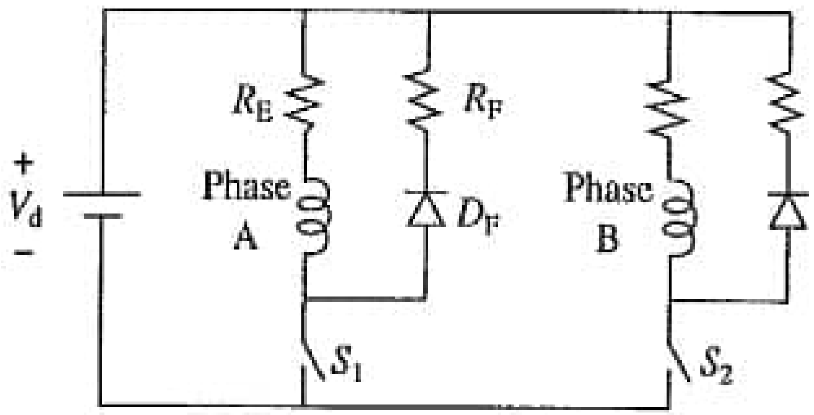


Fig. 8.9 Drive circuit requirement

- A Drive Circuits for Stepper Motor is usually driven from a low voltage dc source.
- When a phase is to be energised, the dc source is connected to the phase by a semiconductor switch S
- The phase current builds up at the rate decided by the phase winding's electrical time constant.
- When the phase is to be de-energised, switch is turned off, which transfers the current to freewheeling diode D_F.
- The current drops to zero, again at the rate decided by the time constant of the phase winding.
- Motor torque, which is a function of i_{ph}, builds up and decays in the same manner.
- In order to maximize torque capability of a stepper motor, current builds up and decay as fast as possible, ideally as shown by dotted lines in Fig. (b).
- This is specially important when high stepping rates are required, as demonstrated in Fig. (c). The Drive Circuits for Stepper Motor are designed to incorporate this requirement.

i. Unipolar Drive for Variable Reluctance Motors

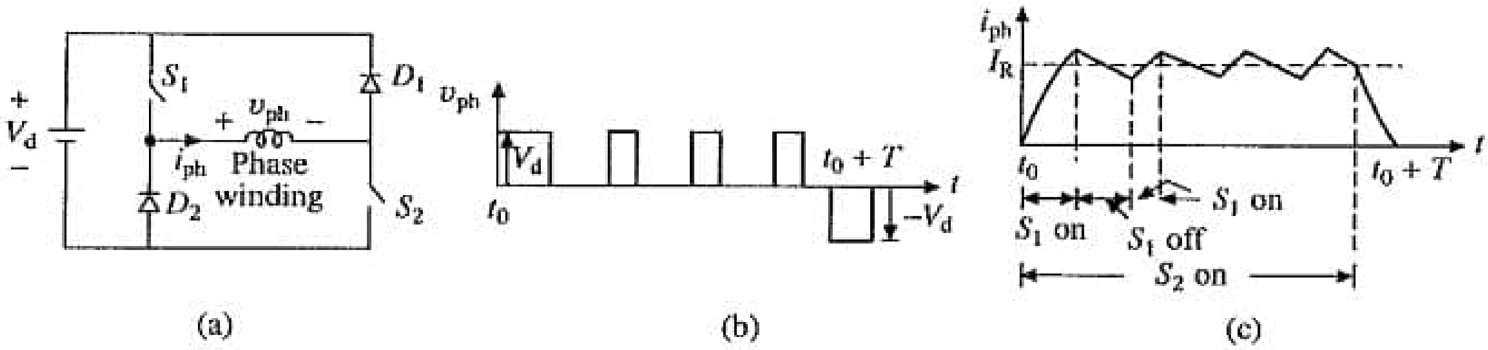


g. 8.10 Unipolar drive circuit for a low power variable reluctance motor

- In case of variable reluctance motors, phase currents need only be switched on or off and the current polarity does not matter.
- Unipolar drive, which is capable of supplying current only in one direction, is sufficient.
- Unipolar drive circuit for low power two phase variable reluctance motor is shown in Fig.
- When switch S_1 is closed, phase A winding is connected to the dc source V_d and the phase current builds up
- When S1 is opened, the phase current decays in the freewheeling path consisting of phase A, D_F and R_F.
- The external resistor R_E reduces the electrical time constant, speeding up the current build-up.

$$V_d = I_R(R_E + R_P)$$

- During on period of the switch, phase current also flows through the external resistor R_E, energy dissipated in R_E.
- Further, energy stored in the phase winding inductance during the on period of the switch is all dissipated in free-wheeling circuit resistances when the switch is turned off

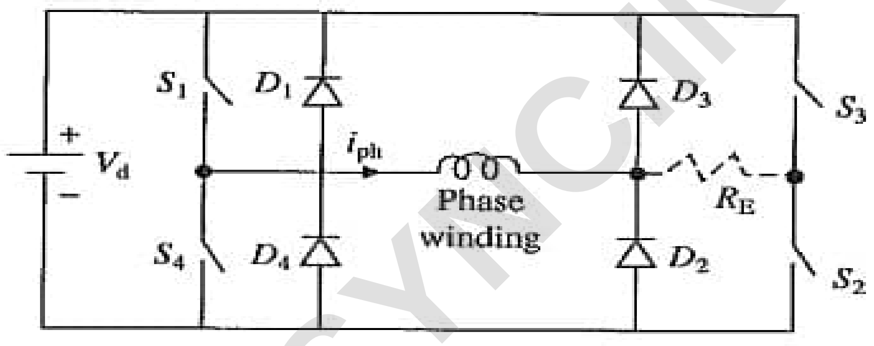


Efficient unipolar drive for variable reluctance motor

(a) (b) and (c) show drive circuit, phase voltage and current waveforms respectively

- An efficient unipolar drive circuit is shown in Fig. It uses chopper principle.
- To energise the phase, semiconductor switches S1 and S2 are closed at t = to.
- This connects phase winding to the dc source voltage Vd and phase current iph builds up fast.
- When it crosses the rated current I_R, S1 is switched off.
- The phase current freewheels through S2 and D2 and decreases below I_R.
- After a fixed interval, S1 is turned on. Phase current iph increases.
- When it exceeds the rated current IR, again S1 is turned off.

ii. Bipolar Drive for Permanent Magnet and Hybrid Motors



Bipolar drive circuit

- The phase winding carries a positive current when semiconductor switches S1 and S2 conduct and it carries a negative current when S3 and S4 conduct.
- The phase winding is energised with a positive current when S1 and S2 are turned on.
- The external resistance RE reduces the electrical time constant allowing rapid build-up of phase current.
- The phase is de-energised by turning off S1 and S2. Winding current now flows through the path consisting of D3, source Vd and D4.
- The major proportion of energy stored in phase winding inductance is fed back to the source and phase current decays rapidly to zero.

Industrial Drives for Applications

Drives requirement for Industrial Applications

1. The torque-speed curve of the industrial load is required. This fixes up the type of motor required to drive the load.

2. The environmental conditions in the industry where the motor is located. This also decides the ambient temperature at which the motor operates.

3. Duty cycle of the load, and the frequency of starting and braking.

4 The speed control needed also decides the type of motor.

5. The necessary information is required to decide between the individual and group drive.

6. To meet certain specific duties in a particular application special designs of the motors may be required.

Drive Considerations for Textile Mills

Ginning (separating): The process of separating seeds from the raw cotton picked from the field is called ginning.

Blowing: The ginned cotton in the form of bales is opened up and is cleaned up very well in a blowing room.

Cording -The process of converting cleaned cotton into laps (sheet form of definite width and length) is done by lap machines which are normal three-phase standard squirrel cage motors.

Control of ac Motors to have Torque Control

It is clear that the motors used for textile applications must have

i. high starting torque
ii. torque control providing uniform acceleration so that the breakage of the yam is minimum and the quality of the product is improved.

	Starting torque	Overload capacity	Acceleration	Speed range	Speed control method	Type of motor
1. Textile mills ginning	Standard	Standard		Operating speed range 200 to 1500 rpm. The operation is however at constant speed.	No speed control is required as the operation is at constant speed and load.	Standard TEFC squirrel cage motor.
Cording	High starting torque. 2.75 to 3.5 times rated value.	High overload capacity 3.75 to 3.00 times rated value.	Should be capable of prolonged acceleration as the starting period is large proper rating must be there for the motor due to losses at starting.	Operating speed is 600 rpm or 700 rpm. Constant speed operation.	No speed control.	Slip ring rotor with rotor resistance starting. High torque motors with DOL starting.
Spinning	150–200% of rated value	200– 275% of rated value.	Acceleration must be constant or uniform so that there is no breakage of thread.	Constant speed operation.	Two speed motors are preferred.	Ring frame motors.
Looms	2 to 2.3 times the rated torque.	2.3 to 2.7 times rated torque.	Frequent starts and stops.	Constant speed of operation.	No speed control.	Totally enclosed high torque squirrel cage motors 0.3 to 2.2 kW.

Table: Summary of requirements of motors for different industrial drives

Drives for Steel Rolling Mills

- Steel rolling mills are either hot rolled or cold rolled.
- These may be either reversing type or continuous type.
- The motors used for reversing mills need operation in both the directions of rotation.
- A four quadrant operation of the motor may be required.
- In the continuous type the motor rotates only in one direction.

i. <u>Reversing Hot Rolling Mills</u>:

- A wide range of speeds of operation is required.
- The direction of rotation must be reversible without causing serious disturbances to power handling circuits.
- High Reliability and accuracy.
- Ward Leonard control of dc motors is very much suitable here.
- Ac motors employing a variable frequency supply for speed control may be employed.
- The Cyclo-converter have advantages at very low speeds over the dc link converters.
- So, Cyclo-converter fed synchronous motors are used very commonly for driving steel mills, The converters facilitate four quadrant operation.

ii. <u>Continuous Hot Rolling Mills</u>

- When a mill has to produce billets of different sizes the gap between working rolls of the mill-stand must be adjustable.

- To be able to reduce the thickness of the metal gradually the motors of consecutive mill-stands must have differing speeds.
- The sag of the metal between two stands must be avoided.
- The dc motors controlled by Ward Leonard control, ac commutator motors and ac motors fed from thyristor converters may be advantageously employed here.

iii. <u>Reversing Cold Rolled Mills</u>

- The drive must be capable of reverse rotation. A four quadrant operation must be possible.
- One or two individually driven motors may be used.
- The coiling motors besides the driving coilers ensure the desired tension of the strip between the coilers and mill-stand.
- The gap adjustment must he made simultaneously with the reversing.
- The inertia of the motor must be kept low and lower than that of the rollers.
- Torque control as well as speed control must be possible to maintain constant tension
- of the strip.
- It is also limited by stability conditions of the motor. The armature current control may be employed beyond this limit.
- The acceleration of the drive must be uniform to avoid breaking.
- The motor selected for this purpose must have its torque developed, causing a smooth acceleration.
- It should be capable of four quadrant operation with smooth speed reversal. Torque control at different speeds must be possible.

iv. <u>Continuous Cold Rolling Mills</u>

- These work only in the forward direction and no reversing is required.
- The metal passes in one direction only in different stands till the product has the required thickness.
- The mill may be two high or four high.
- The coiler roller requires accurate torque and speed control.
- The strip tension must be constant and large.
- Low speed operation is required while threading the steel into the rolls.
- Immediately after the threading the speed of the motor must be increased.
- The thyristor power converters provide a variable frequency supply which can be used for speed control of ac motors. Both torque control and speed control are possible.
- For low speeds, cycloconverters can be used to give a smooth speed control.
- Thyristorized dc drives can be used in the place of Ward Leonard dc drives

Drive Considerations for Machine Tools

- The motors must be reliable and low cost, requiring less maintenance.
- They must be capable of speed control. Some applications may require operation at fixed speeds.
- Starting torque may vary from about 10% to 250% of full load torque depending upon the type of machine tool.

- The acceleration of the motor should be sufficiently fast to avoid motor heating during starting.
- The duty cycles are specified for the machine tool operations. The design of the machine tool depends upon the duty cycle.
- Peak loads of short duration may alternate with light load in certain operations. A smaller size motor may be selected if a flywheel is used.
- The motor should have sufficient speed regulation to make use of flywheel. High slip induction motors or cumulatively compound motors are used.
- Variable speed operation with constant torque at all speeds may be required in machine tools, such as grinder, planer, polishing, rapid reversing, etc. Variable speed operation with constant power also finds application.
- Some machine tools require very high speeds of operation. These are high speed grinders.
- Numerically controlled machine tools are being preferred to conventional machine tools.
- The requirements of the drive motor are fast response, wide range of speed control, low vibrations, better thermal capacity, low maintenance, etc. To have fast.
- Due to the simple, economical and robust construction, reliability and less maintenance, squirrel cage motors are suitable for driving machine tools.
- Till the advent of thyristor power converters which are capable of providing variable voltage, variable frequency supply, the speed control of these motors was a problem.
- Pole change multi speed motors are available when definite stepped speed operation is allowed.
- These connections are available for constant torque as well as constant power operation. They provide high and low speeds.

The motors for duty cycles S1-S6 are listed:

S1 -Hydraulic pump motors, lubrication pump motor, coolant pump motor.

S2 -Rapid transverse motor.

S3- Main motor for gear shaper, and for drilling machine.

S4- Main drive motor in lathes without clutch in the drive, work head motor in grinding machine, main drive motor in gear nobbing machine, coolant pump motor with frequent starting and stopping.

S5- Work head motor in grinding machine with electric braking.

S6- Main and feed drive motors with clutch in the drive.

Drive Considerations for Cranes & Hoist

- The motion of the crane hook is in all three dimensions.
- In crane drives, the acceleration and retardation must be uniform. This is more important than the speed control.
- For exact positioning of the load creep speeds must be possible.
- When the motion is in the horizontal direction braking is not a problem.
- The speed must be constant while lowering the loads. The steady braking of the motor against overhauling must be possible.

- The drive must have high speeds in both the directions. The motor must have high speeds at light loads.
- Mechanical braking must be available under emergency conditions.
- Power lowering may be used when an empty cage or light hooks are lowered.

The duty cycle of cranes depends upon some requirements. These are:

- it must be able to perform strenuous duty
- it must withstand high ambient temperature
- it must be able to work in a dusty atmosphere
- it must provide trouble free operation
- it should have rigid safety measures.
-

DC drive	*AC drive*
1. Fast acceleration and smooth speed control	All ac motors are not self starting
2. Speed-torque curve can be modified to suit the purpose in a simple manner with resistance in the armature or field circuit.	Induction motors are self starting. Squirrel cage motors require special designs for improved starting performance. Slip ring induction motors can be made to have improved starting performance by means of rotor resistance control.
They reduce the time cycle.	They have large time cycle.
3. Dc series motors have very high torque at low speeds particularly at zero speed, which is more attractive for crane operation.	
4. Frequent maintenance of the motor is required due to commutator	Less maintenance.
5. The drive motor and its control are costly	Squirrel cage motors are cheaper, simple in construction and robust.
6. Dc source is required. A rectifier may be used to convert ac to dc	
7. Inertia of the motor is high.	Inertia of cage motors is less.

Stages in Cement Production

The raw materials of cement are lime and silica. Alumina and ferric oxide are used as fluxing agents.

i. Collection of raw materials such as lime stone. This is transported to the mill site and crushed there if the quarry is far off. If the quarry is nearer it is crushed at the quarry itself and transported to the mill site.
ii. Grinding of this crushed lime stone after the addition with bauxite, iron ore, etc. By passing air through bottom the lime powder is homogenised
iii. This is fed to the cement kilns where the cement clinker is made at high temperature. The process where dry powder is used is called dry process.

iv. Wet processes of cement making are also popular. Here the slurry is made by crushing or grinding the lime stone, bauxite with water. This is then fed to the kiln through the kiln feed tank.

v. Dry process is preferred to wet process due to the reduced quantity of fuel required. However the latter becomes economical if the materials are already wet and drying them may not be economical.

vi. The hot clinker is then air cooled in special types of coolers and made ready for storage.

vii. After storing for a few days gypsum is added in required quantities and ground to the required fineness. Every stage has its own drive. Several drives in cement making are raw mill drives, cement mill drives, kiln drives, crusher drives, waste gas fan drives and compressor drives.

Requirement of Mill Motors

a. They should have high starting torque. The starting current must be limited to a maximum of two times full load value to minimise voltage dips. The breakdown torque should also be high so that sufficient overload capacity is available.
b. An overload capacity of 50% for one minute may be necessary, occurring for four times in an hour.
c. Three starts from cold conditions and two consecutive starts from hot conditions per hour against full load.

These are very well met by a three-phase slip ring induction motor. Suitable starting torques may be accomplished at reduced starting currents by means of rotor resistance. The motor must have sufficient thermal rating to have frequent starts both under cold as well as hot conditions. The power factor may be improved by capacitor bank.

Paper Mills

Process:

Paper making involves two main processes: pulp production and paper conversion.

Pulp is made either by a purely mechanical process or a combination of chemical and mechanical processes.

Purely mechanical pulp production involves grinding wood logs in large machines at a constant speed (200-300 rpm), often using synchronous motors with geared drives or cycloconverters.

Chemical and mechanical pulp production begins with chopping wood into smaller pieces, treating them with chemicals, and beating them into pulp using beaters. Suitable motors include slip ring induction motors for beaters and synchronous motors for processes like chipping and refining.

The paper conversion process includes several stages: wire (couch) section, pressing section, dryer, calender, and reel section.

Each section contributes to removing water from the pulp and forming it into sheets of paper, which are then wound up on a mandrel.

Paper making machine should satisfy the following requirements.

i. The speed of the paper machine must be constant in view of economy while forming the sheets of paper.
ii. A speed control range of 10:1 is required so that it is suitable for performing several jobs.
iii. The speeds of individual sections should be varied independently to allow an elongation of 5% of the web on the wet end of the paper. The quality of the paper is decided by this elongation. To allow free hanging of the web between sections, at the dry end of the paper a definite amount of tension is required and it must be regulated. The successive sections must be run at speeds with a definite difference. This relative speed between the sections also affects the pull on the paper. It must be regulated so that there is no tearing of the paper.
iv. The arrangement should be capable of taking up sag.
v. Even with correct speeds in the last two sections, uneven drying of the paper may cause variations in tension, which must be taken care of by suitable tension control.
vi. The motor must be capable of inching in order that the wire be cleaned up.
vii. Every section must be able to run at crawling speeds.
viii. The starting and acceleration of the sections must be smooth as well as. The starting system should be such that peaks of starting current may be avoided, besides obtaining sufficiently high accelerating torques for fast acceleration.