UNIT – 1

CHARACTERISTICS OF ELECTRICAL DRIVES

Speed – torque characteristics of various types of loads and drives motors:

Classification of load torques:

1. Active Load torques
2. Passive Load torques

Active Load Torques:

Load torques which have the potential to drive the motor under equilibrium conditions are called active load torques.

Load torques usually retain sign when the drive rotation is changed.

Passive Torque:

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

Torque due to friction cutting – Passive torque.

Components of load torques:

1. Friction Torque (TF)

The friction torque (TF) is the equivalent value of various friction torques referred to the motor shaft.

2. Windage Torque (Tw)

When a motor runs, the wind generates a torque opposing the motion. This is known as the winding torque.

3. Torque required to do useful mechanical work (Tm)

Nature of the torque depends of type of load.

It may be constant and independent of speed, some function of speed, may be time invariant or time variant.

The nature of the torque may change with the change in the loads mode of operation.

Characteristics of different types of load:

In electric drives the driving equipment is an electric motor.

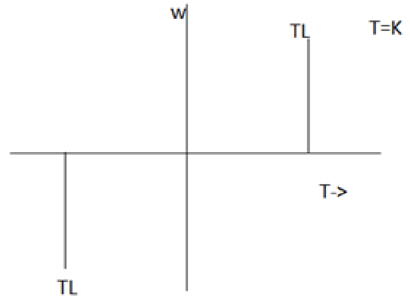
Selection of particular type of motor driving an m/c is the matching of speed-torque characteristics of the driven unit and that of the motor.

· Different types of loads exhibit different speed torque characteristics.

· Most of the industrial loads can be classified into the following 4 general categories:

1. Constant torque type load.
2. Torque proportional to speed (generator type load)
3. Torque proportional to square of the speed (fan type load)
4. Torque inversely proportional to speed (constant power type load)

1. Constant Torque Characteristic:

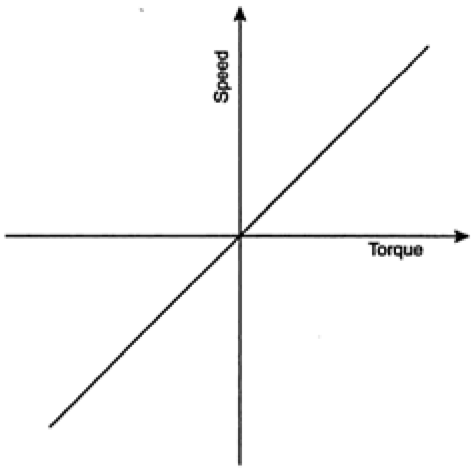


The speed – torque characteristic of this type of load is given by T=K.

Working motor have each mechanical nature of work like shaping , cutting, grinding or sharing, require constant torque irrespective of speed. Similarly cranes during the hoisting.

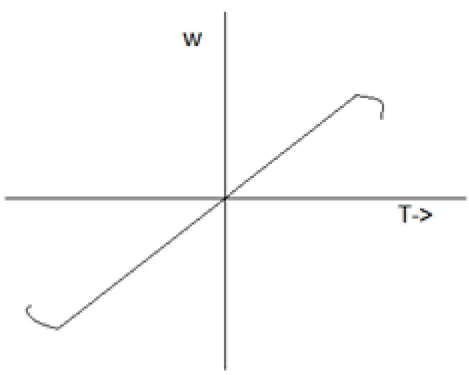
Similarly cranes during the hoisting and conveyors handling constant weight of material / unit, time also exhibit this type of characteristics.

Torque proportional to speed:



Separately executed dc generators connected to a constant resistance load, eddy current brakes and calendaring m/cs have a speed torque characteristics m/cs have a speed – torque characteristics given by T= Kw.

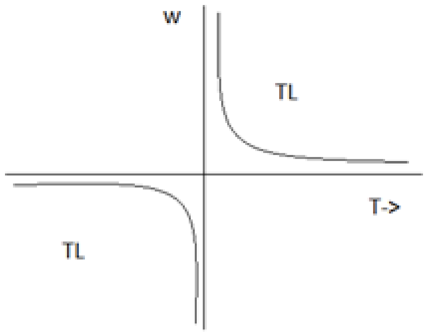
Torque propositional to square of the speed:



Load Torque Square of speed

Example: Fans, Rotary pumps, compressors, ship propellers. The speed – torque characteristics of this type of load is given by

Torque inversely propositional to speed:



· In such types of loads, torque is inversely proportional to speed or load power remains constant.

· E.g.: Lathes, boring m/cs, milling m/cs, steel mill coiler and electric traction load.

· This type of characteristics is given by

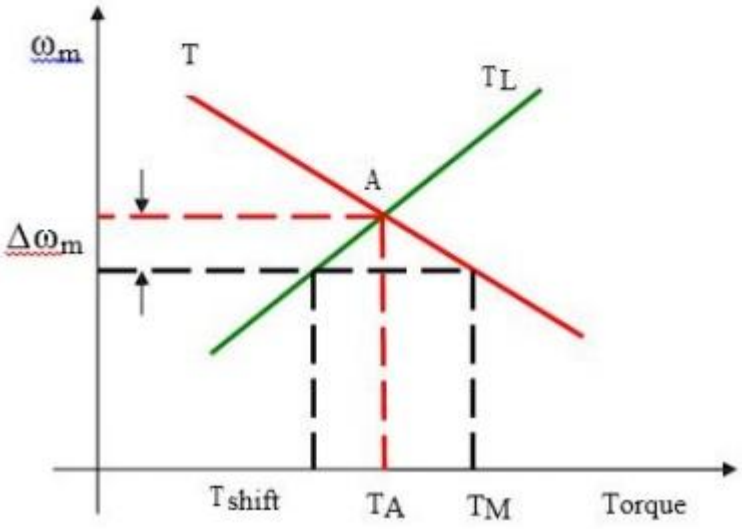
· Most of the load require extra effort at the time of starting to overcome static friction. In power application it is known as brake away torque and load control engineers call it "stiction". Because of stiction, the speed torque characteristics of the load is modified near to zero speed.

Joint speed – torque characteristics

Equilibrium speed of motor-load system can be obtained when motor torque equals the load torque. Electric drive system will operate in steady state at this speed, provided it is the speed of stable state equilibrium.

Concept of steady state stability has been developed to readily evaluate the stability of an equilibrium point from the steady state speed torque curves of the motor and load system. In most of the electrical drives, the electrical time constant of the motor is negligible compared with the mechanical time constant. During transient condition, electrical motor can be assumed to be in electrical equilibrium implying that steady state speed torque curves are also applicable to the transient state operation.

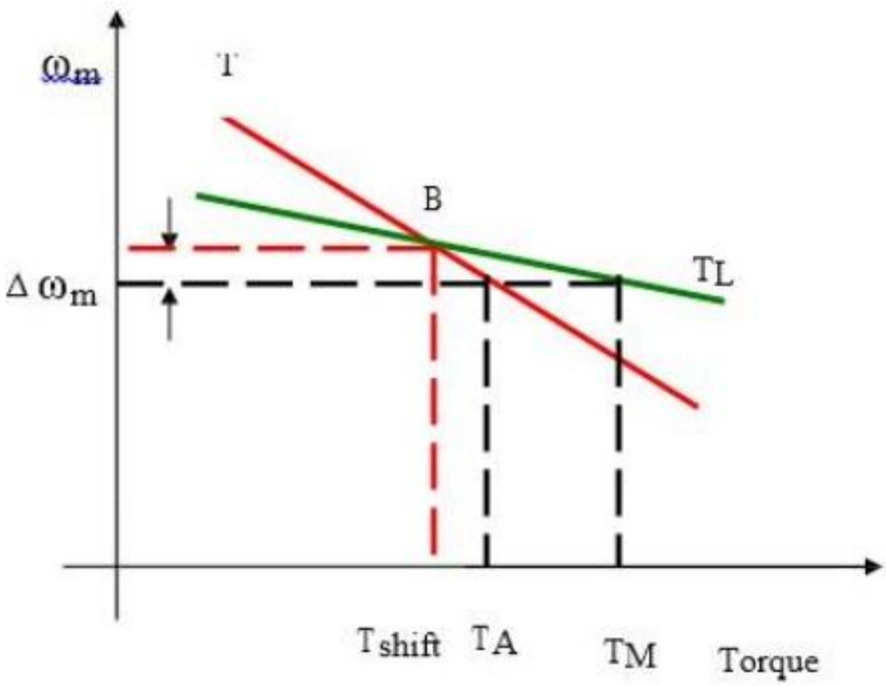
Now, consider the steady state equilibrium point A shown in figure below



Now consider equilibrium point B which is obtained when the same motor drives another load as shown in the figure.

A decrease in speed causes the load torque to become greater than the motor torque, electric drive decelerates and operating point moves away from point B.

Similarly when working at point B and increase in speed will make motor torque greater than the load torque, which will move the operating point away from point B.



Basics of Regenerative Braking

In the regenerative braking operation, the motor operates as generator, while it is still connected to the supply. Here, the motor speed is greater than the synchronous speed.

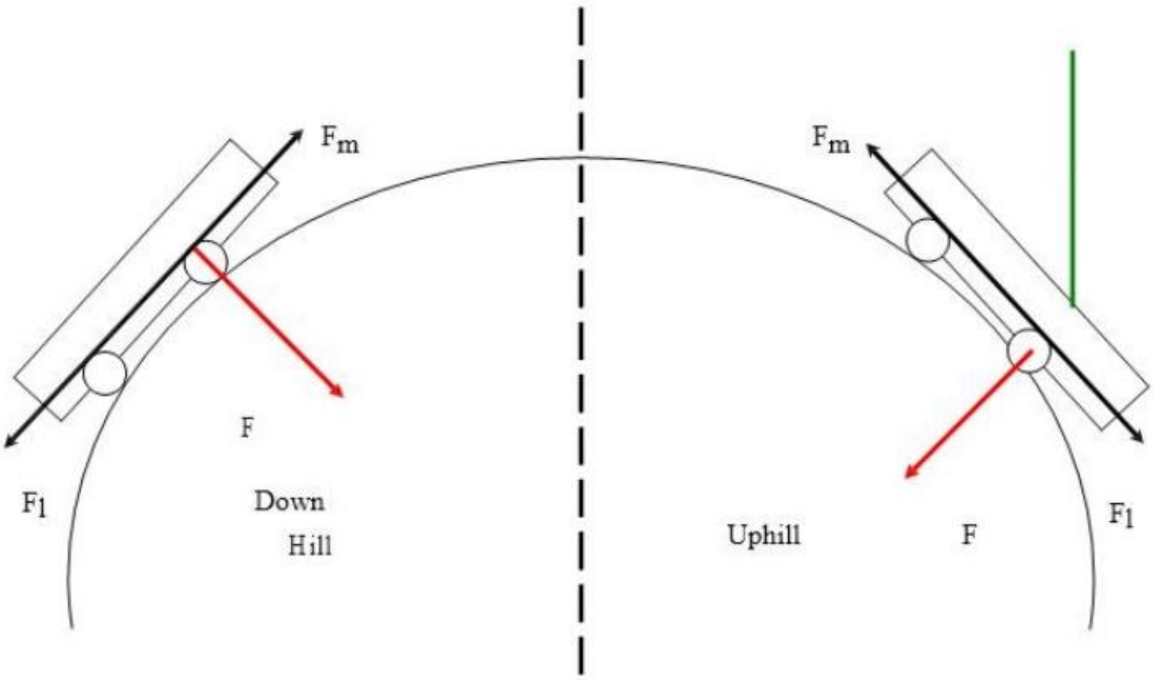
Mechanical energy is converted into electrical energy, part of which is returned to the supply and rest of the energy is last as heat in the winding and bearings of electrical machines pass smoothly from motoring region to generating region, when over driven by the load.

An example of regenerative braking is shown in the figure below. Here an electric motor is driving a trolley bus in the uphill and downhill direction. The gravity force can be resolved into two components in the uphill direction.

One is perpendicular to the load surface (F) and another one is parallel to the road surface Fl. The parallel force pulls the motor towards bottom of the hill.

If we neglect the rotational losses, the motor must produce force Fm opposite to Fl to move the bus in the uphill direction.

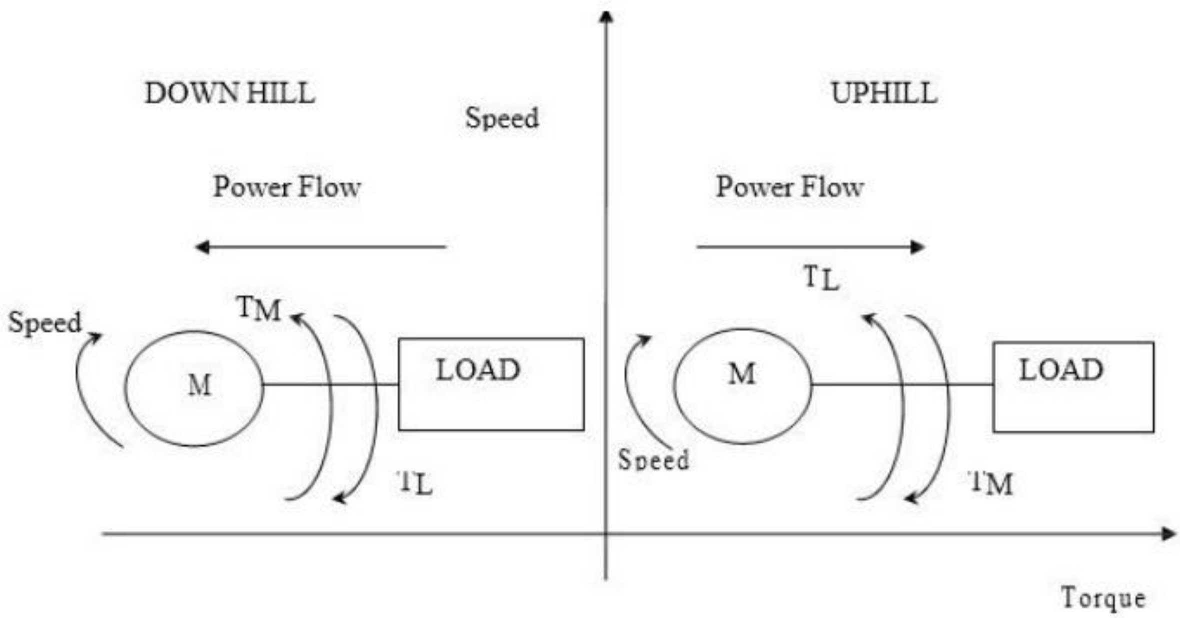
Here the motor is still in the same direction on both sides of the hill. This is known as regenerative braking. The energy is exchange under regenerative braking operation is power



flows from mechanical load to source.

This operation is indicated as shown in the figure below in the first quadrant. Here the power flow is from the motor to load.

Now we consider that the same bus is traveling in downhill, the gravitational force doesn't change its direction but the load torque pushes the motor towards the bottom of the hill. The motor produces a torque in the reverse direction because the direction of the motor torque is always opposite to the direction of the load torque.



Here the motor is still in the same direction on both sides of the hill. This is known as regenerative braking. The energy is exchange under regenerative braking operation is power flows from mechanical load to source. Hence, the load is driving the machine and the machine is generating electric power that is returned to the supply.

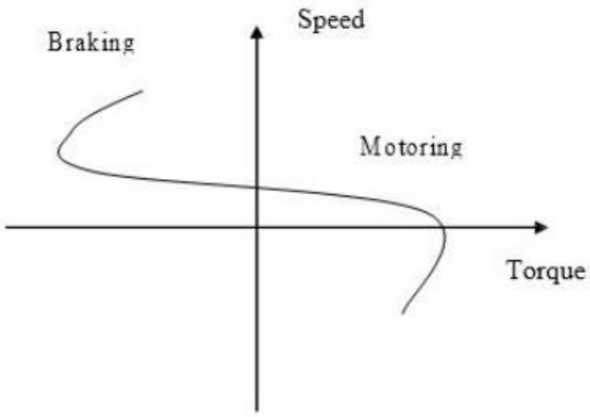
Regenerative braking of Induction motor:

An induction motor is subjected to regenerative braking, if the motor rotates in the same direction as that of the stator magnetic field, but with a speed greater than the synchronous speed. Such a state occurs during any one of the following process.

- Downward motion of a loaded hoisting mechanism
- During flux weakening mode of operation of IM.

Under regenerative braking mode, the machine acts as an induction generator. The induction generator generates electric power and this power is fed back to the supply. This machine takes only the reactive power for excitation.

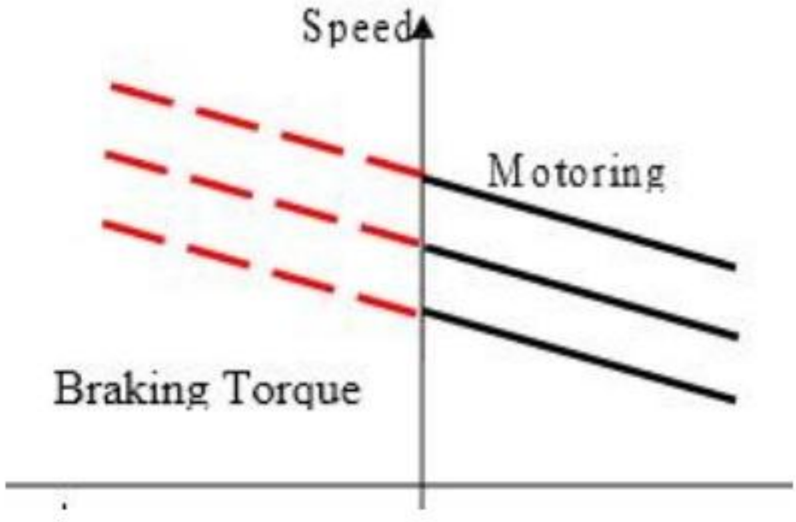
The speed torque characteristic of the motor for regenerative braking is shown in the figure.



Regenerative Braking for DC motor:

In regenerative braking of dc motor, generated energy is supplied to the source. For this the following condition is to be satisfied.

$E > V$ and I_a should be negative



Modes of Operation:

An electrical drive operates in three modes

- Steady state
- Acceleration including Starting
- Deceleration including Stopping

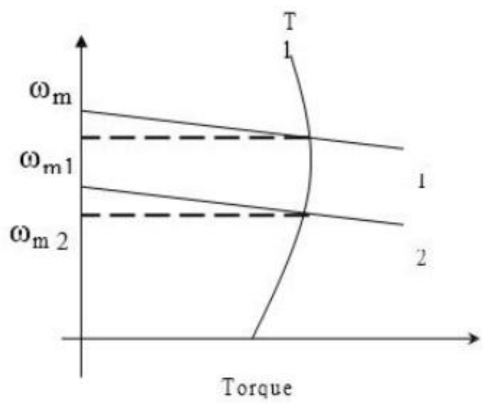
We know that

$$T=T_1 + J\, d/dt\, (\omega_m)$$

According to the above expression the steady state operation takes place when motor torque equals the load torque. The steady state operation for a given speed is realized by adjustment of steady state motor speed torque curve such that the motor and load torques are equal at this speed. Change in speed is achieved by varying the steady state motor speed torque curve so that motor torque equals the load torque at the new desired speed. In the figure shown below when the motor parameters are adjusted to provide speed torque curve 1, drive runs at the desired speed$\omega_{m\,1}$.

Speed is changed to $\omega_{m\,2}$ 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.



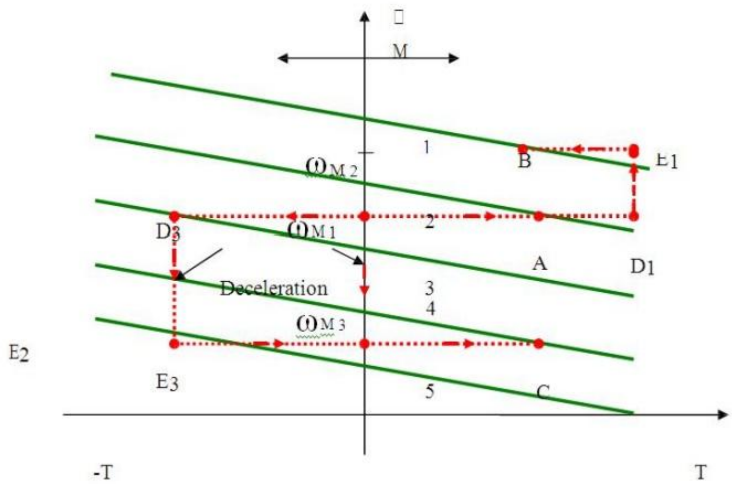
Acceleration and Deceleration modes are transient modes. Drive operates in acceleration mode whenever an increase in its speed is required. For this motor speed torque curve must be changed so that motor torque exceeds the load torque. Time taken for a given change in speed depends on inertia of motor 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. Care must be taken to restrict the motor current with in a value which is safe for both motor and power modulator. In applications involving acceleration periods of long duration, current must not be allowed to exceed the rated value. When acceleration periods are of short duration a current higher than the rated value is allowed during acceleration.

In closed loop drives requiring fast response, motor current may be intentionally forced to the maximum value in order to achieve high acceleration. Figure shown below shows the transition from operating point A at speed.

Point B at a higher speed$\omega_{m\ 2,}$ when the motor torque is held constant during acceleration. The path consists of AD1E1B. In the figure below, 1 to 5 are motor speed torque curves. Starting is a special case of acceleration where a speed change from 0 to a desired speed takes place. 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 step lessly from its zero value. Such a start is known as soft start.



Electric Motor Power Rating:

Power rating for electrical machines indicates the required supply voltage for smooth running of that machine, it also shows the permissible maximum amount of current which can easily flows through the machine and there will be a chance of breakdown in the machine if those parameters goes beyond this limit.

Similarly when we discuss about motor power rating, we are looking for the suitable conditions where maximum efficiency is obtained from the electric motor. When the motor have insufficient rating, there will be frequent damages and shut downs due to over loading, and this is not intended.

On the other hand, if the power rating of a motor is decided liberally, the extra initial cost and then loss of energy due to operation below rated power makes this choice totally uneconomical. Another essential criteria of electrical motor power rating is that, during operation of motor, heat is produced and it is inevitable due to I^2R loss in the circuit and friction within the motor. So, the ventilation system of the motor should be designed very carefully, to dissipate the generated heat as quickly as possible. The output power of the motor is directly related with the temperature rise, that's why it is also called thermal loading. The thermal dissipation will be ideal when the ventilation system is designed in such a way that the heat generated during the operation is equal to or less then heat dissipated by the motor to the surrounding. Now, due to the design of motors, temperature is not same everywhere inside the motor. There is a high amount of heat produced in the windings because, windings cause higher heat generation. The insulating materials used in the winding are also chosen depending on the amount of heat generated inside the motor during operation. So in the end it can be said that the main objectives of selecting and finding out motor power rating are

- To obtain the suitable thermal model of motor and design the machine properly.
- Finding out motor duty class.
- Calculating motor ratings for various classes of duty.

Selection of Motor Power Rating:

- Selection of power rating is important to achieve economy with reliability.
- Improper selection of motor power rating results extra initial cost and extra loss of energy due to the operation below rated power makes the choice uneconomical.
- Furthermore, induction and synchronous motors operate at a low power factor when operating below the rated power.
- During operation of the machine, heat is produced due to losses and temperature rises. An amount of developed heat is dissipated into the atmosphere. When the dissipation of heat is equal to the developed heat, then it is said to be equilibrium condition. "Motor temperature then reaches a steady state value.
- Steady state temperature depends on power loss, which in turn depends on the output power of the machine. Since temperature rise has a direct relation with the output power, it is termed thermal loading on the machine.
- Steady state temperature varies in different parts of the machine. It is usually high is the windings because loss density in conductors is high and dissipation is slow; and the conductors which are wrapped in insulating material are partly embedded in slots and thus are not directly exposed to the cooling air.

Insulating materials have lowest temperature limit. $hey are classified based on temperature limit as follows:

Insulation Class	Temperature (in ^{0}C)
γ	90
A	105
E	120
B	130
F	155
H	180
C	>180

- "Motor rating should be selected in such a way that the insulation temperature never exceeds the prescribed limit; otherwise it loses its thermal stability.
- It is simple to calculate the motor power rating of the motor which operate at a constant power and speed. But most loads operate at variable power and speed at different applications.

Thermal model of Motor for Heating and Cooling:

- It is difficult to predict the heat flow and temperature rise inside an electrical motor because of its complex geometry and heterogeneous materials.

Load equalization:

Load equalisation is the process of smoothing the fluctuating load. The fluctuate load draws heavy current from the supply during the peak interval and also cause a large voltage drop in the system due to which the equipment may get damage. In load equalisation, the energy is stored at light load, and this energy is utilised when the peak load occurs. Thus, the electrical power from the supply remains constant.

The load fluctuation mostly occurs in some of the drives. For example, in a pressing machine, a large torque is required for a short duration. Otherwise, the torque is zero. Some of the other examples are a rolling mill, reciprocating pump, planning machines, electrical hammer, etc.

In electrical drives, the load fluctuation occurs in the wide range. For supplying the peak torque demand to electrical drives the motor should have high ratings, and also the motor will draw pulse current from the supply. The amplitude of pulse current gives rise to a line voltage fluctuation which affected the other load connected to the line.

Method of Load Equalisation:

The problem of load fluctuation can be overcome by using the flywheel. The flying wheel is mounted on a motor shaft in non-reversible drives. In variable speed and reversible drive, a flywheel cannot be mounted on the motor shaft as it will increase the transient time of the drive. If the motor is fed from the motor generator set, then flywheel mounted on the motor generator shaft and hence equalises the load on the source but not load on the motor.

When the load is light, the flywheel accelerated and stored the excess energy drawn from the supply. During the peak load, the flying wheel decelerates and supply the stored energy to the load along with the supply energy. Hence the power remains constant, and the load demand is reduced.

Moment of inertia of the flying wheel required for load equalisation is calculated as follows. Consider the linear motor speed torque curve as shown in the figure below.

$$\omega_m = \omega_{m0} - \frac{\omega_{m0} - \omega_{mr}}{T_r} \times T \ldots\ldots\ldots\ldots equ(1)$$

Assumed the response of the motor is slow due to large inertia and hence applicable for transient operation. Differentiate the equation (1) and multiply both sides by J (moment of inertia).

$$J\frac{d_{\omega m}}{dt} = \frac{J(\omega_{m0} - \omega_{mr})}{T_r}\frac{dT}{dt} \ldots\ldots\ldots\ldots equ(2)$$

$$J\frac{d_{\omega m}}{dt} = -T_m\frac{dT}{dt} \ldots\ldots\ldots\ldots equ(3)$$

$$T_m = \frac{(\omega_{m0} - \omega_{mr})}{T_r} \ldots\ldots\ldots\ldots\ldots\ldots equ(4)$$

Where T_m is the mechanical time constant of the motor. It is the time required for the motor speed to change by ($\omega_{m0} - \omega_m$) when motor torque is maintained constant at rated value τ_r. Fromequation(2)and(3)

$$T_m\frac{dT}{dt} + T = T_l \ldots\ldots\ldots equ(5)$$

Consider a periodic load torque a cycle which consists of one high load period with torque T_{lh} and duration the, and one light load period with torque T_{ll} and duration t_l

$$T = T_{lh}\left(1 - e^{-t/\tau_m}\right) + T_{max}e^{-t/\tau_m} \ldots\ldots equ(6)$$

$$for\ 0 \le t \le t_h$$

Where T_{min} is the motor torque at t = 0 which is also the instant when heavy load T_{lh} is applied. If motor torque at the end of heavy load period is T_{max}, then from the equation (6)

$$T_{max} = T_{lh}\left(1 - e^{-t/\tau_m}\right) + T_{max}e^{-t/\tau_m} \ldots\ldots equ(7)$$

Solution of equation (5) for the light load period with the initial motor torque equal to T_{max} is

$$T = T_{ll}\left(1 - e^{-t/\tau_m}\right) + T_{max}e^{-t/\tau_m} \ldots\ldots equ(8)$$

$$for\ 0 \le t' \le t_h$$

Where $t' = t - t_h$

When operating at steady state the motor torque at the end of a cycle will be the same as at the beginning of a cycle. Hence at $t' = t_l$, $T = t_{min}$.

Substituting in equation (8) give

$$T_{min} = T_{ll}\left(1 - e^{-t/\tau_m}\right) + T_{max}e^{-t/\tau_m} \dots\dots. equ(9)$$

From equation (7)

$$\tau_m = \frac{t_h}{log_e\left(\frac{T_{lh} - T_{min}}{T_{lh} - T_{max}}\right)} \dots\dots\dots\dots. equ(10)$$

From equation (4) and (10)

$$J = \frac{T_r}{(\omega_{m0} - \omega_{mr})} \times \frac{t_h}{log_e\left(\frac{T_{lh} - T_{min}}{T_{lh} - T_{max}}\right)} \dots\dots\dots\dots. equ(11)$$

Also from equation (9)

$$\tau_m = \frac{t_1}{log_e\left(\frac{T_{lh} - T_{min}}{T_{lh} - T_{max}}\right)} \dots\dots\dots\dots. equ(12)$$

From equation (4) and (11)

$$J = \frac{T_r}{(\omega_{m0} - \omega_{mr})} \times \frac{t_1}{log_e\left(\frac{T_{lh} - T_{min}}{T_{lh} - T_{max}}\right)} \dots\dots\dots\dots. equ(13)$$

Moment of inertia of the flywheel required can be calculated either from equation (11) and (12)

$$J = WR^2, kg - m^2 \dots\dots\dots\dots equ(14)$$

Where W is the weight of the wheel (Kg), and R is the radius (m).

Starting, braking and reversing operation:

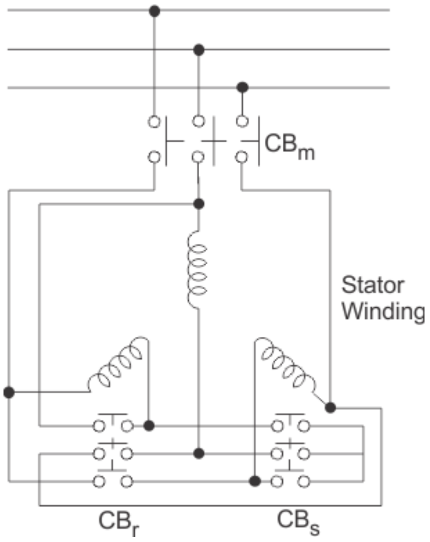
Starting of Induction Motors:

We know that the induction motor is self-starting i.e. when the supply is given to the motor it starts to rotate without any external help. When an induction motor is started as there is no resistance initially (i.e., during starting), there is a tendency of huge current flow through the rotor circuit which may damage the circuit permanently. To overcome this problem various methods have been introduced to limit the starting current. Some of the methods are

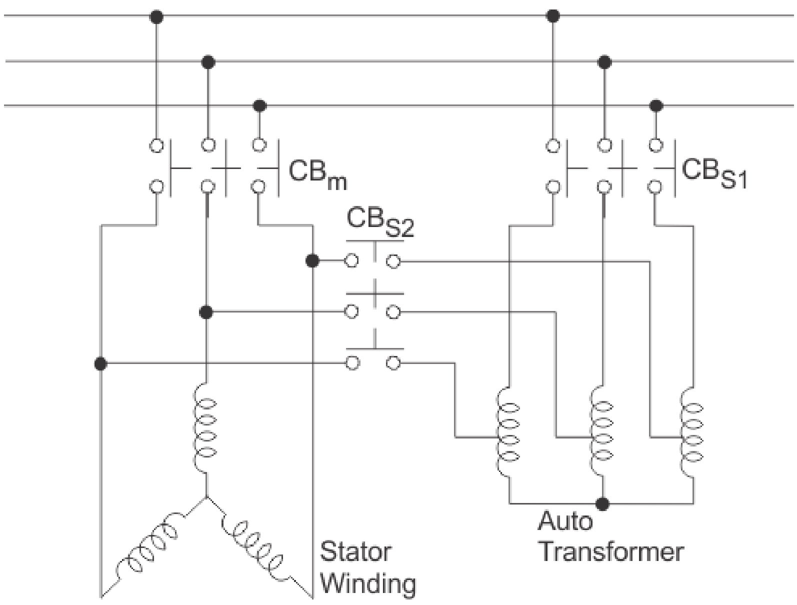
- Star delta starter
- Auto-transformers starter
- Reactor starter
- Saturable reactor starter
- Part winding starter
- AC voltage controller starter

- Rotor resistance starter is used for starting of wound rotor motor.

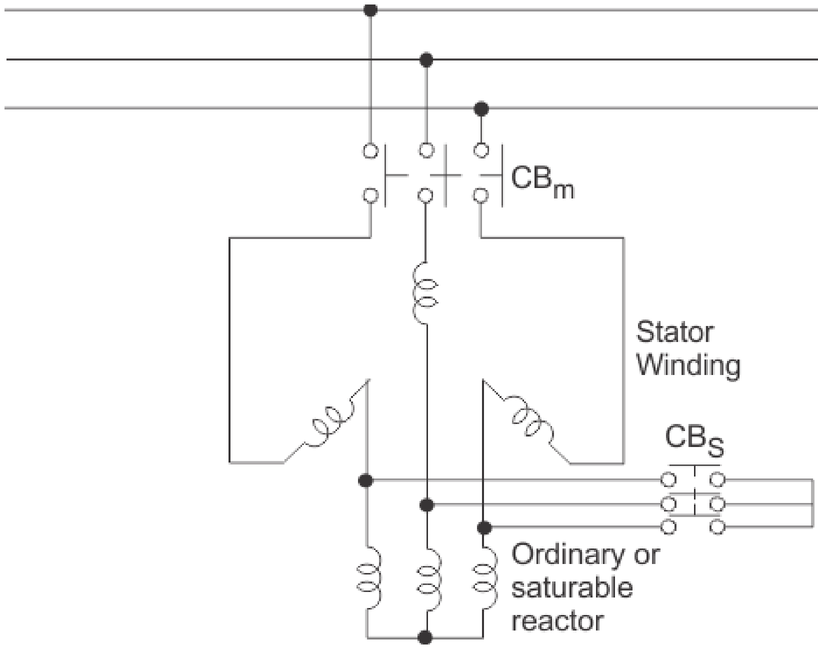
The induction motor drives are normally designed to run on delta connection, but during starting the supply is given from star connection because then the starter voltage and current reduces by 1/√3 times than the delta connection. When the motor reaches a steady state speed the connection changes from star to delta connection.



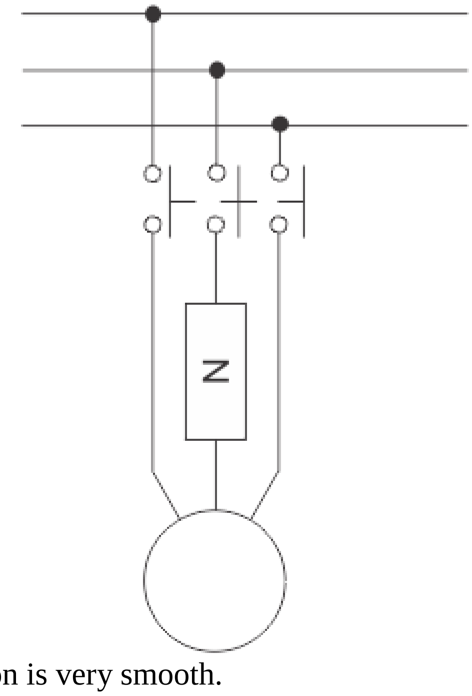
Another type of starting method of induction motors is the auto transformer starting. Since we know that the torque is proportional to square of the voltage. By auto transformers the starting voltage and current are reduced to overcome the problem of overheating due to very high current flow. During starting the ratio of the transformer is set in a way that the starting current does not exceed the safe limit. Once the induction motor starts running and reaches a steady state value, the auto transformer is disconnected from the supply. The circuit diagram is given here with

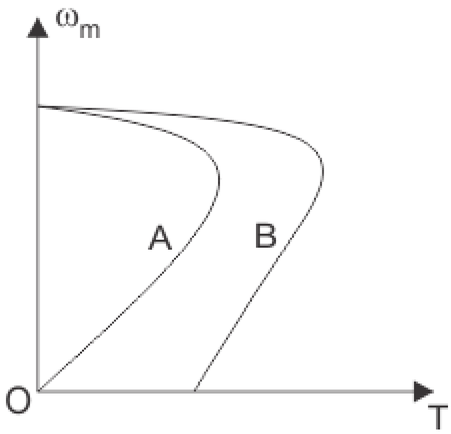


Another method of starting is soft start using saturable reactor drivers. In this method high reactance is introduced into the circuit so that the starting torque is closed to zero. Now the reactance is reduced smoothly during starting and the starting current increases and the torque also varies steplessly. In this method the motor starts without any jerk and the acceleration is smooth, that’s why its called soft start also.



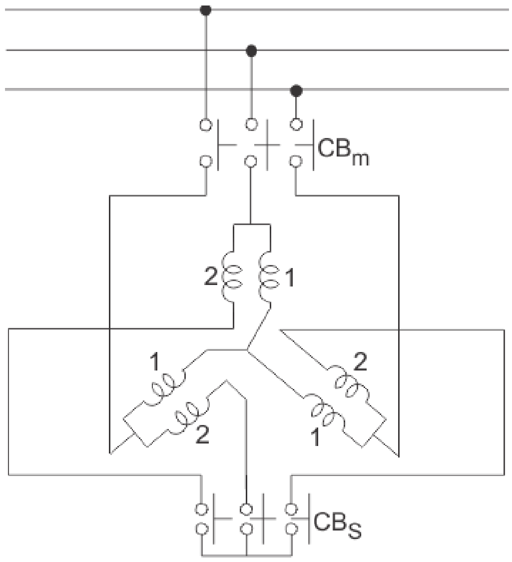
Unbalanced starting scheme for soft start is another type of starting method where the impedance is introduced only in one of the supply phases. During starting the impedance is kept very high so that the motor operates as a single phase motor, the speed torque characteristics at that time is similar to curve A in the graph. When the speed attains a steady state value the impedance is removed completely, at that time the curve is similar to B, which is the natural characteristics of the matine. This starting method is also without any jerk and the



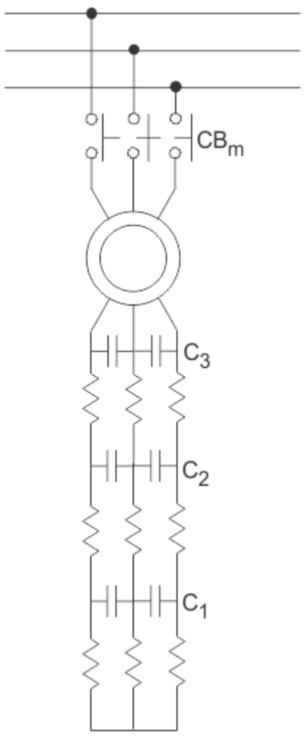


operation is very smooth.

Part winding starting method is special for squirrel-cage induction motors. In this method two or more starter winding are connected in parallel. When the motor starts, any one of the winding is connected as a result the starter impendence is increased and starting current is reduced. When the steady speed is acquired by the motor both the windings are connected.



Especially for wound rotor motors. Rotor resistance starter is used. In this method external resistors are used in the rotor circuit to limit the starting current. Maximum value of resistance is chosen to limit the current at zero speed within the safe value. As the speed increases, the sectional resistance is the temperature rise is lower than other methods of starting high acceleration, frequent starts and stops starting with heavy loads can be done with this type of starting method.



Braking of Induction Motors

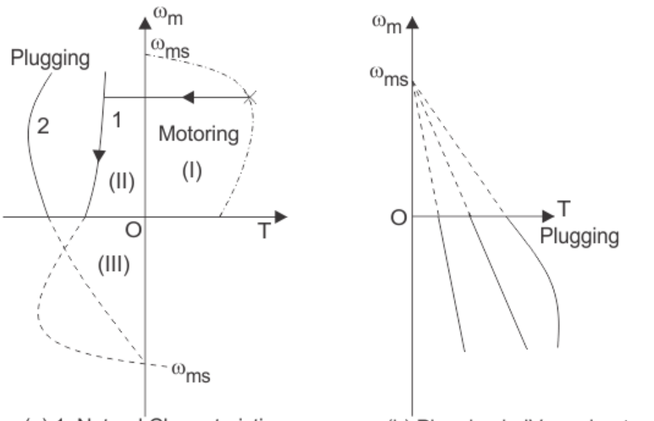
When it comes to controlling an electric machine by electric drivers braking is a very important term because it helps to decrease the speed of the motor according to will and necessity. Braking of induction motors can be classified mainly in three types

- Regenerative braking.
- Plugging or reverse voltage braking
- Dynamic braking which can be further classified as
- AC dynamic braking
- Self-excited braking using capacitors
- DC dynamic braking
- Zero sequence braking

To explain that regeneration braking for induction motor, we can take help of the equation

$$P_{in} = 3NI_s Cos\theta_s$$

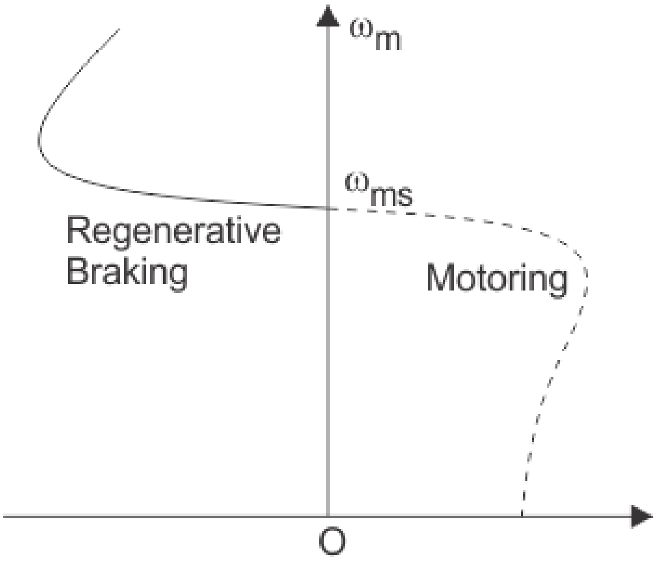
Here, θ_s is the phase angle between the stator voltage and stator current, the simple words whenever this phase angle exceeds 90° (i.e θ_s>90°) regenerative braking can take place. To explain this more clearly and easily we can say that whenever the speed of the rotor exceeds synchronous speed, regeneration braking occurs. That is because whenever the rotor rotates at a speed more than synchronous speed there is a reverse field occurs which opposes the normal rotation of the motor and therefore braking takes place. Main disadvantage of this type of braking is that the speed of the motor has to exceed synchronous speed which may not be possible every time. To acquire regenerative braking at a lower speed than synchronous speed, variable frequency source can be used.



(a) 1: Natural Characteristic
2: With external resistance
rotor

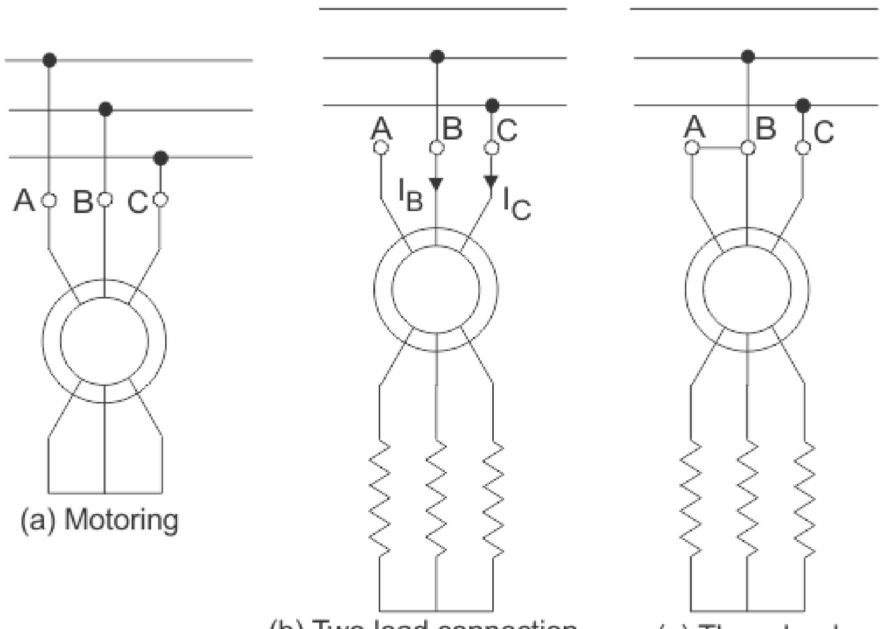
(b) Plugging in IV quadrant
with large external resistance
in rotor

Plugging of induction motors is done by interchanging any two of the supply terminals. When the terminals are reversed the operation of the machine changes from motoring to plugging. From technical point of view and for better understanding it can be said that the slip changes from‘s’ to (2-s), which indicates that due to reversal of the terminals the torque also changes its direction and braking occurs.

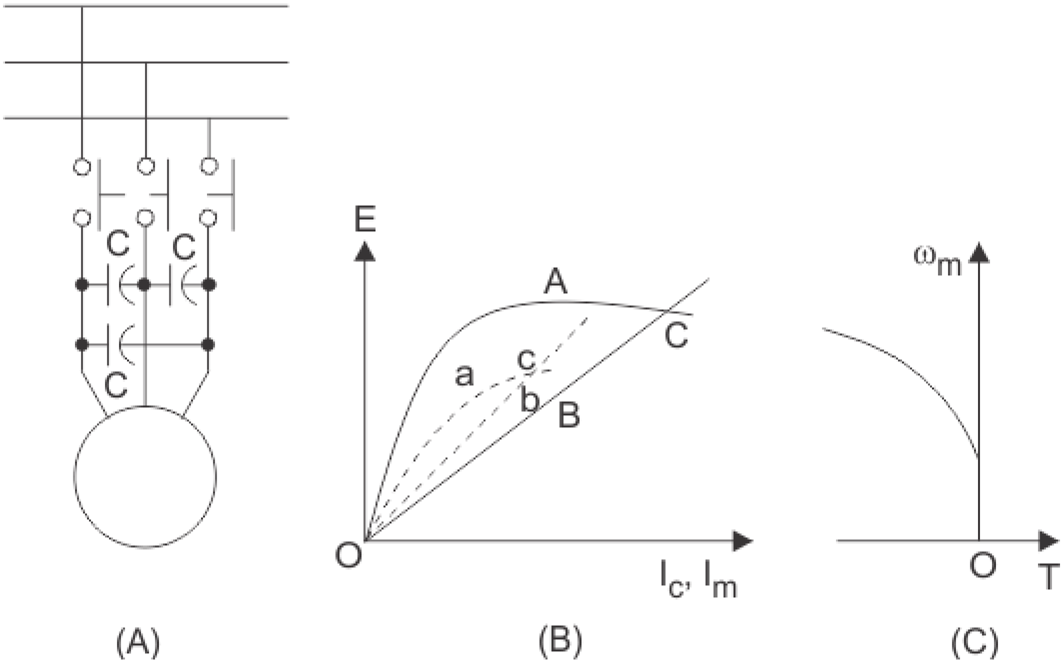


Regenerative Braking

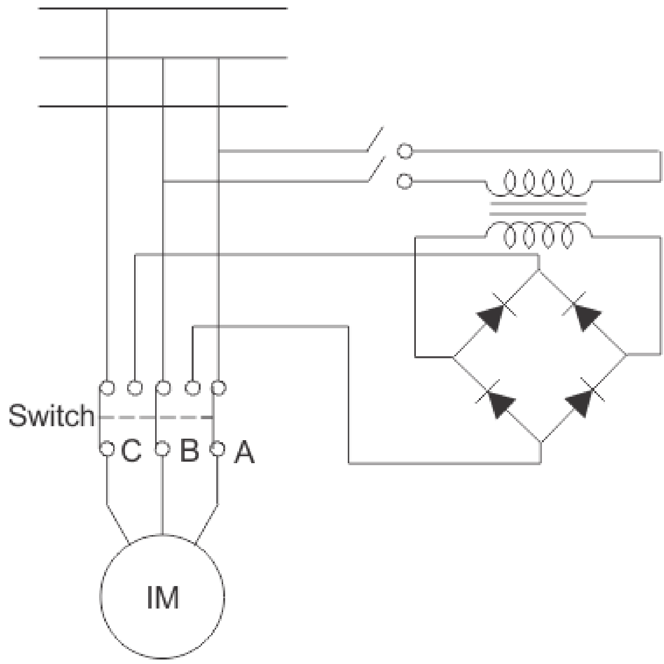
The first classification of dynamic braking of induction motors is AC dynamic braking any one of the supply phase is disconnected from the supply and then it is either kept open or connected with the other phase. The first type is known as two lead connection and the second one is known as three lead connection. To understand this braking method clearly we can assume the system to be a single phase system. Now the motor can be considered to be fed by positive and negative sequence voltages. That’s why when the rotor resistance is high the net torque is negative and braking can be acquired.



Sometimes capacitors are kept permanent by connected across the supply terminals of the motor. This is called self-excited braking using capacitors of induction motors. This type of braking works mainly by the property of the capacitors to store energy. Whenever the motor is disconnected from the supply the motor starts to work as a self-excited induction generator, the power comes from the capacitors connected across the terminals. The values of the capacitor are so chosen that they are sufficient to make the motor work as an induction generator after being disconnected from the supply. When the motor works as an induction generator the produced torque opposes the normal rotation of the motor and hence braking takes place.



Another type of dynamic braking is dc dynamic braking. In this method the stator of running induction motor drives is connected to dc supply. The consequences of connecting a dc supply to the stator is as follow, the DC current produces a stationary magnetic field, in the rotor keeps rotating and as a result there is a induced voltage in the rotor winding, therefore the machine works as a generator which opposes the motion of the motor and braking is acquired

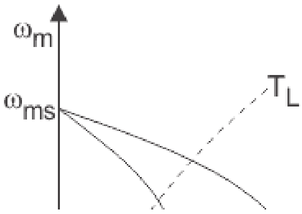


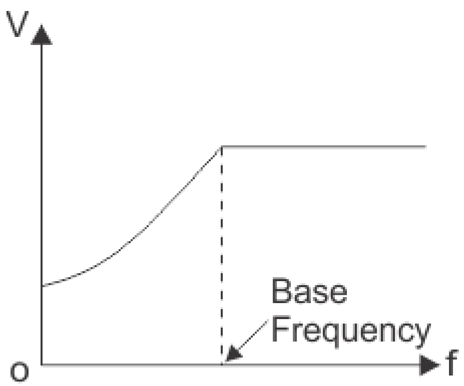
Speed Control of Induction Motors

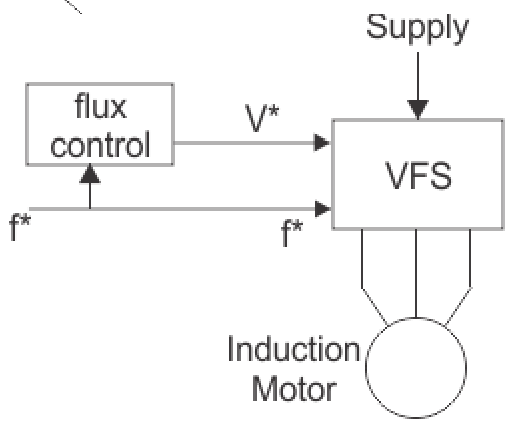
We have discussed about the starting and braking of induction motors but what about controlling the speed during the running time. **Speed control of induction motors** can be done in six methods which are

1. Pole changing
2. Stator voltage control
3. Supply frequency control
4. Eddy current coupling
5. Rotor resistance control
6. Slip power recovery

We know that the speed of the induction motor is inversely proportional to number of poles. So it is possible to increase or decrease the speed of the induction motor if the number of the poles are decreased or increased respectively. The motor in which the provision of changing the number of poles is present, they are called ‘pole changing motor’ or ‘multi speed motor’. Another method of controlling the speed of induction motor drives is the stator voltage control. Stator voltage is directly responsible for the rotating speed of the rotor. Torque is proportional to voltage squared and the current is proportional to the voltage. So, if the stator voltage is reduced the speed reduces and similarly if the stator voltage is increased the speed also increases.





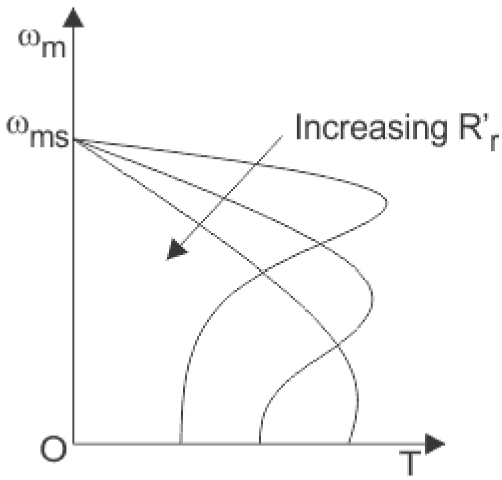


V-f relation

Variable frequency control

The speed of an induction motor is proportional to the product of the supply frequency and air gap flux. But as there is a chance of magnetic saturation while decreasing the supply frequency, that’s why not only the frequency but the v/f (i.e. the ratio of supply voltage and frequency) is controlled and this ratio is tried to be kept constant. And if the speed is needed to be changed the ratio of v/f is changed accordingly.

The eddy current speed control method is done by placing an eddy current clutch between an induction motor is running at a fixed speed and the variable speed load. Now what is this eddy current clutch? It is nothing but an induction motor drives in which both stator and the rotor are allowed to rotate. The rotor is coupled with the main induction motor. When eddy currents are produced in the rotor drum, their interaction with the stator field and a torque is produced which rotates the main motor. By controlling the DC current through the stator winding the speed of the motor can be controlled.



Rotor resistance control

Depending on the rotor resistance, the speed of the rotor falls or increases. The variation of speed torque characteristics with respect to change in rotor resistance is shown in the figures below. This speed controlling method is better than many other methods because of low cost.

Unit 2

DC Drives

Speed control of DC Motors

The basic principle of the DC motor is a device which converts DC energy into mechanical energy. When the current carrying armature is connected to the supply end though commentator segment, brushes are placed within the North South Poles of permanent or electromagnets. By using these electromagnets operating principle is depends on the Fleming's left hand rule to determine the direction of the force acting on the armature conductors of the DC motor.

Methods:

Speed of a DC motor can be varied by varying flux, armature resistance or applied voltage. Different speed control methods for different DC shunt and series methods are there.

Speed Control of Shunt Motors

- Flux control method
- Armature and Rheostatic control method
- Voltage control method

1. Multiple voltage control
2. Ward Leonard system

Speed Control of Series Motors

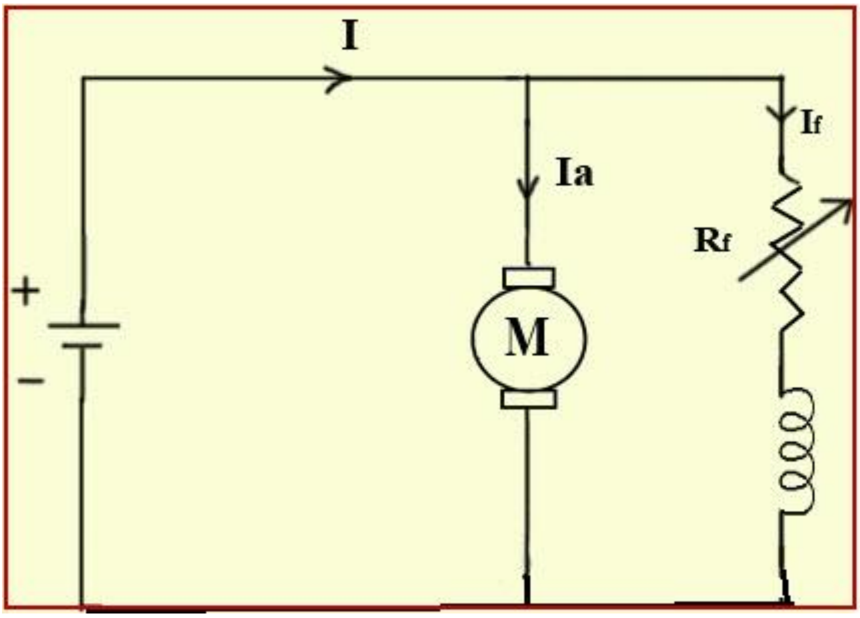
- Flux control method

1. Field diverter
2. Armature diverter
3. Trapped field control
4. Paralleling field coils

- Variable Resistance in series with motor
- Series -parallel control method

Flux Control Method

In this flux control method, speed of the motor is inversely proportional to the flux. Thus, by decreasing flux and speed can be increased vice versa. To control the flux, the rheostat is added in series with the field winding will increase the speed (N), because of this flux will decrease. So, the field current is relatively small and hence I2R loss is decreased. This method is quite efficient.



Armature Control Method

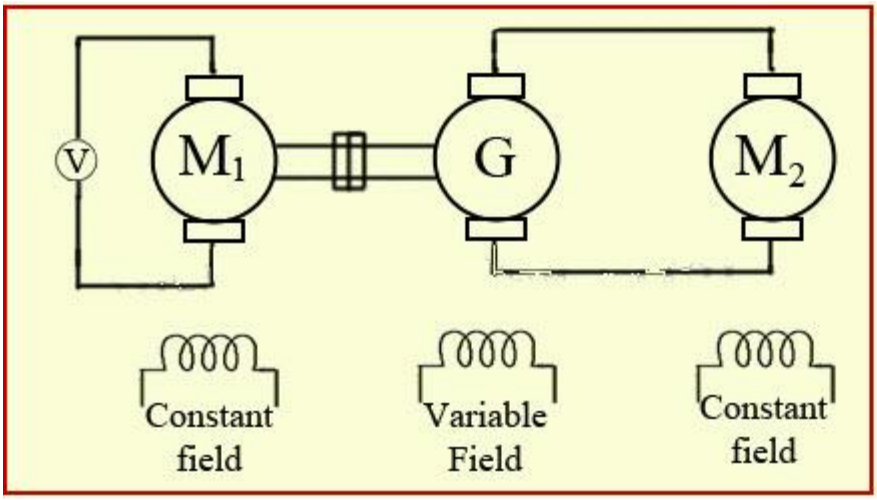
The basic equation of the armature control method, N is directly proportional to the V-ia (Ra+Rc) where Rc is controller resistance and Ra is the armature resistance. Due to the voltage back in the controller resistance the back EMF is decreased. Since N is directly proportional to the Eb.

Voltage Control Method of DC Motor

Multiple Voltage Control: In this method, the shunt field is connected to a fixed exciting voltage, and the armature is supplied with different voltages. So the Voltage across armature is changed with the help of a suitable switchgear devises. Armature speed is approximately proportional to the voltage across the armature.

Ward-Leonard System: This Ward –Leonard system is used where very sensitive speed control of the motor is required (e.g. electric excavators, elevators, etc.). The arrangement of this system is as required in the figure shown below.

M2 is the motor, it controls the speed of the generator. M1 may be any AC motor or DC motor with constant speed. G is the generator directly coupled to M1. In this method the output from the generator G is fed to the armature of the motor M2 whose speed is to be controlled. The generator output voltage can be connected to the motor M2 and it can be varied from zero to its maximum value, and hence the armature voltage of the motor M2 is varied very smoothly. Hence very smooth speed control of motor can be obtained by this method.



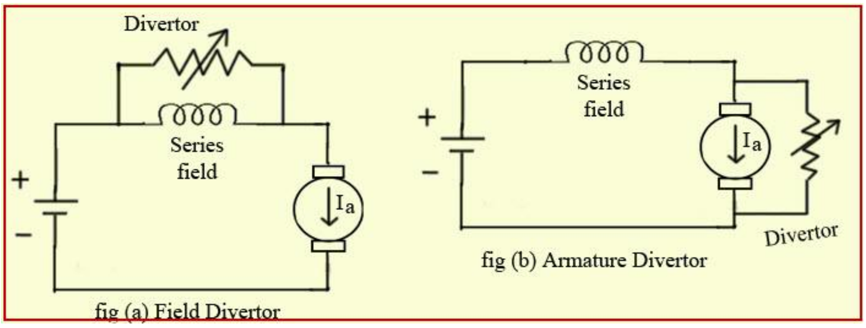
Ward Leonard System

Speed Control Of Series Motor

- ***Flux Control Method***

Field Diverter: A Rheostat is connected parallel to the series field as shown in fig (a). This variable resistor is also called as a diverter, as desired value of the current can be diverted through this resistor and hence current through field coil can be decreased. Hence flux can be decreased to desire amount and speed (N) can be increased.

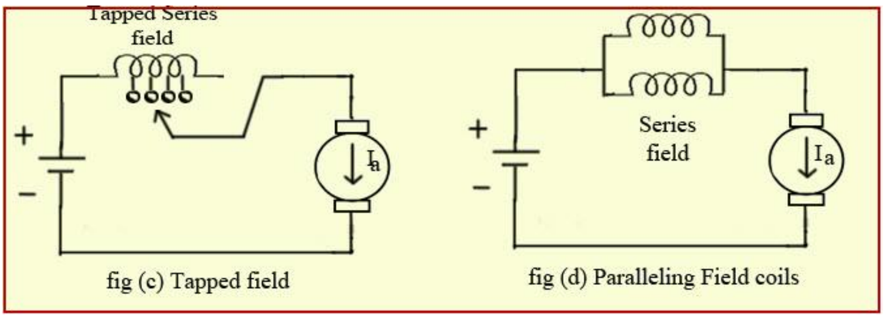
Armature Diverter: Rheostat (Divider) is connected across the armature of the coil as shown in fig (b). For a given constant load torque, if armature current is reduced, then flux must increase. As armature torque Ta α ØIa. This will result in an increase in current taken from the supply and hence flux Ø will increase and subsequently speed of the motor will decrease.



Field Armature

Tapped Field Control

This tapped field control method is shown in fig (c). In this method, field coil is tapped dividing the number of turns. Thus we can select different value of Ø by selecting a different number of turns. In this method flux is reduced and speed is increased by decreasing the number of the turns of the series field winding. The switch S can be short circuit any part of the field winding, thus decreasing the flux and raising the speed (N) with full turns of coil.



Tapped Field

Paralleling Field Coils: This is used for fan motors several speed can be obtained by regrouping the field coils in series with the DC armature.

Variable Resistance in Series with Armature Method

In this method, an introducing resistance (R) is series with the armature of motor. The voltage across the armature can be reduced. So the speed reduces in proportion with it. It is seen that for a 4 pole motor, the speed of the motor can be obtained easily.

Series-Parallel Control Method: This type of the method can be widely used in electric traction, where two or more mechanisms coupled series motors are employed. If required low speed motors are joined in series, and for higher speed motors are joined in parallel.

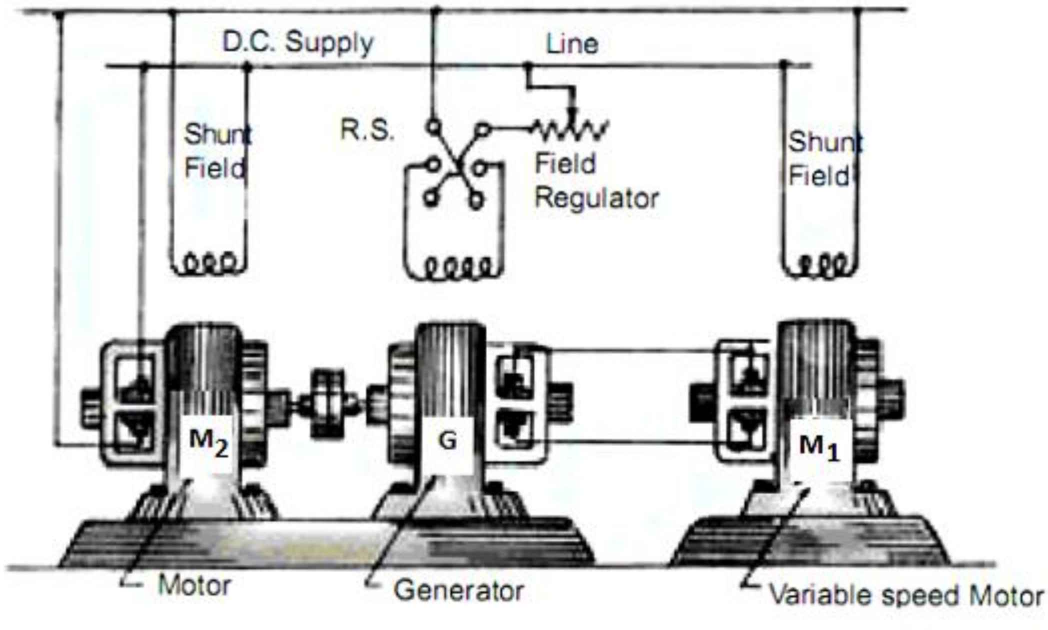
When motors are connected in series, the motors have the same current passing through them, although voltage across each motor is divided. When in parallel, the voltage across each motor is same, although current gets divided

Ward Leonard Method of Speed Control

Ward Leonard control system is introduced by Henry Ward Leonard in 1891. Ward Leonard method of speed control is used for controlling the speed of a DC motor. It is a basic armature control method. This control system is consisting of a DC motor M_1 and powered by a DC generator G. In this method the speed of the DC motor (M_1) is controlled by applying variable voltage across its armature. This variable voltage is obtained using a motor-generator set which consists of a motor M_2 (either AC or DC motor) directly coupled with the generator G. It is a very widely used method of speed control of DC motor.

Principle of Ward Leonard Method

Basic connection diagram of the **Ward Leonard speed control system** is shown in the figure below.



WARD LEONARD SYSTEM OF SPEED CONTROL

The speed of motor M_1 is to be controlled which is powered by the generator G. The shunt field of the motor M_1 is connected across the DC supply lines. Now, generator G is driven by the motor M_2. The speed of the motor M_2 is constant. When the output voltage of the generator is fed to the motor M_1 then the motor starts to rotate. When the output voltage of the generator varies then the speed of the motor also varies. Now controlling the output voltage of the generator the speed of motor can also be controlled. For this purpose of controlling the output voltage, a field regulator is connected across the generator with the dc supply lines to control the field excitation. The direction of rotation of the motor M_1 can be reversed by excitation current of the generator and it can be done with the help of the reversing switch R.S. But the motor-generator set must run in the same direction.

Advantages of Ward Leonard System

1. It is a very smooth speed control system over a very wide range (from zero to normal speed of the motor).
2. The speed can be controlled in both the direction of rotation of the motor easily.
3. The motor can run with a uniform acceleration.
4. Speed regulation of DC motor in this Ward Leonard system is very good.
5. It has inherent regenerative braking property.

Disadvantages of Ward Leonard System

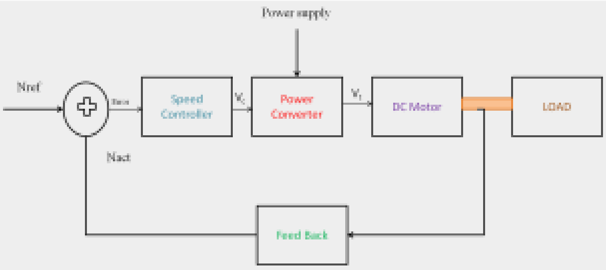
1. The system is very costly because two extra machines (motor-generator set) are required.
2. Overall efficiency of the system is not sufficient especially if it is lightly loaded.
3. Larger size and weight. Requires more floor area.
4. Frequent maintenance.
5. The drive produces more noise.

Application of Ward Leonard System

This **Ward Leonard method of speed control system** is used where a very wide and very sensitive speed control is of a DC motor in both the direction of rotation is required. This speed control system is mainly used in colliery winders, cranes, electric excavators, mine hoists, elevators, steel rolling mills, paper machines, diesel-locomotives, etc.

DC Motor is very extensively used machine where the speed control is desired. The operation of DC motor in different steps is easy compared to AC motors. By the open loop control the DC motor can be operated at any intermediate speed by changing the voltage, armature current etc. But in open loop (Prediction based) control accuracy in speed cannot be obtained i.e. the speed will not be constant for load variations on the motor. There will not be any feedback to the controller to indicate the change in speed due to load. This disadvantage restricts the use of open loop speed control DC motor in applications where constant speed is essential.

To avoid this disadvantage a closed loop technique is implemented where the output measured speed is fed back to the speed controller. In closed loop controller the speed can be maintained by adjusting terminal voltage according the speed difference caused by the load torque. I.e. a fine control of speed can be obtained using closed loop speed control. The below figure shows the basic block diagram of closed loop speed control.

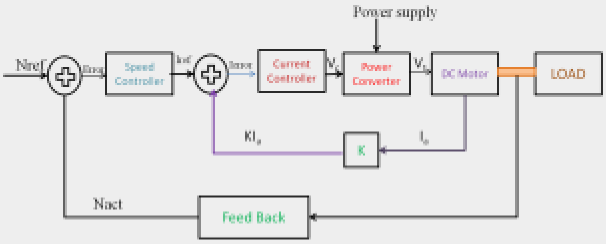


Closed Loop speed Control

The measured speed at the motor shaft is fed back and compared with reference speed. The difference speed error is applied to the speed controller to generate a control voltage V_c which controls the power converter and produces the desired terminal V_t .This terminal voltage controls the speed of the motor and thus the speed of the motor can maintained for any variations in the load torque. For example if the load torque has been increased, due to this high load the motor speed reduces momentarily from its desired value. Thus the speed error at the output of the comparator increases which increases the control signal V_c. The speed controller can be proportional (P) or proportional integral (PI) and it also takes care of the maximum speed limit of the motor. This control signal decreases the firing angle of the thyristor if it is phase controlled converter or it increases the duty cycle to increase the switching On time if it is a chopper converter and thus the output terminal voltage will increase. This increased terminal voltage (armature voltage) develops more torque to compensate the effect of load torque and to maintain the constant speed. The same operation in the reverse way will be performed if the load torque reduces. When the applied torque matches the load torque then the motor speed will be constant. There will be small oscillations during this control which can be reduced by the perfect controller time constant.

Improved closed loop speed control with inner loop current control

In the above said circuit the speed control output is directly changes the terminal voltage of the DC motor. But in D motor the armature resistance and armature impedance are very small and thus the time constant also very less. Due to this less time constant for a small increase in terminal voltage the armature current increases drastically. This quick high armature current may damages the solid state devices used in the power converter. To avoid this the armature current should increase slowly to produce the required torque. This can be obtained by placing a current control loop in between the speed control and power converter as shown in figure.



Closed Loop speed Control with inner current controller

Here the speed output signal generates a corresponding armature current signal and this signal is compared with the existing armature fed back to the comparator circuit. The difference in the current drives the current loop controller and produces a control signal to the power converter. This introduces a very smooth increase in terminal voltage and thus armature current by providing a dual controller. The current controller can be proportional or proportional integral (PI) controller. Most probably PI controller is used because of less steady state error and smooth response compared to proportional controller.

Advantages of closed loop speed control

- Greater accuracy with fine control of speed
- Improved dynamic response
- The motor can be operated at constant torque and constant speed
- Stabilized operation without any major deviations
- Circuit protections also can be incorporated int the closed loop speed control.

2.2.1. Construction of Motor

As for the construction of a brushless motor, a coil is star-wired (Y-wired) with three-phases: U, V, and W and is located in the stator, and the rotor is made of magnets magnetized in a multi-pole configuration as shown in Fig. 14.
Inside the stator, three hall ICs are arranged as magnetic elements so that the phase difference of the output signal from each hall IC will be 120 degrees apart for every rotation of the rotor.

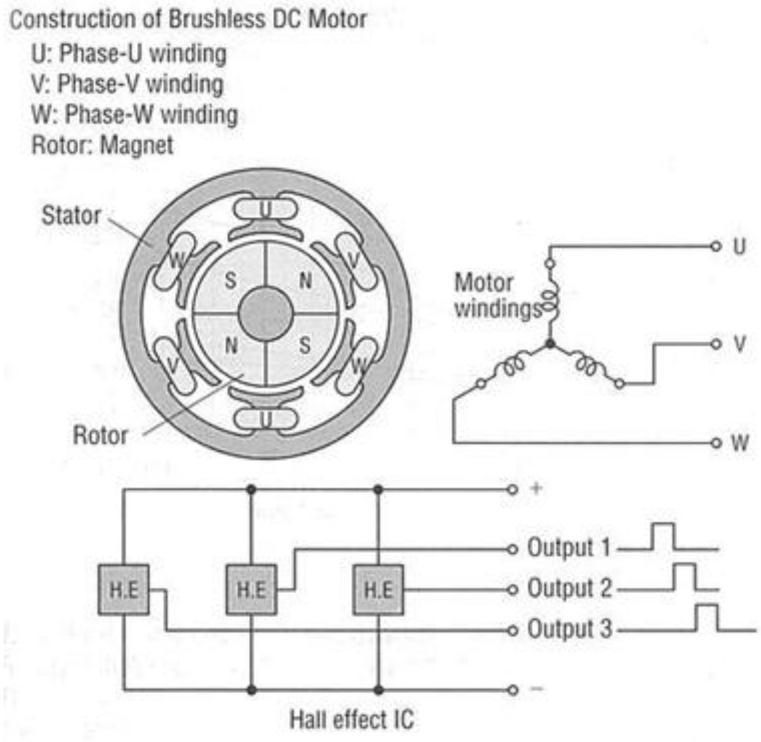


Fig. 14 Construction of a Brushless DC Motor

2.2.2. Principle of Speed Control

As shown in Fig. 15, the Rotational Speed-Torque characteristics of a brushless DC motor show a negative sloping characteristic when its speed is not controlled which is similar to that of a brushed DC motor.

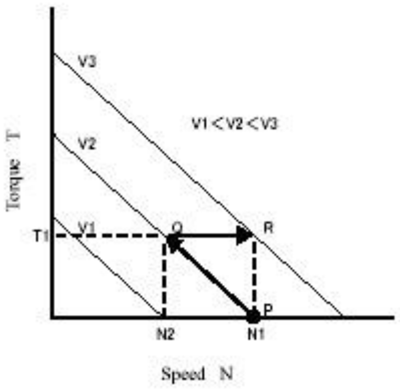


Fig. 15 Rotational Speed-Torque Characteristics of a Brushless DC Motor

When no load is applied and the input voltage is set at V2 in Figure 15, the operation point of the motor becomes P, and the rotational speed is N1. When the load torque T1 is applied, the operation point shifts to Q, and the rotational speed slows to N2, however, the rotational speed returns to N1 if the voltage is raised to V3. Therefore, since the rotational speed changes whenever the load torque changes, the speed control mechanism will only have to change the input voltage whenever a change in the speed is seen in order to maintain a constant speed on the PR line.

This voltage control is realized by an inverter in the output part of the control circuit (driver). This inverter generates a three-phase AC voltage from DC current by turning ON and OFF like the sequence shown in Fig. 16 (b) by using the six switching elements (FET or IGBT) shown in Fig. 16 (a).

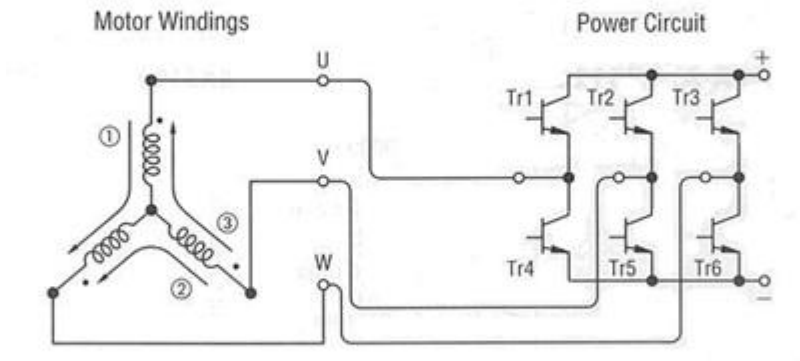


Fig. 16 (a) Output Part of Control Circuit (Driver)

Transistor \ Step	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬
Tr1	ON					ON	ON					ON	ON
Tr2		ON	ON					ON	ON				
Tr3				ON	ON					ON	ON		
Tr4			ON	ON					ON	ON			
Tr5					ON	ON					ON	ON	
Tr6	ON	ON					ON	ON					ON
Phase U	N	—	S	S	—	N	N	—	S	S	—	N	N
Phase V	—	N	N	—	S	S	—	N	N	—	S	S	—
Phase W	S	S	—	N	N	—	S	S	—	N	N	—	S

Fig. 16 (b) Switching Sequence

The switching elements are connected to the motor winding as shown in Fig. 16 (a), and the ON/OFF state of the switching element determines which coil of the stator is energized and in which direction the current will flow, that is, which coil becomes a N pole or S pole. In fact, the position of the rotor's magnetic pole is detected by the hall IC, and an appropriate switching element is turned ON or OFF as shown in Fig. 16 (b). For example, in case of step 1, the transistors Tr1 and Tr6 are turned ON, and the current flows from the U-phase to the W-phase. At this time, U-phase is excited as an N pole and W-phase becomes a S pole, and the rotor rotates by 30 degrees moving to step 2. One rotation of the rotor is made by repeating this operation 12 times (Step 1 ~ 12).
Fig. 17 shows the configuration for the speed control of a brushless DC motor unit in a block diagram.

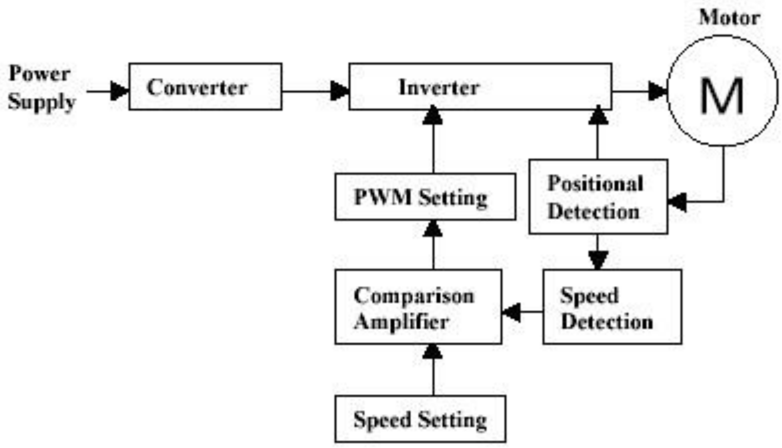


Fig. 17 Block Diagram of a Brushless DC Motor System

The switching sequence of the inverter is decided by the signal from the hall IC in the positional detection part of the block diagram, and the motor rotates. Then, the signal from the hall IC is sent to the speed detector to become a speed signal, and it is compared with the speed setting signal in the comparison amplifier block, which then generates a deviation signal. The value of the motor input current is determined by the PWM setting block based on the deviation signal.
Brushless DC motor units have the following features.
1) It has high-efficiency because a permanent magnet rotor is used and secondary loss is small.

2) The rotor inertia can be reduced, and a high-speed response is obtained.
3) It is possible to downsize the motor because it is highly efficient.
4) Speed fluctuations with changing loads is low.

Fig. 16 shows a typical switching sequence (120-degree energizing method). An even more efficient brushless DC motor system uses a sine-wave drive method by obtaining high-resolution rotor position information from software from the hall IC signal. This method results in a low-noise drive method since the current that flows to the motor does not change rapidly. (2)

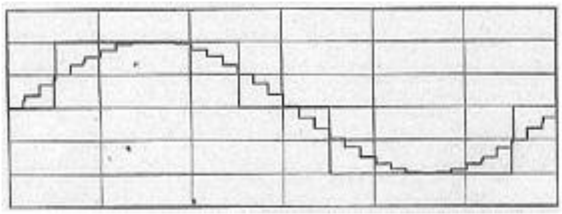


Fig. 18 Comparison of voltages applied by sine-wave drive method and 120-degree drive method

2.2.3. Characteristics

The rotational speed-torque characteristics of a brushless DC motor system have a limited duty region in addition to the continuous operation area.
The limited duty operation area is very effective when starting an inertial load. However, when operation in the limited duty region is continued for five seconds or more, the driver's overload protection function is activated and the motor decelerates to a stop.

2.3. Inverter Speed Control Unit

2.3.1. Principle of Speed Control

The inverter unit controls the speed of a three-phase induction motor by changing the frequency, f, of the voltage applied to the motor. The inverter unit changes the frequency, f, by changing the ON/OFF cycle of the six switching elements, and the rotational speed (N) of the motor changes in proportion to the expression in formula (1).

$N = 120 \cdot f \cdot (1-s)/P$ ·· · · · · · · · · (1)

N: Rotational speed [r/min]
F: Frequency [Hz]
P: Number of poles of a motor
S: Slip

In addition, to make the voltage applied to the winding have a sine-wave shape, the inverter controls the ON/OFF duty cycle as shown in Fig. 21. The ON/OFF time is controlled so that the average voltage applied to the motor becomes a sine-wave shape by comparing the triangular wave called a carrier signal with the sine-wave shaped signal waveform. This method is called PWM control.

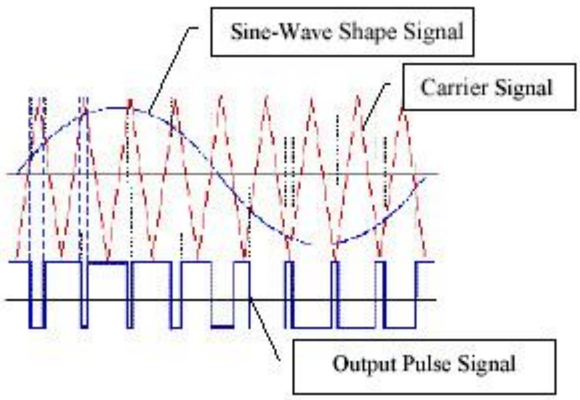


Fig. 19 Duty Control of ON/OFF

The speed control method of our inverter units is divided into the two types: open-loop control that simply changes the speed and closed-loop control that reduces the speed

variation with load changes of the motor.
1) Open-loop control
Fig. 22 shows a configuration of the open-loop control in a block diagram.

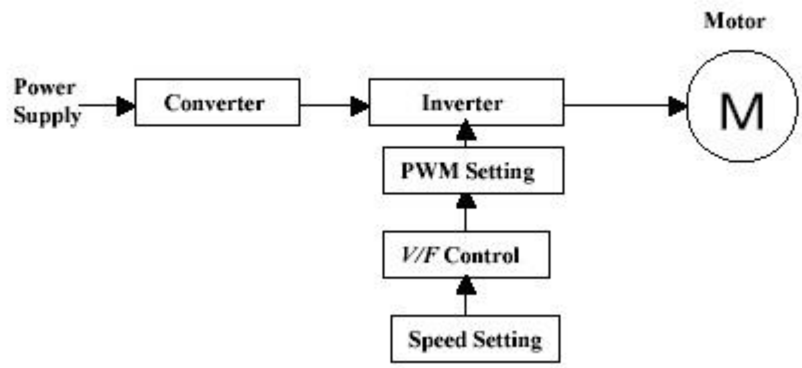


Fig. 20 Block Diagram of Open-Loop Control

This method is used to change the input voltage and frequency of the motor according to a set frequency. This method is suitable for changing speed and can obtain high speeds (The frequency can be set up to 80Hz.) simply when speed regulation with varying loads is not so much of a concern.
The generated torque T of the motor is shown by the formula (2). From this relation, it can be said that the torque will also be constant by making V/f, the ratio of voltage V to frequency f, constant.

$$T = K \cdot I \cdot V / f \quad \cdots \quad (2)$$

T : Torque [N·m]
V : Power supply voltage [V]
I : Motor current [A]
f : Frequency [Hz]
K : Constant

However, the lower the speed is, the more difficult it is to keep constant the input impedance of the induction motor with the change in f. Therefore, to obtain a torque that is constant from low speed to high speed it is necessary to adjust the V/f ratio at low speed in accordance to the characteristics of the motor like the solid line shown in Fig. 23.

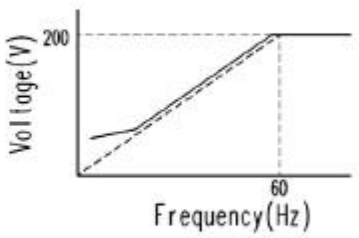


Fig. 21 V/f Control

2) Closed-Loop Control
Fig. 24 shows the block diagram configuration of the closed-loop control system used in our BHF Series.

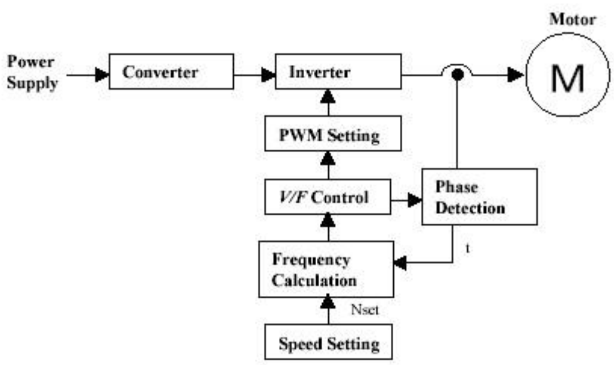


Fig. 22 Block Diagram of Closed-Loop Control

This method detects the phase difference between the voltage of the inverter output block and the primary current, which calculates the driving frequency corresponding to the load using the characteristics data table (Fig. 25) prepared beforehand, and controls the inverter frequency without the need for a speed sensor on the motor.

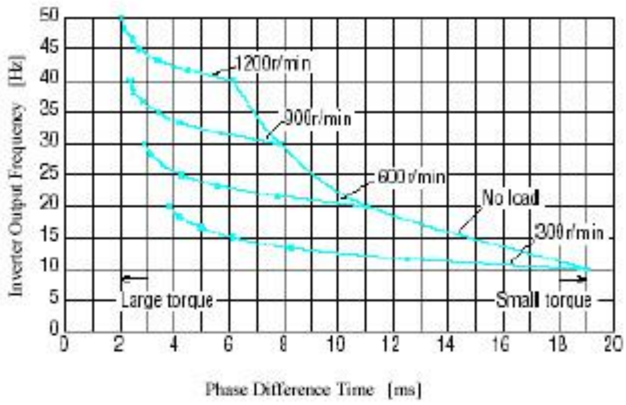


Fig. 23 Characteristics Data Table

With this characteristic table and the detected phase difference time t, the inverter calculates an inverter output frequency that corresponds to the rotational speed command Nset set by the speed potentiometer, and outputs it as the inverter output frequency. After receiving the output frequency, the V/f control block calculates the voltage applied to the motor corresponding to the output frequency f, and performs the speed control by driving the PWM inverter. As a result, when a load is applied, the output frequency of the inverter is boosted so that the decrease in the rotational speed may be compensated for. (3)

2.3.2. Characteristics

The Rotational Speed-Torque characteristics of the inverter unit are shown Fig. 26 and Fig. 27. As explained in the AC speed control motor section, a "Safe-operation line" is drawn on the torque characteristic. This line represents the limit for the continuous operation, and the area under this line is called the continuous operation area.

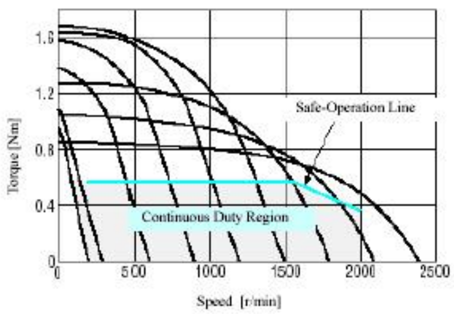


Fig. 24 Rotational Speed-Torque Characteristics for Open-Loop Control

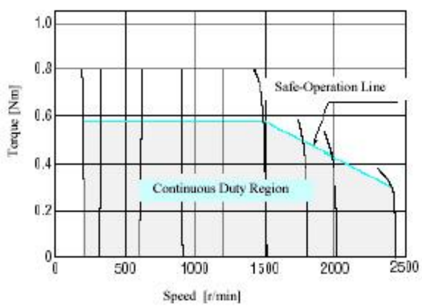


Fig. 25 Rotational Speed-Torque Characteristics for Closed-Loop Control

Unit – 3

Three phase induction motor drives

Speed control of 3Φ Induction motor:

A three phase induction motor is basically a constant speed motor so it's somewhat difficult to control its speed. The speed control of induction motor is done at the cost of decrease in efficiency and low electrical power factor. Before discussing the methods to control the speed of three phase induction motor one should know the basic formulas of speed and torque of three phase induction motor as the methods of speed control depends upon these formulas.

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

Synchronous Speed

Where,

f = frequency and P is the number of poles

The speed of induction motor is given by,

$N = N_s(1-s)$

Where,
N is the speed of rotor of induction motor,
N_s is the synchronous speed, S is the slip.

$$T = \frac{3}{2\pi N_s} X \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

The torque produced by three phase induction motor is given by,

When rotor is at standstill slip, s is one.

$$T = \frac{3}{2\pi N_s} X \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

So the equation of torque is,

Where,

E2 is the rotor emf

Ns is the synchronous speed

R2 is the rotor resistance

X2 is the rotor inductive reactance

The Speed of Induction Motor is changed from Both Stator and Rotor Side

The speed control of three phase induction motor from stator side are further classified as :

V / f control or frequency control.

Changing the number of stator poles.

Controlling supply voltage.

Adding rheostat in the stator circuit.

The speed controls of three phase induction motor from rotor side are further classified as:

Adding external resistance on rotor side.

Cascade control method.

Injecting slip frequency emf into rotor side.

Speed Control from Stator Side

1. V / f control or frequency control - Whenever three phase supply is given to three phase induction motor rotating magnetic field is produced which rotates at synchronous speed given by

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

In three phase induction motor emf is induced by induction similar to that of transformer which is given by

$$E \; or \; V = 4.44\phi K.T.f \; or \; \phi = \frac{V}{4.44KTf}$$

Where, K is the winding constant, T is the number of turns per phase and f is frequency. Now if we change frequency synchronous speed changes but with decrease in frequency flux will increase and this change in value of flux causes saturation of rotor and stator cores which will further cause increase in no load current of the motor . So, its important to maintain flux , φ constant and it is only possible if we change voltage. i.e if we decrease frequency flux increases but at the same time if we decrease voltage flux will also decease causing no change in flux and hence it remains constant. So, here we are keeping the ratio of V/f as constant. Hence its name is V/ f method. For controlling the speed of three phase induction motor by V/f method we have to supply variable voltage and frequency which is easily obtained by using converter and inverter set.

2. Controlling supply voltage: The torque produced by running three phase induction motor is given by

$$T \propto \frac{sE_2^2R_2}{R_2^2 + (sX_2)^2}$$

In low slip region $(sX)^2$ is very small as compared to R_2. So,

$$T \propto \frac{sE_2^2}{R_2}$$

it can be neglected. So torque becomes

Since rotor resistance, R2 is constant so the equation of torque further reduces to

$$T \propto sE_2^2$$

We know that rotor induced emf E2 ∝ V. So, T ∝ sV2.

From the equation above it is clear that if we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remains the same and it is only possible if we increase the slip and if the slip increases the motor will run at reduced speed. This method of speed control is rarely used because small change in speed requires large reduction in voltage, and hence the current drawn by motor increases, which cause over heating of induction motor.

3. Changing the number of stator poles: The stator poles can be changed by two methods

4. Multiple stator winding method.

5. Pole amplitude modulation method (PAM)

6. Multiple stator winding method – In this method of speed control of three phase induction motor, the stator is provided by two separate winding. These two stator windings are electrically isolated from each other and are wound for two different pole numbers. Using switching arrangement, at a time , supply is given to one winding only and hence speed control is possible. Disadvantages of this method is that the smooth speed control is not possible . This method is more costly and less efficient as two different stator winding are required. This method of speed control can only be applied for squirrel cage motor.

7. Pole amplitude modulation method (PAM) – In this method of speed control of three phase induction motor the original sinusoidal mmf wave is modulated by another sinusoidal mmf wave having different number of poles.
   Let f1(θ) be the original mmf wave of induction motor whose speed is to be controlled.
   f2(θ) be the modulation mmf wave.
   P1 be the number of poles of induction motor whose speed is to be controlled.
   P2 be the number of poles of modulation wave.

$$f_1(\theta) = F_1 \sin \frac{P_1\theta}{2}$$

$$f_2(\theta) = F_2 \sin \frac{P_2\theta}{2}$$

After modulation resultant mmf wave

$$F_r(\theta) = F_1 F_2 \sin \frac{P_1\theta}{2} sin \frac{P_2\theta}{2}$$

$$Apply\ formula\ for\ 2 \sin A \sin B = \cos \frac{A-B}{2} - \cos \frac{A+B}{2}$$

$$F_r(\theta) = F_1 F_2 \frac{\cos\frac{(P_1-P_2)\theta}{2} - \cos\frac{(P_1+P_2)\theta}{2}}{2}$$

So we get, resultant mmf wave

Therefore the resultant mmf wave will have two different number of poles

$$i.e\ P_{11} = P_1 - P_2\ and\ P_{12} = P_1 + P_2$$

Therefore by changing the number of poles we can easily change the speed of three phase induction motor.

8. Adding rheostat in the stator circuit - In this method of speed control of three phase induction motor rheostat is added in the stator circuit due to this voltage gets dropped .In case of three phase induction motor torque produced is given by T ∝ sV22. If we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remains the same and it is only possible if we increase the slip and if the slip increase motor will run reduced speed.

Speed Control from Rotor Side

1. Adding external resistance on rotor side - In this method of speed control of three phase induction motor external resistance are added on rotor side. The equation of torque for three phase induction motor is

$$T \propto \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

The three phase induction motor operates in low slip region. In low slip region term (sX)2becomes very very small as compared to R2. So, it can be neglected. and also E2 is constant. So the equation of torque after simplification becomes,

$$T \ \propto \ \frac{s}{R_2}$$

Now if we increase rotor resistance, R2 torque decreases but to supply the same load torque must remain constant. So, we increase slip, which will further results in decrease in rotor speed. Thus by adding additional resistance in rotor circuit we can decrease the speed of three phase induction motor. The main advantage of this method is that with addition of external resistance starting torque increases but this method of speed control of three phase induction motor also suffers from some disadvantages:

   1. The speed above the normal value is not possible.
   2. Large speed change requires large value of resistance and if such large value of resistance is added in the circuit it will cause large copper loss and hence reduction in efficiency.
   3. Presence of resistance causes more losses.
   4. This method cannot be used for squirrel cage induction motor.

2. Cascade control method - In this method of speed control of three phase induction motor, the two three phase induction motor are connected on common shaft and hence called cascaded motor. One motor is the called the main motor and another motor is called the auxiliary motor. The three phase supply is given to the stator of the main motor while the auxiliary motor is derived at a slip frequency from the slip ring of main motor. Let NS1 be the synchronous speed of main motor. NS2 be the synchronous speed of auxiliary motor. P1 be the number of poles of the main motor.

P2 be the number of poles of the auxiliary motor.
F is the supply frequency.
F1 is the frequency of rotor induced emf of main motor.
N is the speed of set and it remains same for both the main and auxiliary motor as both the motors are mounted on common shaft.
S1 is the slip of main motor.

$$S_1 = \frac{N_{S1} - N}{N_{S1}}$$

$$F_1 = S_1 F$$

The auxiliary motor is supplied with same frequency as the main motor i.e

$$F_1 = F_2$$

$$N_{S2} = \frac{120F_2}{P_2} = \frac{120F_1}{P_2}$$

$$N_{S2} = \frac{120S_1F}{P_2}$$

Now put the value of

$$S_1 = \frac{N_{S1} - N}{N_{S1}}$$

$$We\ get,\ \ N_{S2} = \frac{120F(N_{S1} - N)}{P_2 N_{S1}}$$

Now at no load, the speed of auxiliary rotor is almost same as its synchronous speed i.e N = NS2

$$N = \frac{120F(N_{S1} - N)}{P_2 N_{S1}}$$

Now rearrange the above equation and find out the value of N, We get,

$$N = \frac{120F}{P_1 - P_2}$$

This cascaded set of two motors will now run at new speed having number of poles (P1 + P2). In the above method the torque produced by the main and auxiliary motor will act in same direction, resulting in number of poles (P1 + P2). Such type of cascading is called cumulative cascading. There is one more type of cascading in which the torque produced by the main motor is in opposite direction to that of auxiliary motor. Such type of cascading is called differential cascading; resulting in speed corresponds to number of poles (P1 - P2). In this method of speed control of three phase induction motor, four different speeds can be obtained

1. When only main induction motor work, having speed corresponds to.

$$N_{S1} = \frac{120F}{P_1}$$

2. When only auxiliary induction motor work, having speed corresponds to.

$$N_{S2} = \frac{120F}{P_2}$$

3. When cumulative cascading is done, then the complete set runs at a speed of.

$$N = \frac{120F}{(P_1 + P_2)}$$

4. When differential cascading is done, then the complete set runs at a speed of.

$$N = \frac{120F}{(P_1 - P_2)}$$

3. Injecting slip frequency emf into rotor side - When the speed control of three phase induction motor is done by adding resistance in rotor circuit, some part of power called, the slip power is lost as I2R losses. Therefore the efficiency of three phase induction motor is reduced by this method of speed control. This slip power loss can be recovered and supplied back in order to improve the overall efficiency of three phase induction motor and this scheme of recovering the power is called slip power recovery scheme and this is done by connecting an external source of emf of slip frequency to the rotor circuit. The injected emf can either oppose the rotor induced emf or aids the rotor induced emf. If it oppose the rotor induced emf, the total rotor resistance increases and hence speed decreases and if the injected emf aids the main rotor emf the total decreases and hence speed increases. Therefore by injecting induced emf in rotor circuit the speed can be easily controlled. The main advantage of this type of speed control of three phase induction motor is that wide range of speed control is possible whether it's above normal or below normal speed.

Cycloconvertor

Cycloconvertor converts AC signal of a particular frequency to another AC signal with different frequency, without using an intermediate DC stage. It is also called single stage frequency converter. it is classified into two.

1. Step up cycloconverter – output frequency is greater than input frequency
2. Step down cycloconverter – output frequency is lesser than input frequency

Step down cycloconverter uses a thyristor and have line commutation so doesn't need an external circuit for commutation. Step up cycloconverter need external circuit, because here thyristor uses forced commutation

Cycloconverter is used in speed control of high power AC drive, static VAR generator, variable frequency to fixed frequency convertor (vice versa) and induction heating. Step down cycloconverter is a wave synthesiser. Cycloconverter can be used as phase control device. Cycloconverter provide power flow in both direction hence it works with leading, lagging and unity power factor. Output wave is a distorted sine wave

Invertor

Invertor converts DC power to AC power, with desired voltage and frequency. Here DC is supplied to the thyristor and it is turned off by by forced commutation or natural commutation. Forced commutation is used by parallel invertor, serial invertor and three face bridge invertor. Forced commutation requires external commutation where natural commutation doesn't require any external circuit. Inverters are used to control speed of AC series motor, induction heating etc., The ac output voltage waveform of Voltage source invertor (VSI) is composed of high dv/dt. AC output current waveform of Current source invertor (CSI) is composed of high di/dt. A capacitive load in VSI generates large current spikes and can be reduced by using an inductive filter

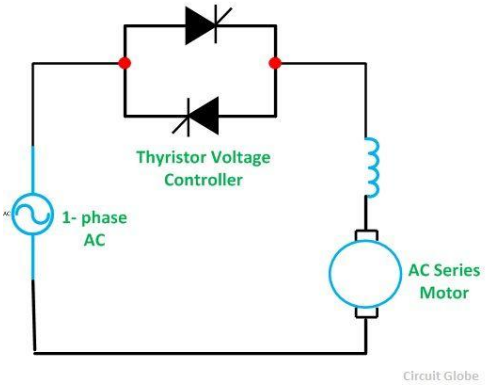
An ideal VSI is independent of load. VSI inverter is also called Mc Murry inverter. If source inductance is small and load inductance is large VSI is used. All VSI have stiff voltage source. Applications of VSI are UPS, ac motor speed control, electronic frequency changer etc.

A single phase full bridge invertor can operate in load commutation mode where load is under damped RLC. Time margin of a series inverter ensures safety of the device. Output of a single phase full bridge inverter, when feed with a fixed DC source is PWM.

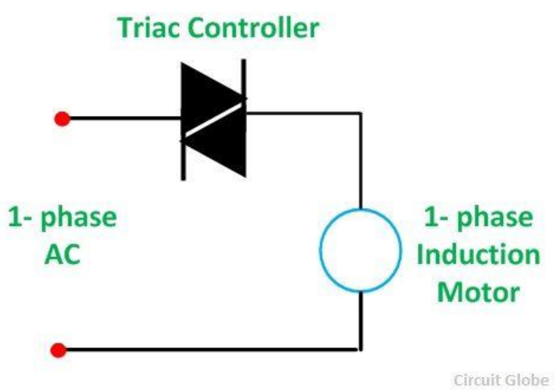
In a series resonant inverter, output depends on the damping of load. In resonant pulse inverter dc saturation of transformer core is minimised. When line commutated converter works in inverter mode then it delivers real and reactive power to AC supply

The static control of rotor resistance using DC Chopper

The Thyristor voltage controller method is preferred for varying the voltage. For a single phase supply, two Thyristors are connected back to back as shown in the figure below.

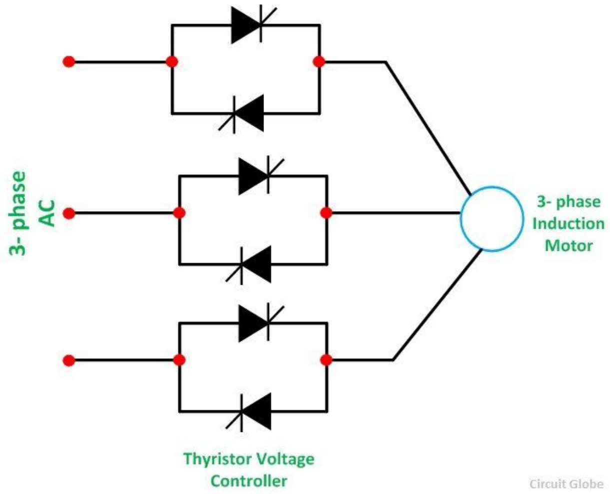


The domestic fan motors, which are single phase are controlled by a single phase Triac Voltage Controller as shown in the figure below.



Speed control is obtained by varying the firing angle of the Triac. These controllers are known as Solid State fan regulators. As the solid state regulators are more compact and efficient as compared to the conventional variable regulator. Thus, they are preferred over the normal regulator.

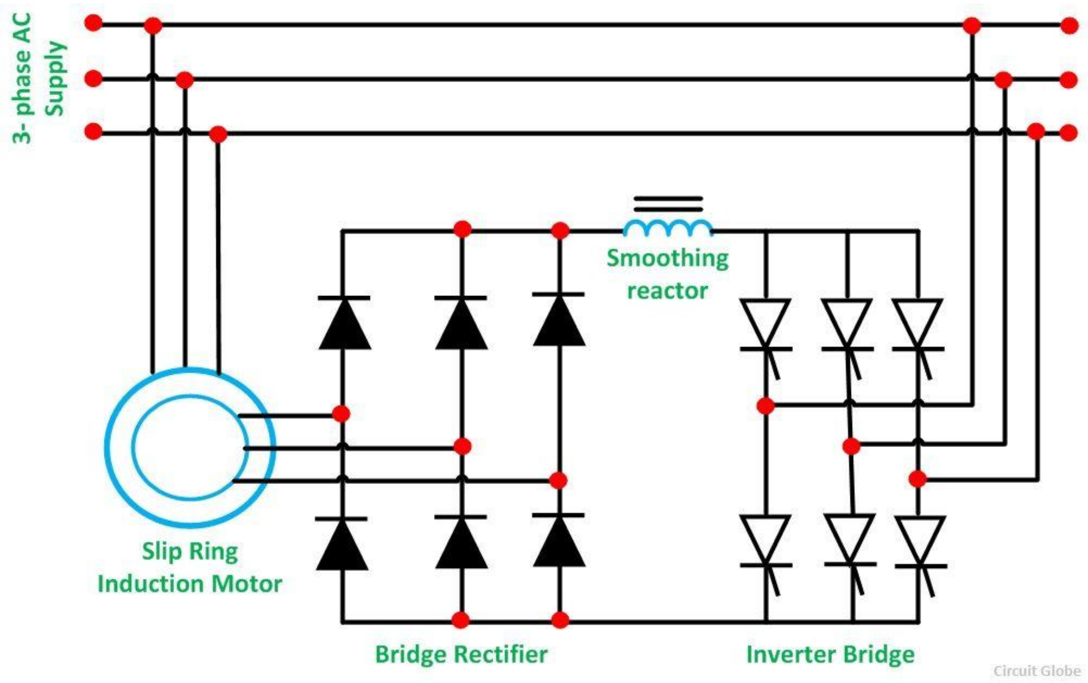
In case of a three phase induction, motor three pairs of Thyristor are required which are connected back to back. Each pair consists of two Thyristor. The diagram below shows the Stator Voltage Control of the three phase induction motors by Thyristor Voltage Controller.



Each pair of the Thyristor controls the voltage of the phase to which it is connected. Speed control is obtained by varying the conduction period of the Thyristor. For lower power ratings, the back to back Thyristor pairs connected in each phase is replaced by Triac.

Scherbius Drive

Slip Energy Recovery is one of the methods of controlling the speed of an Induction motor. This method is also known as Static Scherbius Drive. In the rotor resistance control method, the slip power in the rotor circuit is wasted as I^2R losses during the low-speed operation. The efficiency is also reduced. The slip power from the rotor circuit can be recovered and fed back to the AC source so as to utilize it outside the motor. Thus, the overall efficiency of the drive system can be increased.The figure below shows the connection and method for recovering the slip energy and power recovery of an Induction Motor.



The basic principle of the slip power recovery is to connect an external source of the EMF of the slip frequency of the rotor circuit. The slip energy recovery method provides the speed control of a slip ring induction motor below its synchronous speed. A portion of rotor AC power (slip power) is converted into DC by a diode bridge.

The smoothing reactor is provided to smoothen the rectified current. The output of the rectifier is then connected to the DC terminals of the inverter. The inverter inverts the DC power to the AC power and feeds it back to the AC source. The inverter is a controlled rectifier operated in the inversion mode.

This method of speed control is used in large power applications where the variation of speed over a wide range involves a large amount of slip power.

Static Scherbius drives are capable of bi-directional power flow, with both positive and negative injected voltages possible, in phase with or opposing the rotor current. As a result, a wider set of operating conditions is possible. Considering the torque equation for slip energy recovery:

$$\tau = 3I_r \frac{(I_r R_r + V_i)}{s\omega_s}$$

When motoring, torque is positive, when generating torque is negative.

Operating Modes

Sub-synchronous motoring

In this mode, operation is similar to that obtained with a static kramer drive. Slip and torque are both positive, therefore injected voltage must be in phase with rotor current. Power flows into the stator and back out of the rotor circuit.

Super-synchronous motoring

Above synchronous speed, the slip is negative. In order for the torque to be positive,

$$I_r^2 R_r + I_r V_i$$

Must be negative. Therefore, voltage and current must be out of phase with each other. Power is being injected into the rotor from the drive circuit connected to the slip rings, in addition to input power flowing into the stator

Sub-synchronous generating

If generation below synchronous speed is required, torque must be negative whilst slip is positive. Again,

$$I_r^2 R_r + I_r V_i$$

Must be negative. Power is being injected into the rotor from the slip rings.

Super-synchronous generating

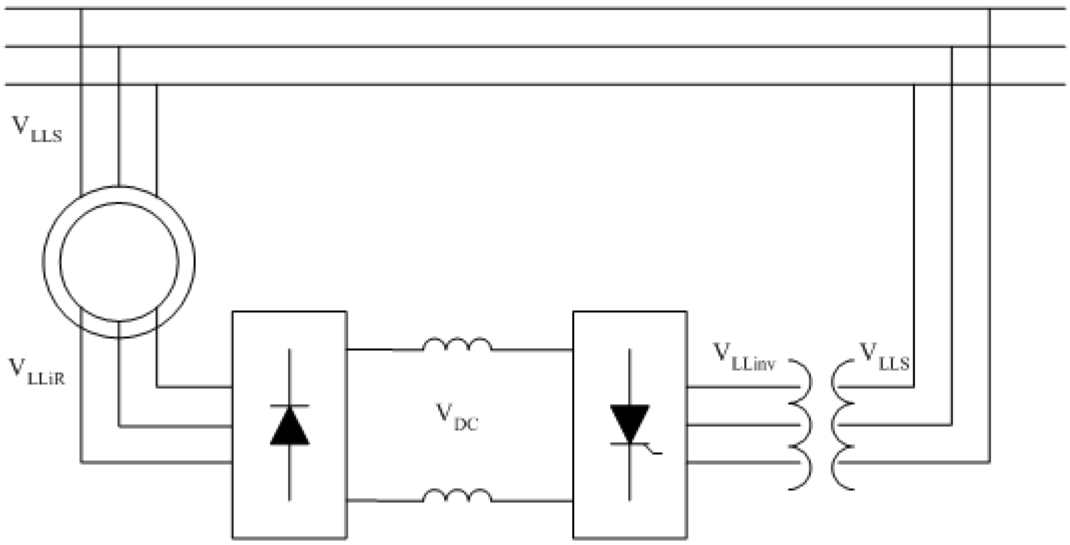
If generating above synchronous speed, slip and torque are both negative, therefore

$$I_r^2 R_r + I_r V_i$$

is positive and injected voltage is in phase with rotor current. In this case, mechanical input power is being supplied from the shaft and both the stator and rotor circuits are providing output power.

Static Kramer Drive

A static Kramer drive is a method to obtain an injected voltage that is in phase with the rotor current. The schematic circuit for a static Kramer drive is shown below



The voltage at the slip rings is forced to be in phase with the rotor currents by the diode rectifier. The magnitude of the slip ring voltage is set by the DC link voltage, which is in turn set by the inverter connected back to the AC supply. In the diagram above and the analysis presented, the inverter used is a thyristor converter. However, a PWM inverter can also be used.

Simple Analysis

This simple analysis of the static Kramer drive illustrates the operation of the drive. It neglects the voltage drops in the drive and any possible commutation overlap in the diode rectifier.

The voltage at the input to the diode rectifier is given by

$$V_{LLiR} = \sqrt{3}\,\frac{V_i}{a_{eff}}$$

And the dc link voltage can be found from the diode input line-line voltage as

$$V_{DC} = \frac{3\sqrt{2}}{\pi} V_{LLiR}$$

Considering the thyristor converter, this circuit can be thought of as a thyristor rectifier connected in reverse, and the DC link voltage is related to the line-line inverter voltage as

$$V_{DC} = -\frac{3\sqrt{2}}{\pi} V_{LLinv} \cos\alpha = \frac{3\sqrt{2}}{\pi} V_{LLinv} \left|\cos\alpha\right|$$

Substituting the above expressions, the voltage injected into the rotor can be calculated as

$$V_i = \frac{a_{eff}}{\sqrt{3}} V_{LLinv} \left|\cos\alpha\right|$$

In the case that the inverter line-line voltage is connected to the supply through a transformer, as shown in the diagram above, the injected voltage can be related to the supply voltage as

$$V_i = \frac{a_{eff}}{\sqrt{3}} \frac{N_{inv}}{N_{Line}} V_{LLS} \left|\cos\alpha\right|$$

Using this simplified analysis together with the slip energy recovery torque equations, the thyristor firing angle required for a particular torque at a particular speed can be found. If necessary, more detailed analysis can be carried out by repeating the above process, but including device voltages and commutation overlap.

Torque-Speed

Because the slip ring voltage is derived using a diode bridge, the torque speed curve for a motor operated using a static Kramer drive does not produce a negative torque as soon as the speed exceeds the no-load speed. If the slip is too low for a given injected voltage, the voltage induced in the rotor circuit by the stator will have a lower magnitude than the DC link voltage. As a result, no rotor current will flow and the torque will be zero.

UNIT IV

THREE PHASE SYNCHRONOUS MOTOR DRIVES

Speed control of three phase synchronous motor:

As soon as variable-frequency inverters became a practicable proposition it was natural to use them to supply synchronous motors, thereby freeing the latter from the fixed-speed constraint imposed by mains-frequency operation and opening up the possibility of a simple open-loop controlled speed drive. The obvious advantage over the inverter-fed induction motor is that the speed of the synchronous motor is exactly determined by the frequency, whereas the induction motor always has to run with a finite slip. A precision frequency source (oscillator) controlling the inverter switching is all that is necessary to give an accurate speed control with a synchronous motor, while speed feedback is essential to achieve accuracy with an induction motor.

In practice, open-loop operation of inverter-fed synchronous motors is not as widespread as might be expected, though it is commonly used in multi-motor drives (see below). Closed-loop or self-synchronous operation is however rapidly gaining momentum, and is already well established in two distinct guises at opposite ends of the size range. At one extreme, large excited-rotor synchronous motors are used in place of D.C. drives, particularly where high speeds are required or when the motor must operate in a hazardous atmosphere (e.g. in a large gas compressor). At the other end of the scale, small permanent magnet synchronous motors are used in brushless D.C. drives. We will look at these closed-loop applications after a brief discussion of open-loop operation.

Open-loop inverter-fed synchronous motor drives

This simple method is attractive in multi-motor installations where all the motors must run at exactly the same speed. Individually the motors (permanent magnet or reluctance) are more expensive than the equivalent mass-produced induction motor, but this is of set by the fact that speed feedback is not required, and the motors can all be supplied from a single inverter, as shown in Figure below.

The inverter voltage-frequency ratio will usually be kept constant to ensure that the motors operate at full flux at all speeds, and therefore have a ‘constant-torque’ capability. If prolonged low-speed operation is called for, improved cooling of the motors may be necessary. Speed is precisely determined by the inverter frequency, but speed changes (including run-up from rest) must be made slowly, under ramp control, to avoid the possibility of exceeding the pull-out load angle, which would result in stalling.

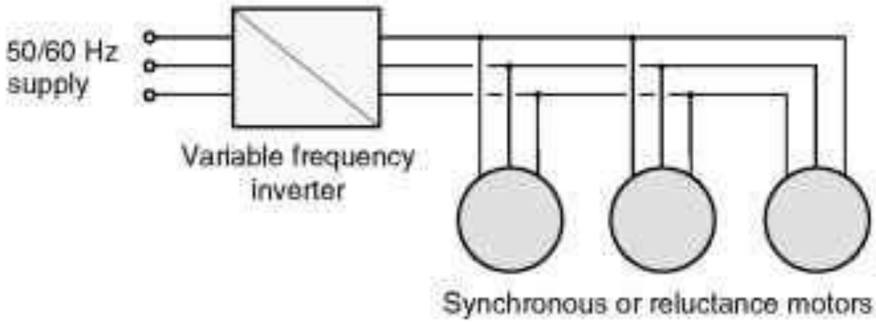


Figure: Open-loop operation of a group of several synchronous or reluctance motors supplied from a single variable-frequency inverter

A problem which can sometimes occur with this sort of open-loop operation is that the speed of the motor exhibits apparently spontaneous oscillation or hunting’. The supply frequency may be absolutely constant but the rotor speed is seen to fluctuate about its expected (synchronous) value, sometimes with an appreciable amplitude, and usually at a low frequency of perhaps 1 Hz. The origin of this unstable behaviour lies in the fact that the motor and load constitute at least a fourth-order system, and can therefore become very poorly damped or even unstable for certain combinations of the system parameters. Factors that influence stability are terminal voltage, supply frequency, motor time-constants and load inertia and damping. Unstable behaviour in the strict sense of the term (i.e. where the oscillations build-up without limit) is rare, but bounded instability is not uncommon, especially at speeds well below the base (50 Hz or 60 Hz) level, and under light-load conditions. It is very difficult to predict exactly when unstable behaviour might be encountered, and provision must be made to combat it. Some inverters therefore include circuitry that detects any tendency for the currents to fluctuate (indicating hunting) and to modulate the voltage and/or frequency to suppress the unwanted oscillations.

Self-synchronous (closed-loop) operation

In the open-loop scheme outlined above, the frequency of the supply to the motor is under the independent control of the oscillator driving the switching devices in the inverter. The inverter has no way of knowing whether the rotor is correctly locked-on to the rotating field produced by the stator, and if the pull-out torque is exceeded, the motor will simply stall.

In the self-synchronous mode, however, the inverter output frequency is determined by the speed of the rotor. More precisely, the instants at which the switching devices operate to turn the stator windings on and off are determined by rotor position-dependent signals obtained from a rotor position transducer (RPT) mounted on the rotor shaft. In this way, the stator currents are always switched on at the right time to produce the desired torque on the rotor, because the inverter effectively knows where the rotor is at every instant of time. The use of rotor position feedback signals to control the inverter accounts for the description ‘closed-loop’ used above. If the rotor slows down (as a result of an increase in load, for example), the stator supply frequency automatically reduces so that the rotor remains synchronised with the rotating field, and the motor therefore cannot pull-out' in the way it does under open-loop operation.

An analogy with the internal combustion engine may help to clarify the difference between closed-loop and open-loop operations. An engine invariably operates as a closed-loop system in the sense that the opening and closing of the inlet and exhaust valves is automatically synchronised with the position of the pistons by means of the camshaft and timing belt. The self-synchronous machine is much the same in that the switching devices in the inverter turn the current on and off according to the position of the rotor. By contrast, open-loop operation of the engine would imply that we had removed the timing belt and chosen to operate the valves by driving the camshaft independently, in which case it should be clear that the engine would only be capable of producing power at one speed at which the up and down motion of the pistons corresponded exactly with the opening and closing of the valves.

It turns out that the overall operating characteristics of a self-synchronous a.c. motor are very similar to those of a conventional D.C. motor. This is really not surprising when we recall that in a d.c. motor, the mechanical commutator reverses the direction of the current in each (rotating) armature coil at the appropriate point such that, regardless of speed, the current under each (stationary) field pole is always in the right direction to produce the desired torque. In the self-synchronous motor the roles of stator and rotor are reversed compared with the D.C. motor. The field is rotating and the 'armature' winding (consisting of three discrete groups of coils or phases) is stationary. The timing and direction of the current in each phase is governed by the inverter switching, which in turn is determined by the rotor position sensor. Hence, regardless of speed, the torque is always in the right direction. The combination of the rotor position sensor and inverter performs effectively the same function as the Commutator in a conventional D.C. motor. There are of course usually only three windings to be switched by the inverter, as compared with many more coils and commutator segments to be switched by the brushes in the D.C. motor, but otherwise the comparison is valid. Not surprisingly the combination of position sensor and inverter is sometimes referred to as an 'electronic commutator', while the overall similarity of behaviour gives rise to the rather clumsy term 'electronically commutated motor' (ECM) or the even worse 'commutator-less d.c. motor' (CLDCM) to describe self-synchronous machines.

Operating characteristics and control

If the D.C. input voltage to the inverter is kept constant and the motor starts from rest, the motor current will be large at first, but will decrease with speed until the motional e.m.f. generated inside the motor is almost equal to the applied voltage. When the load on the shaft is increased, the speed begins to fall, the motional e.m.f. reduces and the current increases until a new equilibrium is reached where the extra motor torque is equal to the load torque. This behaviour parallels that of the conventional D.C. motor, where the no-load speed depends on the applied armature voltage.

The speed of the self-synchronous motor can therefore be controlled by controlling the D.C. link voltage to the inverter. The D.C. link will usually be provided by a controlled rectifier, so the motor speed can be controlled by varying the input converter firing angle, as shown in Figure below

The overall similarity with the D.C. drive (see topic 4) is deliberately emphasised in Figure 10.8. The dotted line enclosing the a.c. motor together with its rotor position detector and inverter is in effect the replacement for the conventional D.C. motor. We note, however, that a tachogenerator is not necessary for closed-loop speed control because the speed feedback signal can be derived from the frequency of the rotor position signal. And, as with the D.C. drive, current control, as distinct from voltage control can be used where the output torque rather than speed is to be controlled. Full four-quadrant operation is possible, as long as the inverter is supplied from a fully controlled converter.
In simple cost terms the self-synchronous system looks attractive when the combined cost of the inverter and synchronous motor is lower than the equivalent D.C. motor. When such schemes were first introduced (in the 1970s) they were only cost-effective in very large sizes (say over 1 MW), but the break-even point for wound-field motors is falling and drives with

ratings in the hundreds of kW are now common. They may utilise converter-grade (relatively cheap) thyristors in the inverter bridge because the thyristors will commutate naturally with the aid of the motor's generated e.m.f. At very low speeds, however, the generated

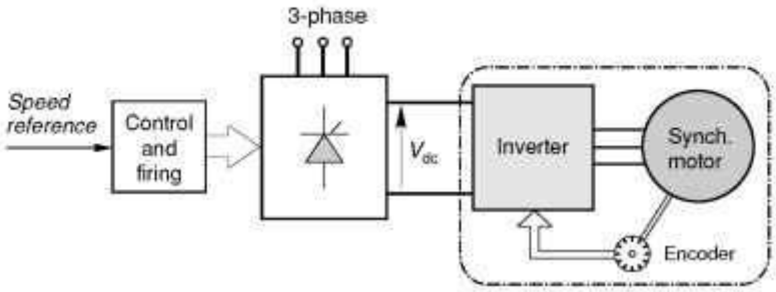


Figure Self-synchronous motor-inverter system. In large sizes this arrangement is sometimes referred to as a 'synch drive'; in smaller sizes it would be known as a brushless D.C. motor drive

e.m.f. is insufficient, so the motor is started under open-loop current-fed operation, in the manner of a stepping motor.

As inverter costs have fallen, lower power drives using permanent magnet motors have become attractive, especially where very high speeds are required and the conventional brushed d.c. motor is unsuitable because of commutator limitations.

Commutator less DC Motor:

Brushless DC motor may be described as electronically commuted motor which do not have brushes. These types of motors are highly efficient in producing large amount of torque over a vast speed range. In brushless motors, permanent magnets rotate around a fixed armature and overcome the problem of connecting current to the armature. Commutation with electronics has large scope of capabilities and flexibility. They are known for smooth operation, and holding torque when stationary.

Working Principle of Motor

Before explaining working of brushless DC motor, it is better to understand function of brushed motor. In brushes motors, there are permanent magnets on the outside and a spinning armature which contains electromagnet is inside. These electromagnets create a magnetic field in the armature when power is switched on and help to rotates armature.

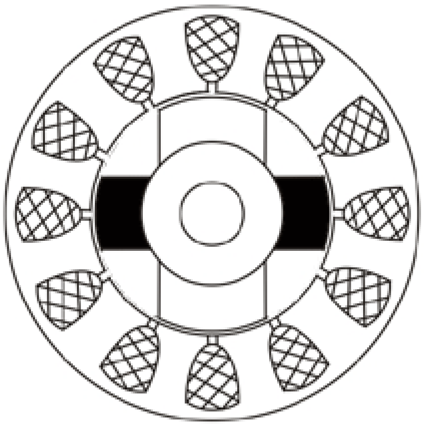
The brushes change the polarity of the pole to keep the rotation on of the armature. The basic principles for the brushed DC motor and for brushless DC motor are same i.e., internal shaft position feedback. Brushless DC motor has only two basic parts: rotor and the stator. The rotor is the rotating part and has rotor magnets whereas stator is the stationary part and contains stator windings. In BLDC permanent magnets are attached in the rotor and move the electromagnets to the stator. The high power transistors are used to activate electromagnets for the shaft turns. The controller performs power distribution by using a solid-state circuit.

Types of Brushless DC Motors

Basically, BLDC are of two types, one is outer rotor motor and other is inner rotor motor. The basic difference between the two are only in designing, their working principles are same.

Inner Rotor Design

In an inner rotor design, the rotor is located in the center of the motor and the stator winding surround the rotor. As rotor is located in the core, rotor magnets does not insulate heat inside and heat get dissipated easily. Due to this reason, inner rotor designed motor produces a large amount of torque and validly used.



Inner Motor

Advantages of Brushless DC Motor

Brushless motors are more efficient as its velocity is determined by the frequency at which current is supplied, not the voltage.

As brushes are absent, the mechanical energy loss due to friction is less which enhanced efficiency.

BLDC motor can operate at high-speed under any condition.

There is no sparking and much less noise during operation.

More electromagnets could be used on the stator for more precise control.

BLDC motors accelerate and decelerate easily as they are having low rotor inertia.

It is high performance motor that provides large torque per cubic inch over a vast sped rang.

BLDC motors do not have brushes which make it more reliable, high life expectancies, and maintenance free operation.

There is no ionizing sparks from the commutator, and electromagnetic interference is also get reduced.

Such motors cooled by conduction and no air flow are required for inside cooling.

Disadvantages of Brushless DC Motors

BLDC motor cost more than brushless DC motor.

The limited high power could be supplied to BLDC motor, otherwise too much heat weakens the magnets and insulation of winding may get damaged.

Closed Loop Control of Drives

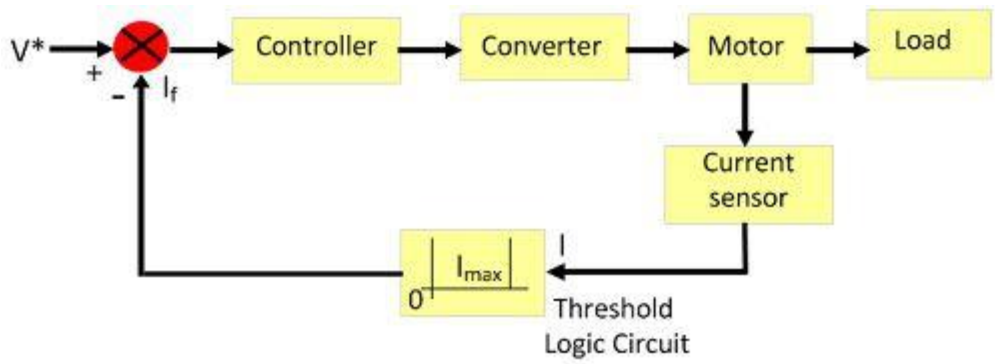
In closed loop system, the output of the system is feedback to the input. The closed loop system controls the electrical drive, and the system is self-adjusted. Feedback loops in an electrical drive may be provided to satisfy the following requirements.

- 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 to rise above the maximum set value. The different types of closed loop configuration are explained below.

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.

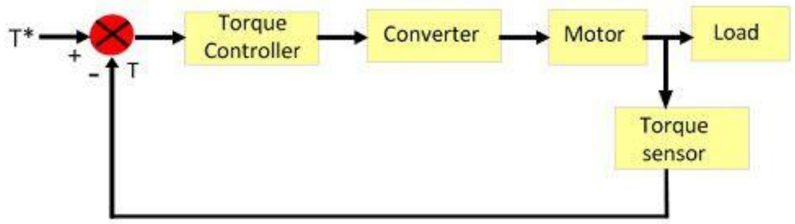


Current Limit Control

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.

Closed-Loop Torque Control

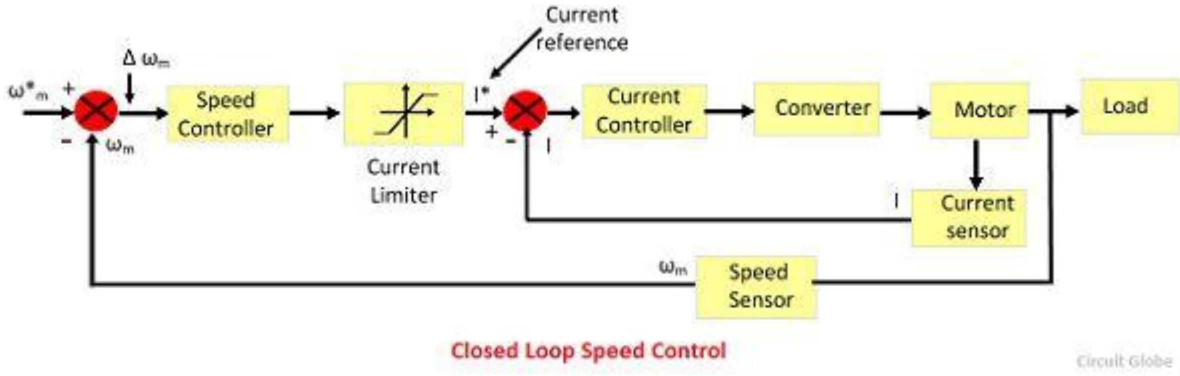
Such types of loop are used in battery powered vehicles, rails, and electric trains. The reference torque T* is set through the accelerator, and this T* follows by the loop controller and the motor. The speed of the drive is controlled by putting pressure on the accelerator.



Close Loop Torque Control

Closed-Loop Speed Control

The block diagram of the closed loop speed control system is shown in the figure below. This system used an inner control loop within an outer speed loop. The inner control loop controls the motor current and motor torque below a safe limit.

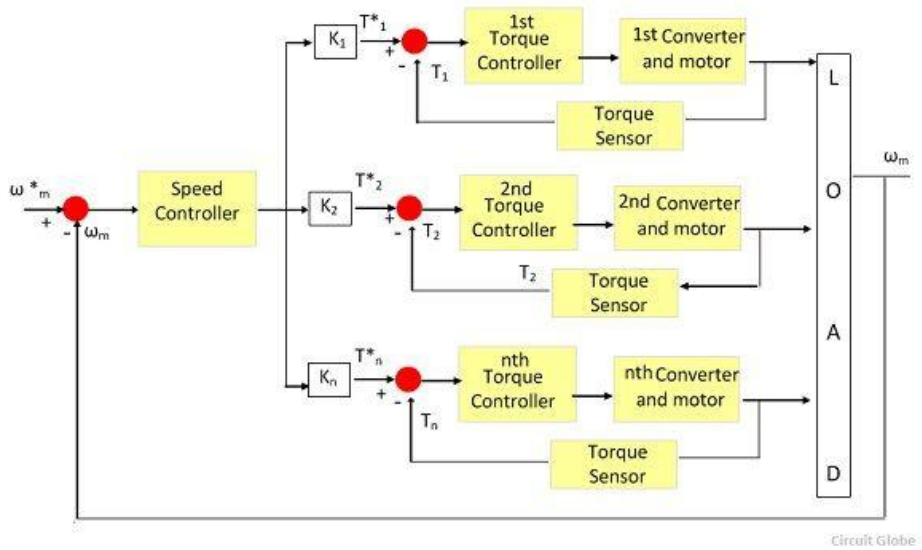


Consider a reference speed ω*m which produces a positive error Δ ω*m. The speed error is operated through a speed controller and applied to a current limiter which is overloaded even for a small speed error. The current limiter set current for the inner current control loop. Then, the drive accelerates, 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.

C losed-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 synchronising torque.

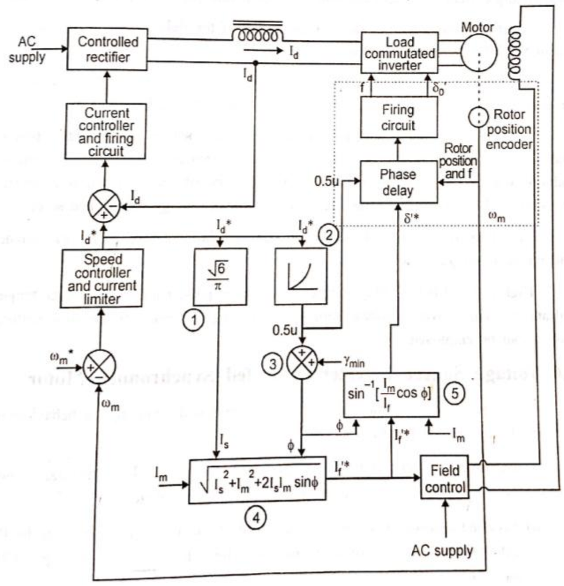


In a locomotive, because of different amount of wear and tear the wheel of the locomotive revolve at the different speed. Thus, the driving speed of the vehicle also vary. Along with speed, it is also essential that the torques are shared equally between the various motor; otherwise, the one motor is fully loaded and another, is under loaded. Thus, the rated locomotive torque will be less than the sum of the individual motor torque rating.

Marginal angle control

The operation of the inverter at the minimum safe value of the margin angle gives the highest power factor and the maximum torque per ampere of the armature current, thus allowing the most efficient use of both the inverter and motor.

Figure (6.12) shows the constant margin angle control for a wound field motor drive employing a rotor position encoder. This drive has an outer speed loop and an inner current loop. The rotor position can be sensed by using rotor position encoder. It gives the actual value of speed ω_m. This signal is fed to the comparator. This comparator compares ω_m and ω_m^* (ref value).



The output of the comparator is fed to the speed controller and current limiter. It gives the reference current value I_d^*. I_d is the dc link current. It is sensed by current sensor and fed to the comparator. The comparator compares I_d and I_d^*. The output of the comparator is fed to the current controller. It generates the trigger pulses.

It is fed to the controlled rectifer circuit. In addition, it has an arrangement to produce constant flux operation and constant margin angle control.

From the value of dc link current command I_d^*, I_s and 0.5 u are produced by blocks (1)&(2) respectively. The signal ϕ is generated from γ_{min} and 0.5u in adder (3). In block (4) I'_f is calculated from the known values of I_s, ϕ and I_m. Note that the magnetizing current I_m is held constant at its rated value I_m to keep the flux constant.

$I_f'^*$ sets reference for the closed loop control of the field current I_F. Block (5) calculates δ'^* from known, values of ϕ and $I_f'^*$.

The phase delay circuit suitably shifts the pulses produced by the encoder to produce the desired value of δ_0'. This signal is fed to the load commutated inverter.

The load commutated inverter drives are used in medium power, high - power and very high power drives, and high speed drives such as compressors, extructers, induced and forced draft fans, blowers, conveyers, aircraft test facilities, steel rolling mills, large ship propulsion, main line traction, flywheel energy storage and so on.

This drive also used for the starting of large synchronous machines in gas turbine and pumped storage plants.

High power drives employ rectifiers with higher pulse numbers, to reduce torque pulsations. The converter voltage ratings are also high so that efficient high voltage motors can be employed.

Power factor control of synchronous motor

One of the major and unique characteristics of this motor is that it can be operated at any electrical power factor leading, lagging or unity and this feature is based on the excitation of the synchronous motor.

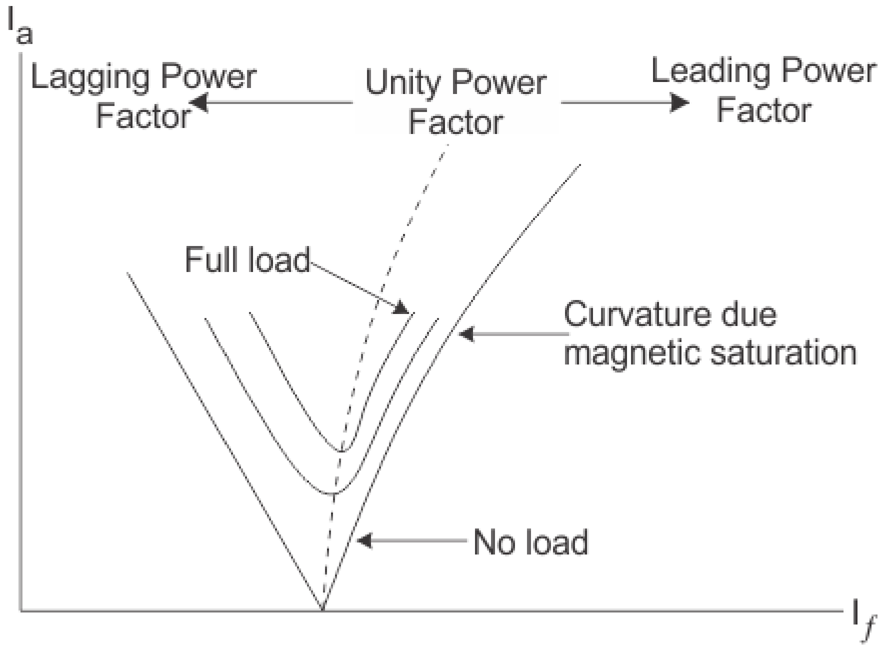
When the synchronous motor is working at constant applied voltage V, the resultant air gap flux as demanded by V remains substantially constant. This resultant air gap flux is established by the co operation of both AC supply of armature winding and DC supply of rotor winding.

CASE 1: When the field current is sufficient enough to produce the air gap flux, as demanded by the constant supply voltage V, then the magnetizing current or lagging reactive VA required from ac source is zero and the motor operate at unity power factor. The field current, which causes this unity power factor is called normal excitation or normal field current.

CASE 2: If the field current is not sufficient enough to produce the required air gap flux as demanded by V, additional magnetizing current or lagging reactive VA is drawn from the AC source. This magnetizing current produces the deficient flux (constant flux- flux set up by dc supply rotor winding). Hence in this case the motor is said to operate under lagging power factor and the is said to be under excited.

CASE 3: If the field current is more than the normal field current, motor is said to be over excited. This excess field current produces excess flux (flux set up by DC supply rotor winding – resultant air gap flux) which must be neutralized by the armature winding. Hence the armature winding draws leading reactive VA or demagnetizing current leading voltage by almost 90o from the AC source. Hence in this case the motor operate under leading power factor.

This whole concept of excitation and power factor of synchronous motor can be summed up



V curves for a synchronous motor with variable excitation

in the following graph. This is called V curve of synchronous motor.

UNIT V
DIGITAL CONTROL AND DRIVE APPLICATION

Digital techniques in speed control

The field of automatic control today is a well-established technology, which has a wide range of application areas. Some of them worth mentioning are

- Generation and distribution of electricity
- Process control in industries
- Manufacturing and robotics
- Medical area
- Various means of transportation
- Structural stabilization and control of heating, ventilation and air conditioning in buildings
- Materials
- Instruments
- Entertainment

Whatever the application area, the approach of a control engineer nowadays to the particular problem is governed by a number of disciplines established inside the automatic control field itself. They can be briefly described as follows.

(a) Systems theory: All real systems that have to be dealt with in automatic control problems can be classified into one of the following system descriptions. These are, linear systems, non-linear systems, stochastic systems, discrete-time systems, time delay systems, distributed parameter systems and decentralized systems. To describe the system behavior, measures such as stability, observability, controllability, robustness, sensitivity, system structure etc. are used.

(b) Modelling and identification: Mathematical models of systems are very important in any automatic control application. If the modelling is completely based on the physics of the particular system, it is called white box modelling. Else, it can be done by conducting experiments, which is called black box modelling. Grey box modelling is the method that uses the physics and experiments in the process. With the maturity of the systems theory, a new sub-field within automatic control called system identification was born. Today it is a well-established discipline inside automatic control area.

(c) Design: For a given process, finding a suitable controller configuration that can tackle either the servo problem or the regulation problem by following a systematic approach, is called as controller design. A lot of creativity has been shown in this area by control engineers. Most of the available methods can now be found in the form of standard textbooks and are also taught at undergraduate and postgraduate levels.

(d) Learning and adaptation: Processes that are being controlled have the tendency to change their properties and thereby dynamics with ageing. Systems that learn about such changes automatically and re-tune the controllers are very handy to have in many applications that need higher reliability throughout their operating life. Learning and adaptation is the answer for such application problems from the automatic control community.

(e) Computing and simulation: Automatic control has been tightly linked to computing throughout its development. Analog computing that was used in the beginning was replaced by digital computing later. Today there are so many mathematical computation tools specially meant for control system analysis and simulation. Examples of such tools are Matlab/Simulink, Matrixx. Some computer algebra software tools such as Maple, Mathematical etc. are also available.

(f) Implementation: This again is a very important aspect in control engineering. Implementation issues form the bridge between the theory and real application. Several practical problems that may sometimes be impossible to incorporate in the theoretical study will have to be overcome at the implementation stage. These implementation aspects are rarely addressed in highly theoretical approaches to problems in automatic control area. However, such research work has a higher possibility of producing novel theoretical contributions to the field. Yet, most of the practical problems associated with the implementation of the methods are not theoretically dealt with in many cases. It is again appropriate to quote one of the great scientists in automatic control, Karl Åström.

(g) Commissioning and operation: Right after a control system has been designed and implemented, it has to be commissioned. Several other interesting problems may occur at this stage. Treating these issues is frequently taken up in today's control engineering forums. In fact, a new sub-area has emerged, known as fault detection and diagnosis. Following the above brief overview of the development of the area of automatic control so far, a quick look at available standard controller design methods will be presented in the next section.

Brief overview of the available methods:

As the automatic control area developed and especially after discrete time control systems were initiated, a steady flow of advanced mathematics poured into controller design. Thus one can find several control design approaches that have also developed as independent sub-fields within the automatic control domain. Some of them to mention are,

- Lead-lag compensation
- PID control
- Optimal control
- Adaptive control
- Robust control
- Non-linear control
- Model predictive control

Advantages of Electric drives:

Quiet,
Less floor space,
Electric power readily available,
Clean-air environments, and,
Precision;

Disadvantages of electric drives:

Conventional gear-driven create backlash, friction,
Compliance and wear problems causing inaccuracies,
Poor dynamic response,
Output power relative to weight is low; and,
To increase torque, a larger and heavier motor must be used which is costly.

Applications of Industrial Drives > ROLLING MILL DRIVES:
The following types of drives are used for rolling mills:
(i) DC motors,
(ii) AC slip ring motors with speed control.

The DC motors, because, of their inherent characteristics, are best suited for the rolling mills. Speed control is effected either through Ward Leonard system or by grid controlled mercury arc rectifiers. AC slip ring motors are suitable for roughing and re-rolling mills where very precise speed control is not required and their efficiency is low because of the power wasted in the rotor resistance. There is also abrupt rise in motor speed when the material leaves the rolling stands.

Applications of Industrial Drive > KILN DRIVES:

Call for a starting torque of about 250% in addition to the speed control feature. The commonly used drives are:

(i) Slip ring induction motor
(ii) Three phase shunt wound commutator motor
(iii) Cascade controlled AC motor
(iv) Ward Leonard controlled DC motor
(v) DC motor with transformer step switch control.

Applications of Industrial Drive > TEXTILE INDUSTRY:
The textile industry requires special types of drives for
(i) Weaving, and
(ii) Spinning.

(i) Applications of Industrial Drive > Weaving:
The motors used in weaving mills must have good cooling capacity to keep their temperatures within limits in the presence of large power losses. The rating of the motors and the cooling facility must be properly selected, because these motors are used in conditions where high moisture content is present along with lot cage induction motors with high rotor resistance, totally enclosed, fan cooled and having high temperature insulation are used to drive looms. For light fabrics like cotton, silk, nylon etc. small motors of less than 1 hp may be sufficient. For heavy fabrics such as wool, the rating of these motors may be 2-3 hps. These motors are normally run at 750-1000 rpm.

(ii) Applications of Industrial Drive > Spinning:
The spinning mills use one of the following three types of drives:
(i) A 4-pole or 6-poIe squirrel cage induction motor,
(ii) A pole amplitude 4/6 or 6/8 poles induction motor,
(iii) Two separate motors to be runs at 1500/1000 or 1000/750 rpm. But whatever may be the types of motor used, the motor must be started with controlled torque.

Applications of Industrial Drive > PAPER INDUSTRY:
In a paper industry, the drives are required for
(i) Pulp making, and
(ii) Paper making.

In the pulp making process, the logs of wood are either ground in mechanical grinders or else they are chemically treated with alkalis and simultaneously beaten up to turn them into soft pulp. In the mechanical method of pulp making, the electrical power requirement is very high because the wood is hard. Since the mechanical grinders operate at a constant speed of about 200-300 rpm, the motors can be started on no load. Thus synchronous motors are used for these drives. These motors normally run at 1000-1500 rpm and gears are used to reduce the speed to 200-300 rpm.

In the chemical method of pulp making, the logs of wood are continuously beaten by the beaters at the time of treatment with alkali. The power requirement of the beater motors is less than those of grinder motors but these motors require high starting torque. Therefore, slip ring induction motors with gears are used to drive these beaters at about 150-200 rpm.

Applications of Industrial Drive > BELT CONVEYRS:
Normal starting current, high starting torque (double cage) squirrel cage motors with direct-on-line starters are used for conveyer drives because they have often to start with full load.

Applications of Industrial Drive > Compressors:
Wound rotor induction motors and synchronous motors are generally used on large size machines. Squirrel cage motors are used for small compressors only.

Applications of Industrial Drive > Blowers-fans:
The squirrel cage induction motors and synchronous motors are used for driving blowers and fans.

Applications of Industrial Drive > Pumps:
Centrifugal pumps are driven by squirrel-cage induction motors or synchronous motors. Reduced voltage starters can be used because of low starting torque requirements.

Applications of Industrial Drive > Machine tools:
Squirrel cage motors are normally used for them.

Applications of Industrial Drive > Jaw crushers:
Belted slip ring induction motor is almost invariably used as, very often, the motor has to start against heavy load or a stuck crusher. Pipe ventilated motors should be used so that supply of cool and clean ventilating air can be ensured even industry dusty atmosphere.
Electric Drives
Electric drives and motors are used to actuate/move certain parts in the robot, these parts can be arms, fingers, wheels and many other things. They are an essential component of any robot, without them we cannot build robots.
Electric Drives are readily adaptable to computer control, the predominant technology used today for robot controllers. Electric drive robots are relatively accurate compared to hydraulically powered robots.