UNIT IV STARTING AND SPEED CONTROL OF THREE PHASE INDUCTION MOTOR

Need for starting – Types of starters – DOL, Rotor resistance, Autotransformer and Star-delta starters – Speed control – Voltage control, Frequency control and pole changing – Cascaded connection-V/f control – Slip power recovery scheme-Braking of three phase induction motor: Plugging, dynamic braking and regenerative braking.

NECESSITY OF A STARTER IN A THREE PHASE INDUCTION MOTOR.

The three phase induction motors are self starting due to rotating magnetic field. But the motors have a tendency to draw very high current at the time of starting. Such a current can be five to eight times the rated current and can damage the motor winding. Hence a starter is used which can limit such high starting current.

In a three phase induction motor, the magnitude of an induced e.m.f. in the rotor circuit depends on the slip of the induction motor. This induced e.m.f. effectively decides the magnitude of the rotor current. The rotor current in the running condition is given by,

$$I_{2r} = \frac{sE_2}{\sqrt{R_2^2 + (s\,X_2)^2}}$$

At start, the speed of the motor is zero and slip is at its maximum i.e. unity. So magnitude of rotor induced e.m.f. is very large at start. As rotor conductors are short circuited, the large induced e.m.f. circulates very high current through rotor at start.

In a three phase induction motor, when rotor current is high, the stator draws a very high current from the supply. This current can be of the order of 5 to 8 times the full load current, at start.

Due to such heavy inrush of current at start

- There is possibility of damage of the motor winding.
- Causes large line voltage drop.
- Other appliances connected to the same line may be subjected to voltage spikes which may affect their working.

To avoid such effects, it is necessary to limit the current drawn by the motor at start. The starter is a device which is basically used to limit high starting current by supplying reduced voltage to the motor at the time of starting. Such a reduced voltage is applied only for short period and once rotor gets accelerated, full normal rated voltage is applied.

Functions of a Starter:

- limits the starting current
- provides the protection against overloading
- Provides the protection against low voltage situations.
- provides protection against single phasing

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WORKING OF DIRECT ON LINE STARTER

If large rating induction motors are connected directly to the supply, a heavy starting current can damage the motor and also cause disturbance of voltage, i.e., voltage dip on mains supply. This can lead malfunctioning of other equipments connected to the same supply.

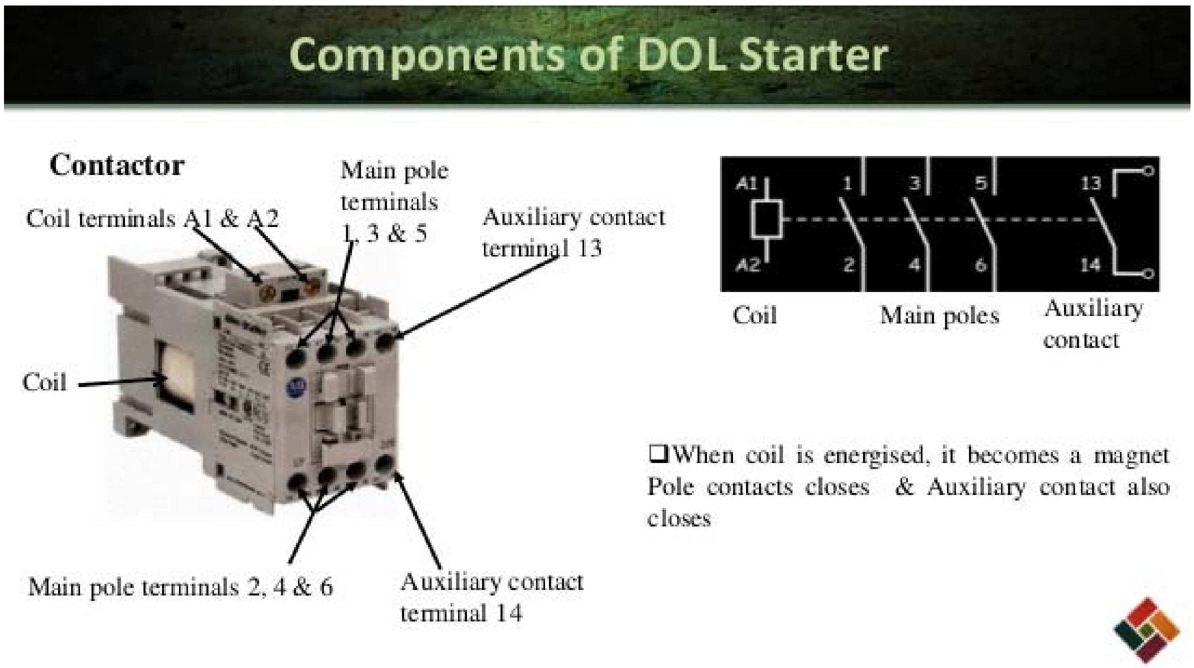
Thus DOL starters are limited to small rating motors where distribution system (mains supply) can withstand high starting currents without excessive voltage dips.

DOL starter consists of MCCB, contactor, and overload relay. It acts as a switch under normal working condition by providing the means to switch ON and switch OFF the motor.

Construction or Parts of DOL Starter

It consists of two push buttons, one is a green button for starting the motor and the other is red for stopping the motor. The switching of power supply is carried through an electromagnetic contactor which can be 3 or 4 pole contactor. This electromagnetic contactor has three NO contacts that connect the motor to the supply line while fourth contact (also called as an auxiliary contact) works as hold-on contact when the start button is released in order to energize the contactor coil.

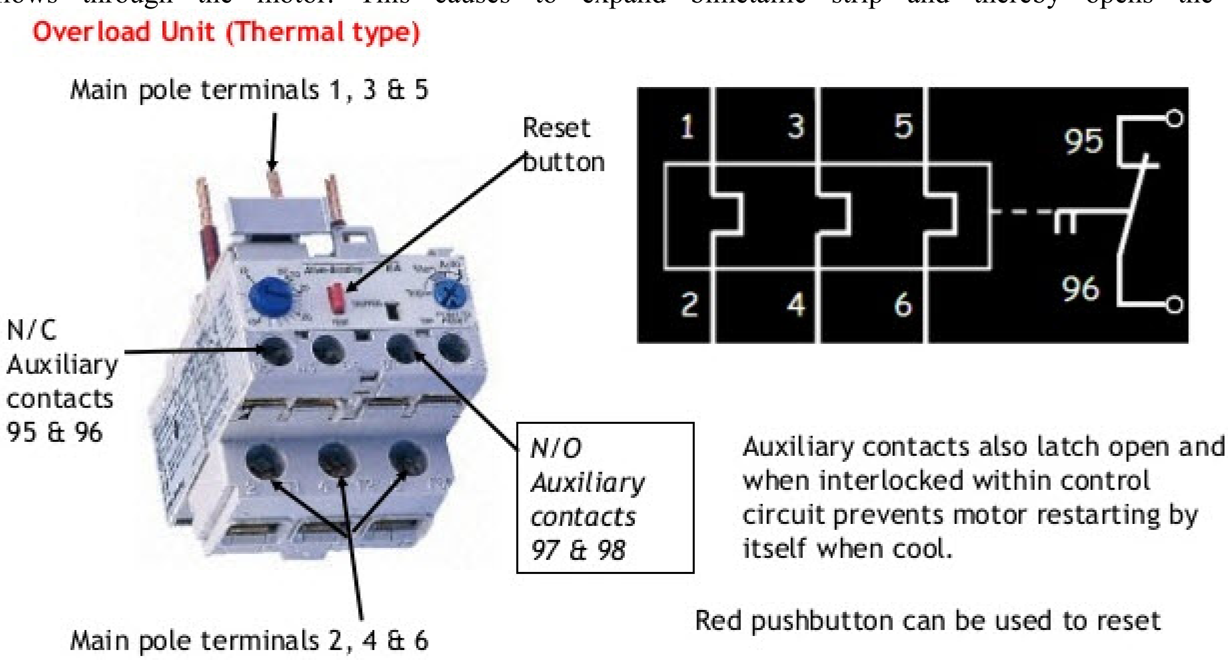
This auxiliary contact (NO or NC) makes the contactor to be electrically latched while motor is operating and these contacts are less power rated than three main NO contacts. If any reason, power supply fails or voltage drops excessively, it releases the latch by de-energizing the coil and thus motor disconnected from the supply.



The contactor coil is connected in series with a start button, stop button and overload trip mechanism. This connection is called control circuit which is generally energized from two lines of three phase supply via a step down transformer.

Overload Protection

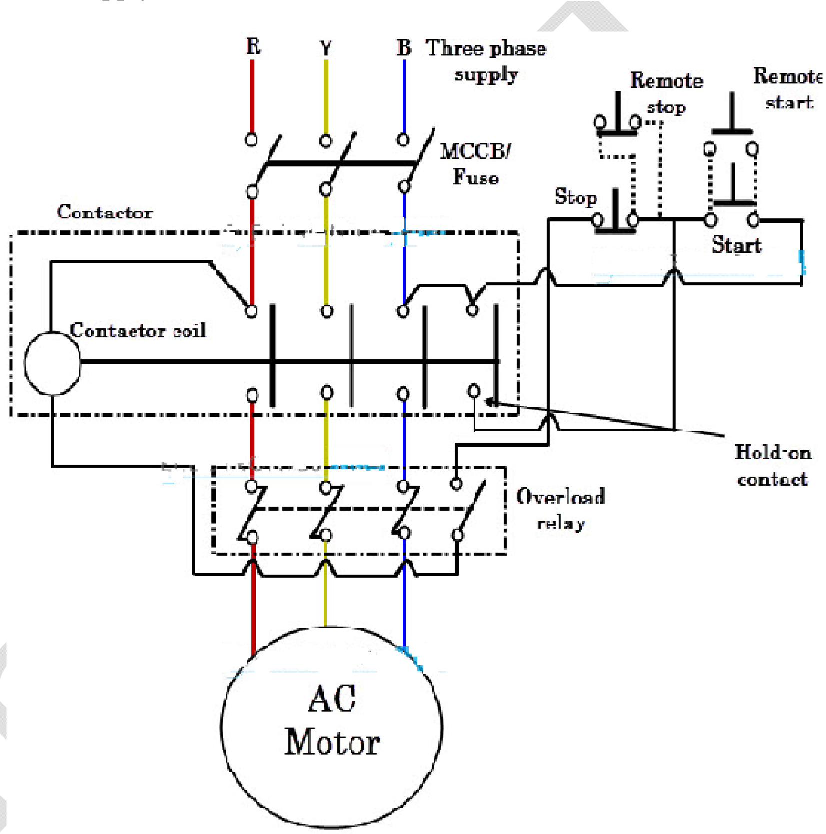
DOL starter is also provided with overload relay to protect the motor from overloads. The overload relays are provided with heating elements inside of which bimetallic strips are arranged. When excessive current flows through the motor, overheating causes to damage the motor winding. The overload coil becomes hot when the over current flows through the motor. This causes to expand bimetallic strip and thereby opens the trip contact.



This overload mechanism should operate at 20 to 30% overload. When the overload coils trips, the current through the contactor coil stops flowing and hence the contactor contacts come to the OFF position.Overload relays are provided with current adjuster such that tripping coil current can be adjusted depending on the load protection requirement.

Working of DOL Starter

- The wiring connection of DOL starter with start and stop buttons is shown in figure below. The DOL starter main terminals are connected between the mains supply terminals and motor terminals while the control circuit is energized with two terminals of three phase supply as illustrated in figure.



- When the start button is pressed, current will flow through one phase to the control circuit and the contactor coil to the other phase. This current energizes the contactor coil which makes to close the contacts thereby three phase supply is connected to the motor. Since the start button is of pushbutton, when it is released the control circuit still maintains the supply through hold-on contact.
- If the stop button is pressed or overload relay coil operate, the current path through contactor coil will break and hence the contactor contacts drops out, thus breaking the supply to the motor. Once the power supply is interrupted, again the supply to the motor is established by pressing the start button.
- The thermal overload protection relay operates depending on the heating effect of the load current. When the load current heats the thermal coils, bimetallic strip inside of it expands such that it trips out the spring-loaded contact in the control circuit. The speed at which relay operates decided by the current adjustment. Typically it will be four to five times the rated motor current.
- DOL starter can be operated remotely for remote control switching of motor from any number of desired places. For remote control switching one should remember that, all the remote ON push buttons must be connected in parallel to ON pushbutton of the starter whereas all remote OFF push buttons must be connected in series with OFF pushbutton of the starter. Connect the remote ON and OFF switches as shown in dotted line in the figure for remote control operation.

Advantages of DOL Starter

- It provides high starting torque.
- Simple to use and most economical.
- Control circuitry is simple to establish and troubleshoot.
- Easy to find fault and make necessary connections.
- More compact in size and thus occupies less space.

Disadvantages of DOL Starter

- High starting current, typically in the range of 6 to 8 times the full load current

- The inrush current of large motor may cause a big voltage dip or drop in electrical supply system which will affect other electrical appliances connected to it.
- The unnecessary high starting torque required by the load may cause increasing mechanical stresses on motor mechanical parts as well as the loads.
- It is not feasible for high rating motors, typically above 10 KW

STARTING METHODS USED FOR THREE PHASE INDUCTION MOTOR

Methods for starting induction motors are:

Squirrel Cage Motor

a. Primary resistors (or reactors or rheostats) or stator resistance starter.
b. Autotransformer (or auto starter)
c. Star-delta starters

Slip ring Motors

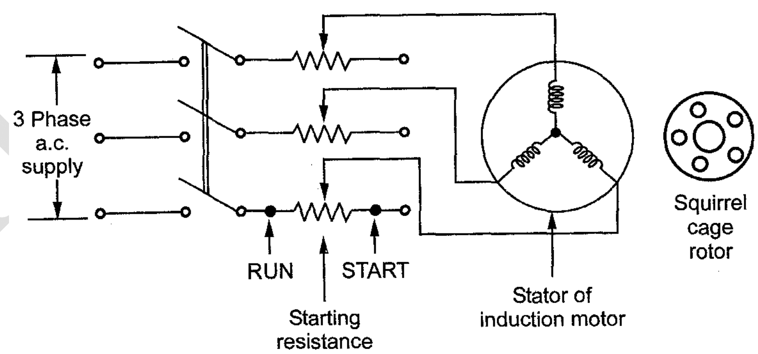
a. Rotor rheostat or rotor resistance starter

Squirrel Cage Motor

a. Primary resistors

In order to apply the reduced voltage to the stator of the induction motor, three resistances are added in series with each phase of the stator winding. Initially the resistances are kept maximum in the circuit. Due to this, large voltage gets dropped across the resistances. Hence a reduced voltage gets applied to the stator which reduces the high starting current. The schematic diagram showing stator resistances is shown in the Fig.

When the motor starts running, the resistances are gradually cut-off from the stator circuit. When the resistances are entirely removed from the stator circuit i.e. rheostats in RUN position then rated voltage gets applied to the stator. Motor runs with normal speed.



- The starter is simple in construction and cheap.
- It can be used for both star and delta connected stator.
- Large power losses due to resistances.
- The starting torque of the motor reduces due to reduced voltage applied to the stator.

$P_2 = T \times \omega$

Where T = torque produced

P_2 = rotor input at N_s

∴ $T \propto P_2$

But $P_2 = \frac{P_c}{s}$ where P_c = total copper loss

$= \frac{3 I_{2r}^2 R_2}{s}$

Therefore $T \propto \frac{I_{2r}^2}{s}$

But rotor current I_{2r} and stator current are related to each other through transformer action.

∴ $T \propto \frac{I_1^2}{s}$ where I_1 = stator current

At start, s = 1, $T = T_{st}$ and $I_1 = I_{st}$

∴ $T_{st} \propto I_{st}^2$ (1)

When stator resistance starter is used, the factor by which stator voltage reduces is say x< 1. The starting current is proportional to this factor x. So if is the normal current drawn under full rated voltage condition at start then,

$I_{st} = x\, I_{sc}$ (2)

$\therefore$ $T_{st} = (x\, I_{sc})^2$ (3)

But $T_{F.L} \propto \frac{I_{FL}^2}{s_f}$ where s_f = full load slip (4)

Taking ratio of (3) and (4),

$$\frac{T_{st}}{T_{FL}} = x^2 \left[\frac{I_{sc}}{I_{FL}}\right]^2 s_f$$

This method is useful for the smooth starting of small machines only.

b. Autotransformer (or auto starter) or compensators

. A three phase star connected autotransformer can be used to reduce the voltage applied to the stator. Such a starter is called an autotransformer starter. The schematic diagram of autotransformer starter is shown in the Fig.

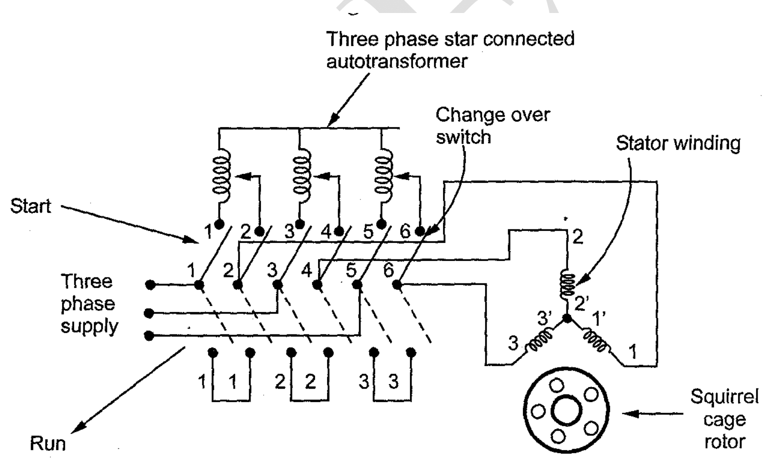
It consists of a suitable change over switch.

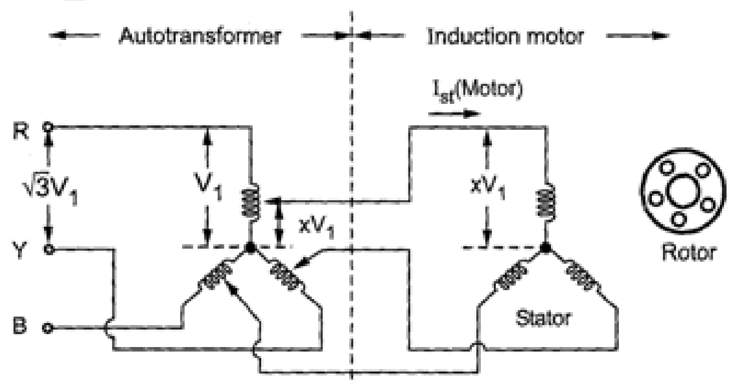
When the switch is in the start position, the stator winding is supplied with reduced voltage. This can be controlled by tappings provided with autotransformer.

The reduction in applied voltage by the fractional percentage tappings x, used for an autotransformer is shown in fig.

When motor gathers 80 % of the normal speed, the change over switch is thrown into run position.

Due to this, rated voltage gets applied to stator winding. The motor starts rotating with normal speed. Changing of switch is done automatically by using relays.





- The power loss is much less in this type of starting.
- It can be used for both star and delta connected motors.
- But it is expensive than stator resistance starter.

Voltage across motor phase on direct switching is V/√3 and starting current is

$I_{st} = I_{sc}$

With auto starter, voltage across motor phase is KV/√3 and $I_{st} = K\, I_{sc}$

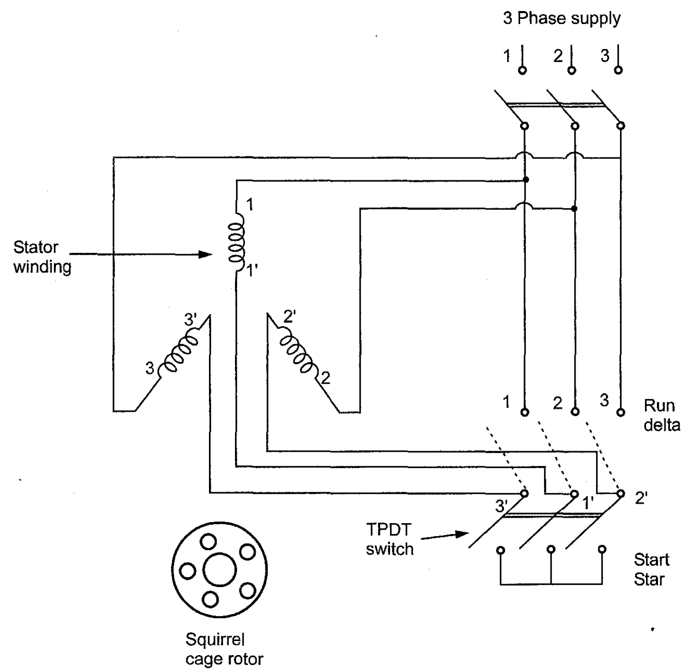
Now, $T_{st} \propto I_{st}^2$ (s = 1) and $T_{FL} \propto \frac{I_{FL}^2}{s_f}$

$\therefore$ $\frac{T_{st}}{T_{FL}} = \left[\frac{I_{st}}{I_{FL}}\right]^2 s_f$ or $\frac{T_{st}}{T_{FL}} = K^2 \left[\frac{I_{sc}}{I_{FL}}\right]^2 s_f$

c. Star-delta starters

This is the cheapest starter of all and hence used very commonly for the induction motors. It uses Triple Pole Double Throw (TPDT) switch. The switch connects the stator winding in star at start. Hence per phase voltage gets reduced by the factor 1/√3. Due to this reduced voltage, the starting current is limited.

When the switch is thrown on other side, the winding gets connected in delta, across the supply. So it gets normal rated voltage. The windings are connected in delta when motor gathers sufficient speed. The arrangement of star-delta starter is shown in the Fig.



The operation of the switch can be automatic by using relays which ensures that motor will not start with the switch in Run position.

Advantages

- The cheapest of all and maintenance free operation.

Limitations

- It is suitable for normal delta connected motors and the factor by which voltage changes is 1 / √3 which cannot be changed.

It is used for machine tools, pumps and motor generators etc.

$$I_{st} \text{ per phase} = \frac{1}{\sqrt{3}} I_{sc} \text{ per phase}$$

$$T_{st} \ \alpha \ I_{st}^2 \ (s = 1)$$

and $$T_{FL} \ \alpha \ \frac{{I_{FL}}^2}{s_f}$$

$$\therefore \quad \frac{T_{st}}{T_{FL}} = \left[\frac{I_{st}}{I_{FL}}\right]^2 s_f = \left[\frac{I_{sc}}{\sqrt{3} I_{FL}}\right]^2 s_f = \frac{1}{3}\left[\frac{I_{sc}}{I_{FL}}\right]^2 s_f$$

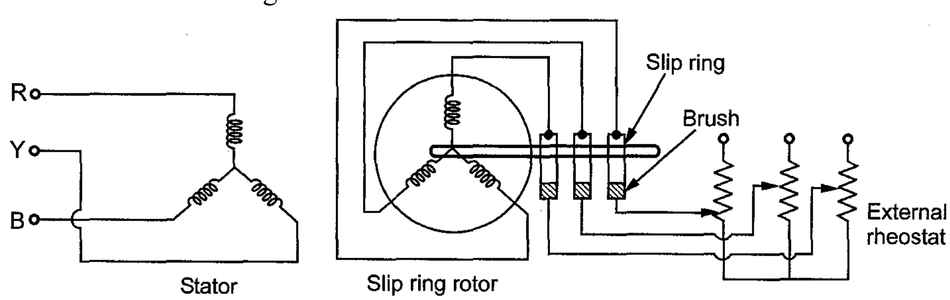
The star-delta switch is equivalent to an autotransformer of ratio 1/√3 or 58% approximately.

Slip ring Motors

a. Rotor rheostat or rotor resistance starter

To limit the rotor current which consequently reduces the current drawn by the motor from the supply, the resistance can be inserted in the rotor circuit at start. This addition of the resistance in rotor is in the form of 3 phase star connected rheostat. The arrangement is shown in the Fig.

The external resistance is inserted in each phase of the rotor winding through slip ring and brush assembly.



Initially maximum resistance is in the circuit. As motor gathers speed, the resistance is gradually cutoff. The operation may be manual or automatic.

The starting torque is proportional to the rotor resistance.

Advantage

- Not only the starting current is limited but starting torque of the motor also gets improved.

Limitation

- It can be used only for slip ring induction motors as in squirrel cage motors; the rotor is permanently short circuited.

SPEED CONTROL OF INDUCTION MOTOR

1. Control from stator side
   a. By changing the applied voltage
   b. By changing the applied frequency
   c. By changing the number of stator poles
2. Control from rotor side
   d. Rotor rheostat control
   e. By operating two motors in concatenation or cascade
   f. By injecting an emf in the rotor circuit.

(a) By changing the applied voltage

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

Rotor induced emf at standstill, E_2 depends on the supply voltage V

$\therefore \quad E_2 \propto V$

For low slip region, $(sX_2)^2 << R_2$, hence

$$T \propto \frac{sV^2R_2}{R_2^2} \propto s\,V^2 \text{ for constant } R_2$$

If supply voltage is reduced below rated value, as per above equation, torque produced also decreases. But to supply the same load it is necessary to develop same torque hence value of slip increases so that torque produced remains same.

Slip increases means motor reacts by running at lower speed, to decrease in supply voltage. So motor produces the required load torque at a lower speed.

This method, though the cheapest and the easiest, is rarely used because

(i) A large change in voltage is required for a relatively small change in speed

(ii) Due to reduction in voltage, current drawn by the motor increases. Due to increased current, the motor may get overheated.

(iii) This large change in voltage will result in a large change in the flux density thereby seriously disturbing the magnetic conditions of the motor.

(b) By changing the applied frequency or supply frequency control or V/f 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

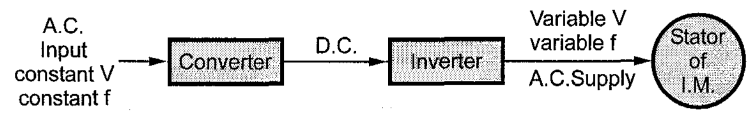
$$E \text{ or } V = 4.44\,\Phi\,K\,T\,f$$

$$\Phi = \frac{V}{4.44\,K\,T\,f}$$

Where, K is the winding constant, T is the number of turns per phase and f is frequency. 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 .

To maintain flux, φ constant, 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.

The normal supply available is constant voltage constant frequency a.c. supply. The converter converts this supply into a d.c. supply. This d.c. supply is then given to the inverter. The inverter is a device which converts d.c. supply, to variable voltage variable frequency a.c. supply which is required to keep V/f ratio constant. By selecting the proper frequency and maintaining V/f constant, smooth speed control of the induction motor is possible.



Disadvantages

- Used where the induction motor is the only load on the generators.
- Range over which the motor speed may be varied is limited.
- The supply cannot be used to supply other devices which require constant voltage.

(c) By changing the number of stator poles

The method is called Pole Changing method of controlling the speed. In this method, it is possible to have one, two or four speeds in steps, by changing the number of stator poles. A continuous smooth speed control is not possible by this method.

The stator poles can be changed by following methods

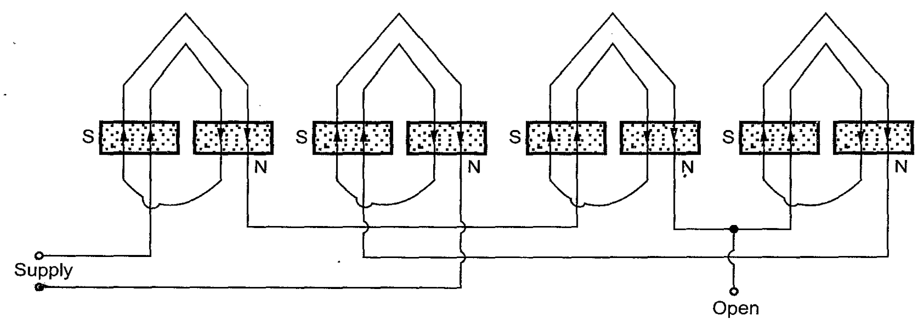
1. Consequent poles method
2. Multiple stator winding method
3. Pole amplitude modulation method.

Consequent Poles Method

In this method, connections of the stator winding are changed with the help of simple switching. Due to this, the number of stator poles get changed in the ratio 2 1. Hence either of the two synchronous speeds can be selected.

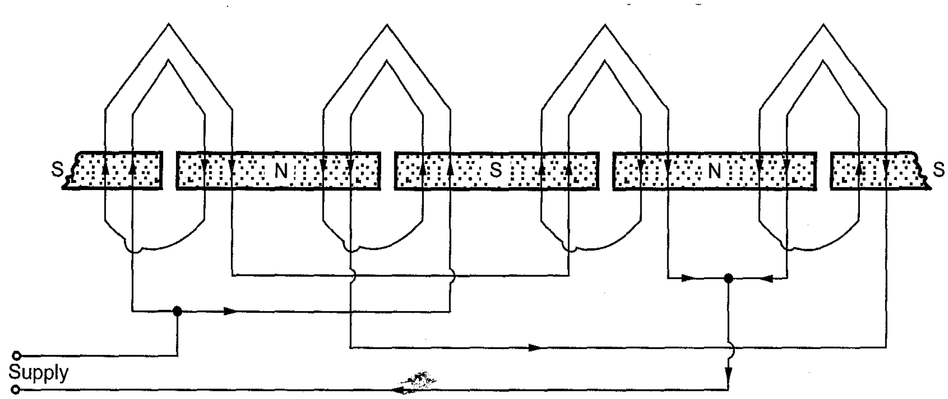
Consider the pole formation due to single phase of a three phase winding, as shown in the Fig. There are three tapping points to the stator winding. The supply is given to two of them and third is kept open.

The current in all the parts of stator coil is flowing in one direction only. Due to this, 8 poles get formed as shown in the Fig. So synchronous speed possible with this arrangement with 50 Hz frequency is N = 750 r.p.m.



If the two terminals to which supply was given earlier are joined together and supply is given between this common point and the open third terminal, the poles are formed as shown in the Fig.

The direction of current through two coils is different than the direction of current through remaining two. Thus upward direction is forming say S pole and downward say N. In this case only 4 poles are formed. So the synchronous speed possible is 1500 r.p.m. for 50 Hz frequency.



Disadvantage

- The speed change is in step and smooth speed control is not possible.

- The method can be used only for the squirrel cage type motors as squirrel cage rotor adjusts itself to same number of poles as stator which is not the case in slip ring induction motor.

Applications

Elevators, traction motors and small motors to drive machine tools.

Multiple stator winding method

In this method instead of one winding, two separate stator windings are placed in the stator core. The windings are placed in the stator slots only but are electrically isolated from each other. Each winding is divided into coils to which, pole changing with consequent poles, facility is provided.

Thus giving supply to one of the two windings and using switching arrangement, two speeds can be achieved. Same is true for other stator winding. So in all four different speeds can be obtained.

Limitations

1. Can be applied to only squirrel cage motor.
2. Smooth speed control is not possible. Only step changes in speed are possible.
3. Two different stator windings are required to be wound which increases the cost of the motor.
4. Complicated from the design point of view.

Pole amplitude modulation method

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

$f_1(\theta)$ be the original mmf wave of induction motor whose speed is to be controlled.

$f_2(\theta)$ be the modulation mmf wave.

P_1 be the number of poles of induction motor whose speed is to be controlled.

P_2 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

$$F_r(\theta) = F_1F_2 \sin \frac{P_1\theta}{2} \sin \frac{P_2\theta}{2}$$

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

So we get, resultant mmf wave

$$F_r(\theta) = F_1F_2 \frac{\cos\frac{(P_1-P_2)\theta}{2} - \cos\frac{(P_1+P_2)\theta}{2}}{2}$$

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

$P_{11} = P_1 - P_2$ and $P_{12} = P_1 + P_2$

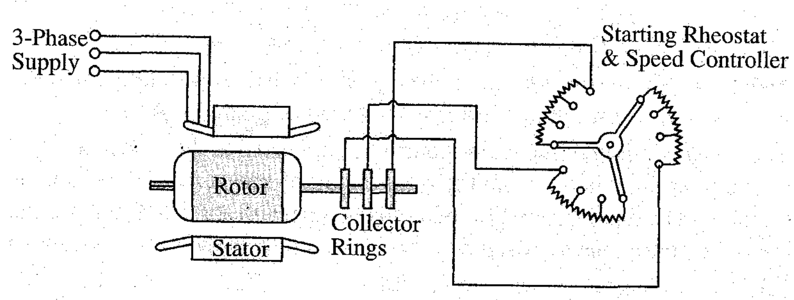
Therefore by changing the number of poles we can easily change the speed of three phase induction motor.

(d) Rotor rheostat control

$$T \,\alpha\, \frac{sE2^2R2}{R2^2 + (sX2)^2}$$

For low slip region, $(sX_2)^2 << R_2$, and can be neglected and for constant supply voltage E_2 is also constant.

$$\therefore \quad T \alpha \frac{sR2}{R2^2} \alpha \frac{s}{R2}$$



Thus if the rotor resistance is increased, the torque produced decreases. But when the load on the motor is same, motor has to supply same torque as load demands. So motor reacts by increasing its slip to compensate decrease in T due to R2 and maintains the load torque constant.

So due to additional rotor resistance R_2, motor slip increases i.e. the speed of the motor decreases.

Advantage

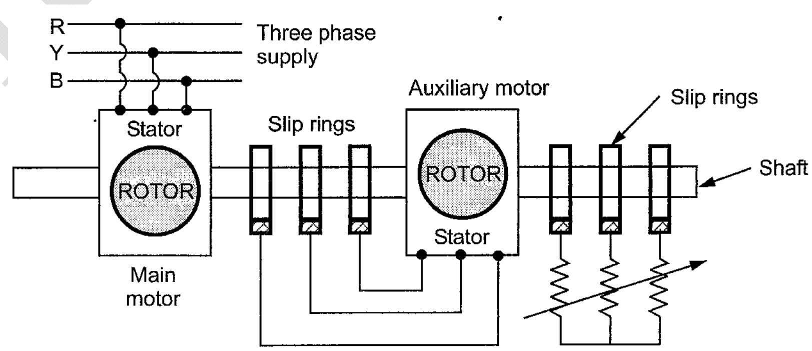
- By increasing the rotor resistance R_2 speeds below normal value can be achieved.
- The starting torque of the motor increases proportional to rotor resistance.

Disadvantage

- The large speed changes are not possible. This is because for large speed change, large resistance is required to be introduced in rotor which causes large rotor copper loss to reduce the efficiency.
- The method cannot be used for the squirrel cage induction motors.
- The speeds above the normal values cannot be obtained.
- Large power losses occur due to large 1^2R loss.
- Sufficient cooling arrangements are required which make the external rheostats bulky and expensive.
- Due to large power losses, efficiency is low.

(e) By operating two motors in concatenation or cascade or Tandem operation

In this method, two induction motors are mounted on the same shaft. One of the two motors must be of slip ring type which is called main motor. The second motor is called auxiliary motor. The arrangement is shown in the Fig.



The auxiliary motor can be slip ring type or squirrel cage type.

The stator of the main motor is connected to the three phase supply while the supply of the auxiliary motor is derived at a slip frequency from the slip rings of the main motor. This is called cascading of the motors.

If the torques produced by both act in the same direction, cascading is called cumulative cascading.

If torques produced are in opposite direction, cascading is called differential cascading.

P_A = Number of poles of main motor

P_B = Number of poles of auxiliary motor

f = Supply frequency

$$N_{SA} = \frac{120\ f}{P}$$

Let N = actual speed of the concatenated set

$$s_A = \frac{N_{SA} - N}{N_{SA}}$$

f_A = frequency of rotor induced emf of motor A

∴ $f_A = s_A f$ as $f_r = sf$

The supply to motor B is at frequency f_A, ie. $f_B = f_A$

∴ $N_{SB} = \frac{120\, f_B}{P_B} = \frac{120\, f_A}{P_B} = \frac{120 s_A\, f}{P_B} = \frac{120(N_{SA} - N)\, f}{P_B \times N_{SA}}$

On no load, the speed of the rotor B i.e. N is almost equal to its synchronous speed N_{SB}.

∴ $N_{SB} = N$

∴ $N = \frac{120(N_{SA} - N)\, f}{P_B \times N_{SA}} = \frac{120\, f}{P_B} \times \left[1 - \frac{N}{N_{SA}}\right] = \frac{120\, f}{P_B} \times \left[1 - \frac{N}{\frac{120\, f}{P_A}}\right]$

$N = \frac{120\, f}{P_B} \times \left[1 - \frac{N P_A}{120 f}\right]$

$N \left[1 + \frac{P_A}{P_B}\right] = \frac{120\, f}{P_B}$

∴ $N = \frac{120\, f}{P_A + P_B}$

If by interchanging any two terminals of motor B, the reversal of direction of rotating magnetic field of B is achieved then the set runs as differentially cascaded set. And in such a case effective number of poles are $P_A - P_B$.

Thus in cascade control, four different speeds are possible as,

a. With respect to synchronous speed of A independently,

$$N_S = \frac{120\, f}{P_A}$$

b. With respect to synchronous speed of B independently with main motor is disconnected and B is directly connected to supply,

$$N_S = \frac{120\, f}{P_B}$$

c. Running set as cumulatively cascaded with,

$$N = \frac{120\, f}{P_A + P_B}$$

d. Running set as differentially cascaded with,

$$N = \frac{120\, f}{P_A - P_B}$$

Disadvantages

1. It requires two motors which makes the set expensive.
2. Smooth speed control is not possible.
3. Operation is complicated.
4. The starting torque is not sufficient to start the set.
5. Set cannot be operated if $P_A = P_B$.

(f) By injecting an emf in the rotor circuit.

In this method, a voltage is injected in the rotor circuit. The frequency of rotor circuit is a slip frequency and hence the voltage to be injected must be at a slip frequency.

The injected voltage may oppose the rotor induced e.m.f. or may assist the rotor induced e.m.f.

- If it is in the phase opposition, effective rotor resistance increases.
- If it is in the phase of rotor induced e.m.f., effective rotor resistance decreases.

  Thus by controlling the magnitude of the injected e.m.f., rotor resistance and effectively speed can be controlled.

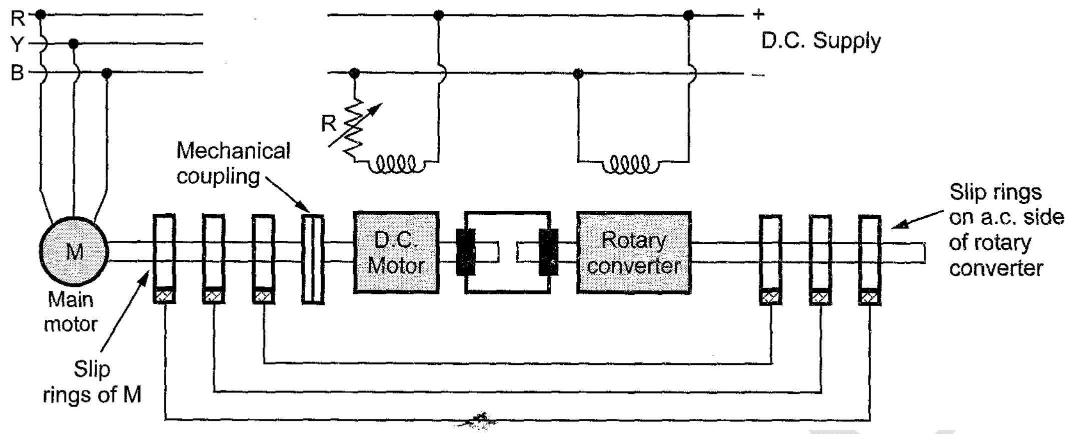
Practically two methods are available which use this principle. These methods are,

1. Kramer system 2. Scherbius system

Kramer system

- It consists of main induction motor M, the speed of which is to be controlled. The two additional equipments are, d.c. motor and a rotary converter.

- The slip rings of the main motor are connected to the a.c. side of a rotary converter.
- The d.c. side of rotary converter feeds a d.c. shunt motor commutator, which is directly connected to the shaft of the main motor.
- A separate d.c. supply is required to excite the field winding of d.c. motor and exciting winding of a rotary converter.
- The variable resistance is introduced in the field circuit of a d.c. motor which acts as a field regulator.



- The speed of the set is controlled by varying the field of the d.c. motor with the rheostat R.
- When the field resistance is changed, the back e.m.f. of motor changes. Thus the d.c. voltage at the commutator changes. This changes the d.c. voltage on the d.c. side of a rotary converter.
- Now rotary converter has a fixed ratio between its a.c. side and d.c. side voltages. Thus voltage on its a.c. side also changes.
- This a.c. voltage is given to the slip rings of the main motor.
- So the voltage injected in the rotor of main motor changes which produces the required speed control.

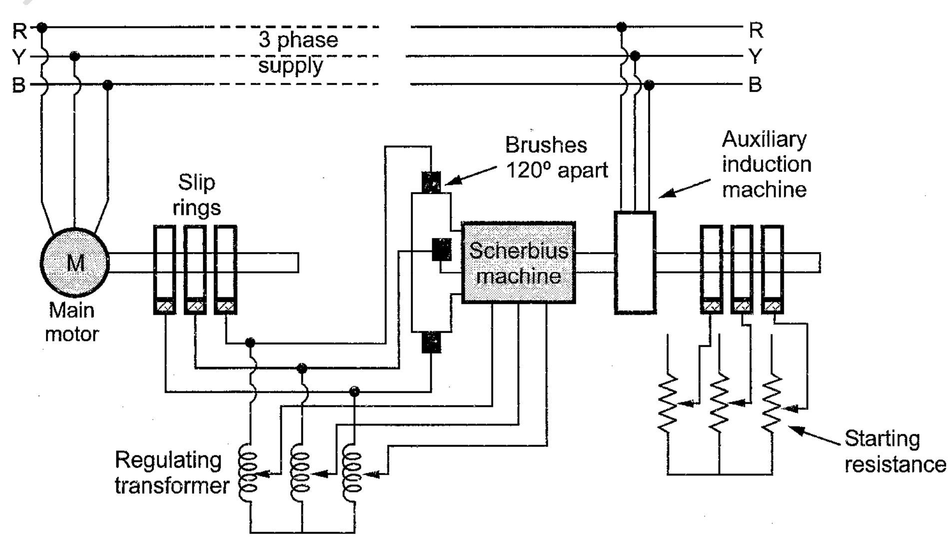
Advantages

- smooth speed control is possible
- wide range of speed control is possible
- the design of a rotary converter is practically independent of the speed control required
- if rotary converter is overexcited, it draws leading current and thus power factor improvement is also possible along with the necessary speed control

Very large motors above 4000 kW such as steel rolling mills use such type of speed control.

Scherbius system

- This method requires an auxiliary 3 phase or 6 phase a.c. commutator machine which is called Scherbius machine.
- The difference between Kramer system and this system is that the Scherbius machine is not directly connected to the main motor, whose speed is to be controlled.
- The Scherbius machine is excited at slip frequency from the rotor of a main motor through a regulating transformer.
- The taps on the regulating transformer can be varied, this changes the voltage developed



in the rotor of Scherbius machine, which is injected into the rotor of main motor. This controls the speed of the main motor.

- The Scherbius machine is connected directly to the induction motor supplied from main line so that its speed deviates from a fixed value only to the extent of the slip of the auxiliary induction motor.
- For any given setting of the regulating transformer, the speed of the main motor remains substantially constant irrespective of the load variations.

Similar to the Kramer system, this method is also used to control speed of large induction motors. The only disadvantage is that these methods can be used only for slip ring induction motors.

SLIP POWER RECOVERY SCHEME

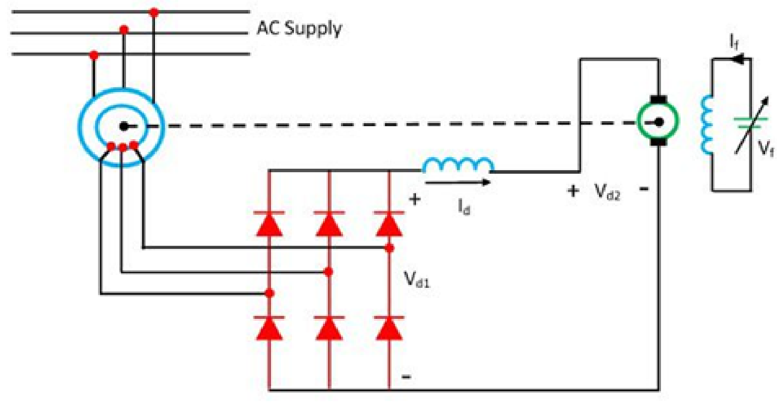
Static Kramer Drive

The static Kramer-drive is the method of controlling the speed of an induction motor by injecting the opposite-phase voltage in the rotor circuit. The injected voltage increases the resistance of the rotor, thus controlled the speed of the motor. By changing the injected voltage, the resistance and speed of an induction motor are controlled.

The static Kramer-drive converts the slip power of an induction motor into AC power and supply back to the line.

The slip power is the air gap power between the stator and the rotor of an induction motor which is not converted into mechanical power.

Thus, the power is getting wasted. The static Kramer drives fed back the wasted power into the main supply. This method is only applicable when the speed of the drive is less than the synchronous speed.



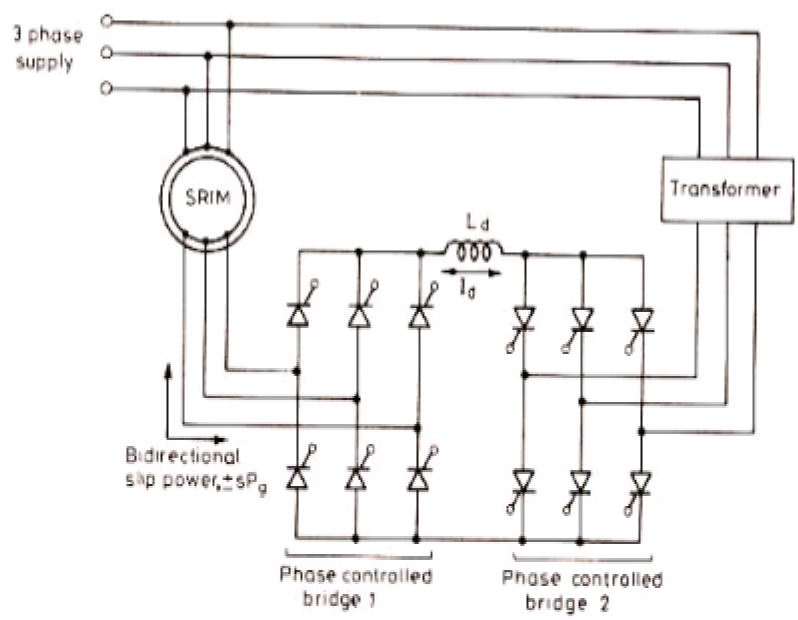
Static Kramer Drive Circuit

Static Scherbius System

- Both the converters are controlled converter. Because of this the power flow in the rotor circuit becomes bidirectional and the induction motor can be operated in sub synchronous as well as super synchronous region of operation.

Sub synchronous mode

- Power must be extracted from the rotor
- Therefore Bridge 1 act as rectifier ($\alpha_1 < 90°$)
- Bridge 2 act as inverter ($\alpha 2 > 90°$) to feed the slip power (extracted from the rotor) back to A.C. supply.
- The slip power flows from the rotor circuit to bridge1, bridge2 and transformer and to the supply.
- At subsynchronous speeds the slip power sP_m is supplied to the rotor by the exciter and so the remaining output power *(1-s) Pm* is supplied to the shaft.



Super- synchronous mode

- Power must be supplied to the rotor

- Bridge '1' act as the inverter ($\alpha_1 > 90°$)
- Bridge '2' operates as the rectifier ($\alpha_2 < 90°$)
- The power flow is now from the supply to transformer, bridge2, bridge1 and to the rotor circuit.
- At supersynchronous speeds, the rotor output power flows in the opposite direction so that the total shaft power increases to (1+s) Pm.

Table shows the summary of operation

Region of operation	Bridge 1	Bridge2	Power flow
Subsynchronous ($\omega < \omega s$)	Rectifier ($\alpha_1 < 90°$)	Inverter ($\alpha_2 > 90°$)	From Rotor to AC supply
Supersynchronous ($\omega > \omega s$)	Inverter ($\alpha_1 > 90°$)	Rectifier($\alpha_2 < 90°$)	From AC supply to rotor

- Rotor voltage and frequency vary linearly with deviation from synchronous speed. For example, if the shaft speed varies in the range of 800-1600 rpm with 1200 rpm as the synchronous speed (s=±0.33) the range of slip frequency will be 0->20Hz for a 60Hz supply frequency.
- Near synchronous speed, slip frequency emf's are insufficient for natural commutation of thyristors. This difficulty can be overcome by using forced commutation.
- Thus, the provision of both sub synchronous and super synchronous speed operation complicates the static converter system and nullifies the advantages of simplicity and economy which are inherent in a purely sub synchronous drive.
- In addition, static scherbius drive is expensive than static Kramer drive because six diodes are replaced by six thyristors and their controlled circuitry.

Advantages

- The machine can be controlled continuously about 50% above and below the synchronous speed with a converter rating of about 50% of the machine capacity
- The static Scherbius drive overcomes the forward motoring only limitation of the static Kramer drive

BRAKING OF THREE PHASE INDUCTION MOTOR.

The braking is the process of reducing the speed of an induction motor. In braking, the motor works as a generator developing a negative torque which opposes the motion of a motor. The braking of an induction motor is mainly classified into three types. They are

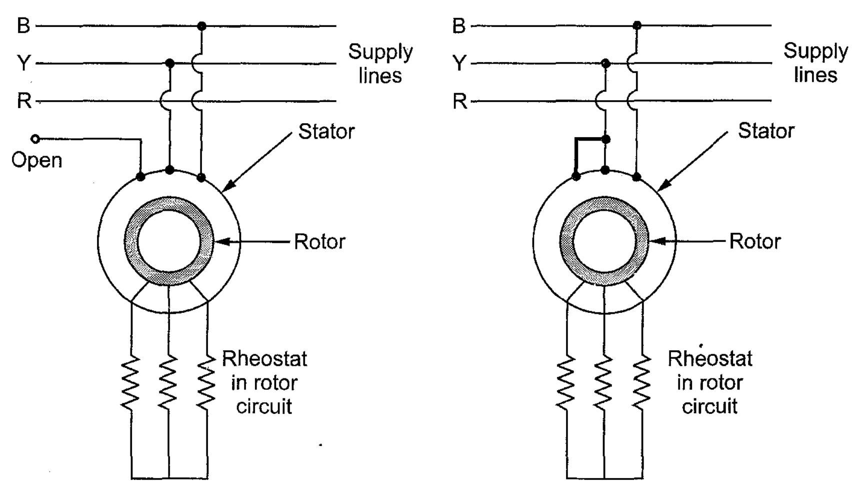
a. Regenerative Braking
b. Plugging or reverse voltage braking
c. Dynamic Braking

Dynamic or Rheostatic Braking

In rheostatic braking, one supply line out of R, Y or B is disconnected from the supply. Depending upon the condition of this disconnected line, two types of rheostatic braking can be achieved.

1. Two lead connections:

In this method, the disconnected line is kept open. This is shown in the Fig. (a) and is called two lead connections.

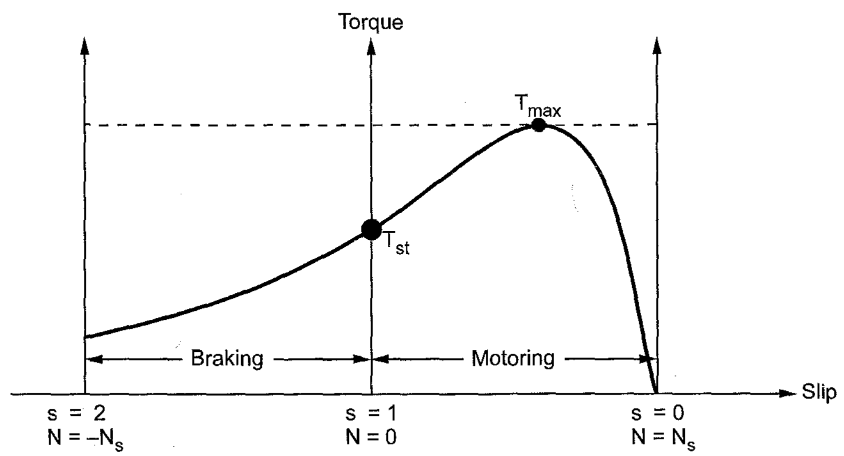


(a) Two lead connections (b) Three lead connections

2. Three lead connections:

In this method, the disconnected line is connected directly to the other line of the machine. This is shown in Fig (b)

- In both cases, a high resistance is inserted in the rotor circuit, with the help of rheostat.
- Thus this method is effective only for slip ring or wound rotor induction motors
- As one of the motor terminal is not connected to the supply, the motor continues to run as a single phase motor. In this case the breakdown torque i.e. maximum torque decreases to 40 % of its original value and motor develops no starting torque at all. And due to high rotor resistance, the net torque produced becomes negative and the braking operation is obtained.
- In two lead connections, the braking torque is small while in three lead connections, the braking torque is high at high speeds.
- But in three lead connections there is possibility of inequality between the contact resistances in connections of two paralleled lines. This might reduce the braking torque and even may produce the motoring torque again.

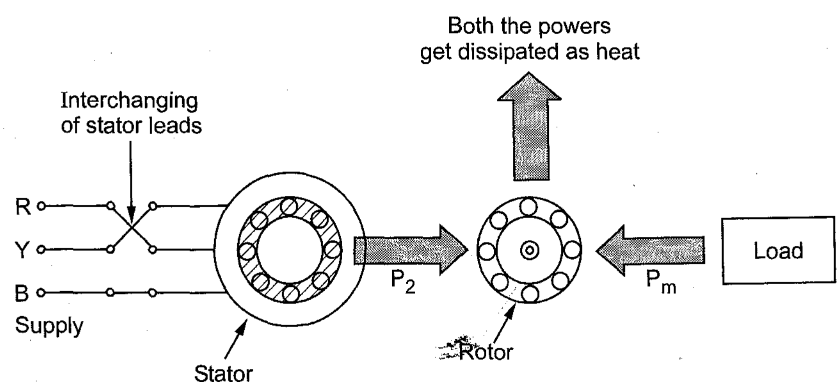


- Hence inspite of low braking torque, two lead connections is preferred over three lead connections.

The torque-slip characteristic for motoring and braking operation is shown in the Fig.

<u>Plugging or Counter Current Braking</u>

- The reversal of direction of rotation of motor is the main principle in plugging of motor.
- In case of an induction motor, it can be quickly stopped by interchanging any two stator leads.
- Due to this, the direction of rotating magnetic field gets reversed suddenly.
- This produces a torque in the reverse direction and the motor tries to rotate in opposite direction.
- Effectively the brakes are applied to the motor. Thus during the plugging, the motor acts as a brake.
- The method can be applied to both squirrel cage as well as wound rotor induction motors.
- One important aspect about plugging is production of very high heat in the rotor.

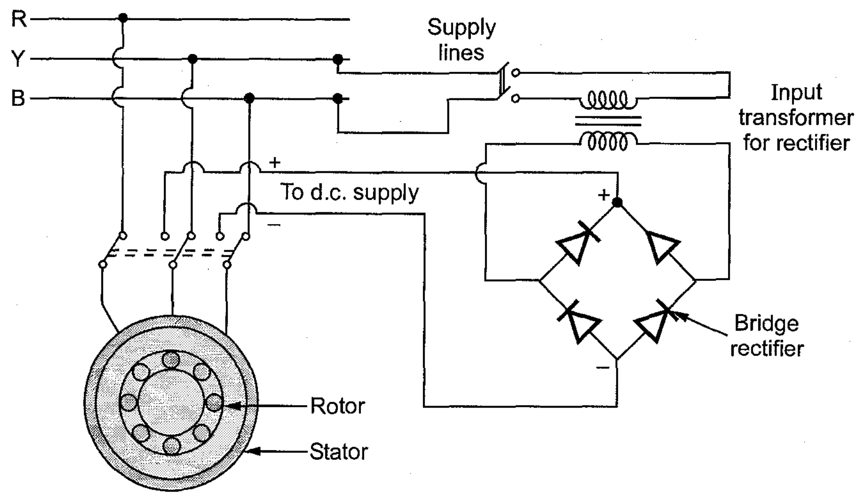


- While plugging, the load keeps on revolving and rotor absorbs kinetic energy from the revolving load, causing speed to reduce.
- The corresponding gross mechanical power P_m is entirely dissipated as heat in the rotor.
- Similarly as stator is connected to supply, rotor continues to receive power P_2 from stator which also gets dissipated as heat in the rotor.

- The plugging should not be done frequently as due to high heat produced rotor may attain high temperature which can melt the rotor bars and even may over heat the stator as well.

D.C. Dynamic Braking

- A quick stopping of an induction motor and its high inertia load can be achieved by connecting stator terminals to a d.c. supply.
- Any two stator terminals can be connected to a d.c. supply and third terminal may be kept open or may be connected directly to other stator terminal. This is called d.c. dynamic braking.
- If third terminal is kept open it is called two lead connections while if it is shorted directly with other stator terminal it is called three lead connections.
- A diode bridge can be used to get d.c. supply.
- The Fig. shows two lead connections with a diode bridge for a d.c. dynamic braking of an induction motor.
- When d.c. is supplied to the stator, stationary poles N, S are produced in stator.
- The number of stationary poles is P for which stator winding is wound.
- As rotor is rotating, rotor cuts the flux produced by the stationary poles. Thus the a.c. voltage gets induced in the rotor.
- This voltage produces an a.c. current in the rotor.



- The motor works as a generator and the $I^2 R$ losses are dissipated at the expenditure of kinetic energy stored in the rotating parts. Thus dynamic braking is achieved.
- When all the kinetic energy gets dissipated as heat in the rotor, the induction motor comes to rest.

ADVANTAGES

1. The heat produced is less compared to the plugging.
2. The energy dissipated in the rotor is not dependent on the magnitude of the d.c. current.
3. The braking torque is proportional to the square of the d.c. current.
4. Quick stopping of the motor is possible.
5. The method can be used for wound rotor or squirrel cage rotor induction motors.

Regenerative Braking

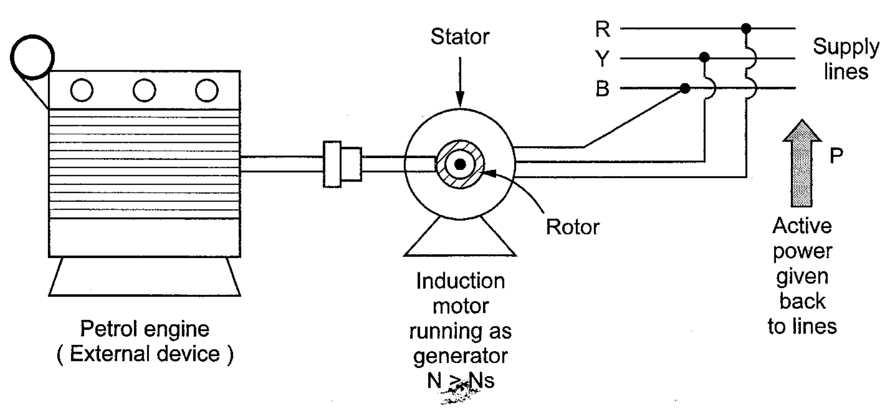
- The input power to a three phase induction motor is given by,

$$P_{in} = 3V_{ph} I_{ph} \cos \Phi$$

where Φ = Angle between stator phase voltage and phase current

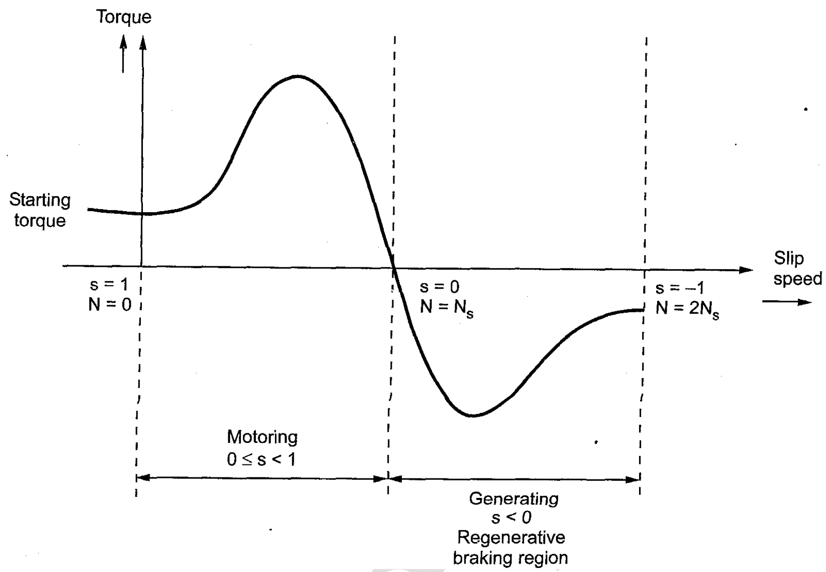
This Φ is less than 90^0 for the motoring action.

- If the rotor speed is increased greater than the synchronous speed with the help of external device, it acts as an induction generator.
- It converts the input mechanical energy to an electrical energy which is given back to supply.



- It delivers active power to the 3 phase line. The Φ becomes greater than 90°.
- The power flow reverses hence rotor induced e.m.f. and rotor current also reverse.
- So rotor produces torque in opposite direction to achieve the braking.
- As the electrical energy is given back to the lines while braking, it is called regenerative braking.
- The arrangement for regenerative braking is shown in the Fig.

The torque-slip characteristic for motoring and generating action is shown in the Fig.



Advantage

- The generated power can be used for useful purposes.

Disadvantage

- For fixed frequency supply it can be used only for speeds above synchronous speed.

QUESTION BANK

PART A

1. What is the effect of change in input voltage on starting torque of induction motor? (April 2017) (April 2016) (Nov 2015)
2. State any two advantages of speed control of induction motor by injecting an emf in the rotor circuit. (April 2017)
3. What is the effect of increasing the rotor resistance on starting current and torque? (Nov 2016)
4. List out the methods of speed control of cage type 3 Φ induction motor. (Nov 2016)
5. What are the different methods of speed control of three phase induction motor? (Nov 2015)
6. Why starter is necessary for the induction motor? (May / June 2012)
7. Mention the various methods of starting of a 3-phase induction motor (May / June 2009)
8. State the effect of rotor resistance on starting torque. (Nov / Dec 2011)
9. State the drawback of star-delta starter. (May / June 2011)
10. What are the advantages of rotor resistance speed control method? (May / June 2011)
11. What are the disadvantages of rotor rheostat speed control method? (may 2010)
12. What is the function of rotary converter? Where it is used?
13. What are the advantages of Kramer system of speed control?
14. Write the expression for concatenated speed of the set.
15. What are the methods of speed control preferred for large motors?

16. How is speed control achieved by changing the number of stator poles?
17. How can varying supply frequency control speed?
18. What is plugging? (May 2014)
19. What is dynamic braking?
20. What is DC dynamic braking?
21. What is regenerative braking?
22. What is slip power recovery scheme? (Dec 2013)
23. Point out the disadvantages of rotor rheostat control to obtain variable speed of induction motor. (Dec-2006)
24. Give the functions performed by induction motor starter. (May 2006)
25. A 3 phase squirrel cage induction motor should not be started directly from the main supply. State reasons. (May 2008)
26. Why is pole changing method of speed control not used with wound rotor motors? (may 2009)
27. Give the advantages of Rotor resistance starter. (Nov 2011)
28. What type of protection is provided in the starter meant for 3 phase induction motors? (Nov 2014)
29. While controlling the speed of an induction motor, how is super synchronous speed achieved? (Nov 2011)
30. Which is the cheapest method of starting a 3 phase induction motor?

PART B

1. Explain the speed control of a 3 phase induction motor with slip power recovery scheme. (16) **(April 2017)**
2. (i) State the different methods of starting of 3 phase induction motor and discuss in detail any two methods. (8)
   (ii) With aid of diagrams explain the principle of the following methods of speed control of a 3 phase induction motor.
   (1) variable Frequency (2) cascade connection (8) (Nov 2016)
3. (i) Describe a starter suitable for a 3 phase slip ring induction motor. (6)
   (ii) Determine approximately the starting torque of an induction, motor in terms of full load torque when. started by
   (1) Star—delta starter and
   (2) Auto—starter with 50% tapping. The short circuit current of the motor at normal voltage is 5 times the full load current and the full load slip is 4%. (10)(Nov 2016)
4. (i) Explain in detail the speed control methods of induction motor. (8)
   (ii) Explain in detail the scherbius system of speed control. (8) (April 2016)
5. (i) Describe a starter available for a 3-phase slip ring induction motor. (8)
   (ii) A small squirrel-cage induction motor has a starting current of six times the full load current and a full-load slip of 0.05. Find in pu of full-load values, the current (line) and starting torque with the following methods of starting ((a) to (d)).
   (a) Direct switching, (b) Stator-resistance starting with motor current limited to 2 p.u, (c) auto-transformer starting with motor current limited to 2 p.u, and (d) Y-delta starting. (e) What auto transformer ratio would give 1 p.u starting torque? (8) (April 2016)
6. Explain the various method of starting of three phase squirrel cage type Induction motor. (16) (Nov 2015)
7. Explain the different methods by which speed control of induction motor is achieved (16) (Nov 2015)
8. Why starters are necessary for starting 3-phase induction motors? What are the various types of starters? Explain any two in detail.
9. Explain the speed control of 3-phase induction motor by slip power recovery scheme with neat sketches.
10. Explain plugging and regenerative braking in 3-phase induction motor.
11. Explain the speed control techniques of induction motor by varying the supply frequency and state the advantages of this method. (May/ June 2011)
12. Explain the various schemes of starting squirrel cage induction motor. (16) (Dec 2006)
13. (i) The rotor of a 4 pole, 50 Hz slip ring induction motor has a resistance of 0.3 Ω per phase and runs at 1440 rpm at full load. Calculate the external resistance per phase which must be added to lower the speed to 1320 rpm, the torque being the same. (6)

(ii) Explain the cascade operation of induction motors to obtain variable speed. (10) (Dec 2006)

14. (i) Is a 3 phase induction motor self starting? How are they started? Discuss the theory of star-delta starter. (8)
    (ii) Explain the speed control of 3 phase squirrel cage induction motor by pole changing. (8) (May 2006)
15. Explain with neat diagram the static Scherbius drive system of slip power recovery scheme. (16) (Dec 2007)
16. (i) With the aid of diagrams, explain the principle of the following methods of speed control of a 3 phase induction motor (a) variable frequency (b) pole changing (10)
    (ii) Describe in detail the different types of electric braking used for 3 phase induction motors. (6) (may 2009)
17. Explain with neat sketches, the working of cascaded connection method and slip power recovery scheme of speed control of induction motor. (16) (May 2009)
18. A 15 HP, three phase, 6 pole, 50 Hz, 400V, delta connected IM runs at 960 rpm on full load. If it takes 86.4 A on direct starting, find the ratio of starting torque to full load torque with a star-delta starter. Full load efficiency and power factor are 88% and 0.85 respectively. (6) (May 2011)
19. A 3 phase 440V distribution circuit is designed to supply not more than 1200 A. Assuming that a 3 phase squirrel cage induction motor has full load efficiency of 0.85 and a full load power factor of 0.8 and that the starting current at rated voltage is 5 times the rated full load current, what is the maximum permissible kW rating of the motor if it is to be started using an auto transformer stepping down the voltage to 80%? (4) (Nov 2014)
20. A 3 phase induction motor takes a starting current which is 5 times full load current at normal voltage. Its full load slip is 4 %. What auto transformer ratio would enable the motor to be started with not more than twice the full load current drawn from the supply? What would be the starting torque under this condition? (8) (May 2014)