SPEED CONTROL OF THREE PHASE INDUCTION MOTOR

A three phase induction motor is practically a constant speed motor like a DC shunt motor. But the speed of DC shunt motor can be varied smoothly just by using simple rheostats. This maintains the speed regulation and efficiency of DC shunt motor. But in case of three phase induction motors it is very difficult to achieve smooth speed control. And if the speed control is achieved by some means, the performance of the induction motor in terms of its power factor, efficiency etc. gets adversely affected.

$$T \propto \frac{sE_2^2 R_2}{R_2^2 + (s X_2)^2}$$

For the induction motor we know that,

From this expression it can be seen that the speed of induction motor can be changed either by changing its synchronous speed or by changing the slip s.

Similarly torque produced in case of three phase induction motor is given by,

$$N = N_s (1 - s)$$

So as the parameters like R_2, E_2 are changed then to keep the torque constant for constant load condition, motor reacts by change in its slip. Effectively its speed changes.

Thus speed of the induction motor can be controlled by basically two methods :

1. From stator side and
2. From rotor side

From stator side, it includes following methods :

a. Supply frequency control to control N_s, called V / f control.

b. Supply voltage control.

c. Controlling number of stator poles to control N_s.

d. Adding rheostats in stator circuit.

From rotor side, it includes following methods :

a. Adding external resistance in the rotor circuit.

b. Cascade control.

c. Injecting slip frequency voltage into the rotor circuit.

Supply Frequency Control or V / f Control

The synchronous speed is given by,

$N_s = 120f / P$

Thus by controlling the supply frequency smoothly, the synchronous speed can be controlled over a wide range. This gives smooth speed control of an induction motor.

But the expression for the air gap flux is given by,

$$\phi_g = \frac{1}{4.44 K_1 T_{ph1}} \left(\frac{V}{f}\right)$$

This is according to the e.m.f. equation of a transformer where,

K_1 = Stator winding constant

T_{ph1} = Stator turns per phase

V = Supply voltage

f = Supply frequency

It can be seen from this expression that if the supply frequency f is changed, the value of air gap flux also gets affected. This may result into saturation of stator and rotor cores. Such a saturation leads to the sharp increase in the (magnetisation) no load current of the motor. Hence it is necessary to maintain air gap flux constant when supply frequency f is changed.

To achieve this, it can be seen from the above expression that along with f, V also must be changed so as to keep (V/f) ratio constant. This ensures constant air gap flux giving speed control without affecting the performance of the motor. Hence this method is called V / f control.

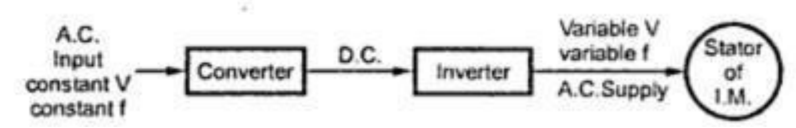


Fig. 4.4.1 Electronic scheme for V/f control

Hence in this method, the supply to the induction motor required is variable voltage variable frequency supply and can be achieved by an electronic scheme using converter and inverter circuitry. The scheme is shown in the Fig. 4.4.1

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.

If f is the normal working frequency then the Fig. 2 shows the torque-slip characteristics for the frequency $f_1 > f$ and $f_2 < f$ i.e. for frequencies above and below the normal frequency.

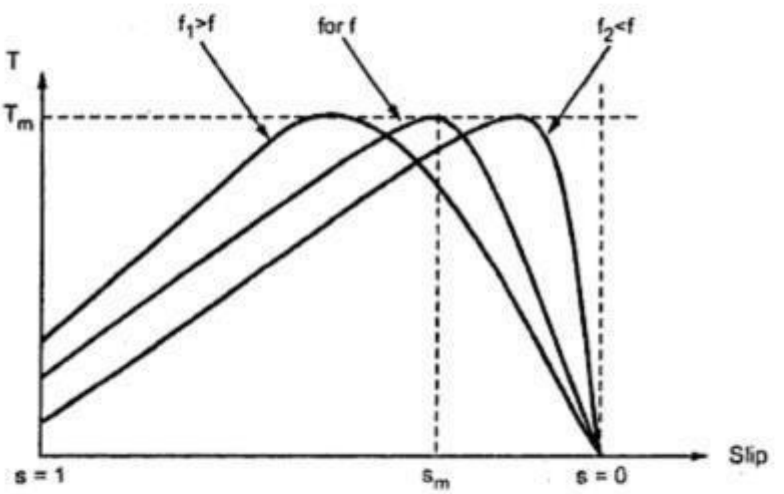


Fig. 4.4.2 Torque-slip characteristics with variable f and constant (V/f)

Another disadvantages of this method is that the supply obtained can not be used to supply other devices which require constant voltage. Hence an individual scheme for a separate motor is required which makes it costly.

SUPPLY VOLTAGE CONTROL

We know that, $T \alpha (k s E_2^2 R_2)/(R_2^2 + (s X_2)^2)$

Now E_2, the rotor induced e.m.f. at standstill depends on the supply voltage V.

$\therefore \quad E_2 \alpha V$

Also for low slip region, which is operating region of the induction motor, $(s X_2)^2 << R_2$ and hence can be neglected.

$\therefore \quad T \alpha (s E_2^2 R_2)/R_2^2) \alpha sV^2$ for constant R_2

Now 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 develope 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. The speed-torque characteristics for the motor using supply voltage control are shown in the Fig. 4.4.3

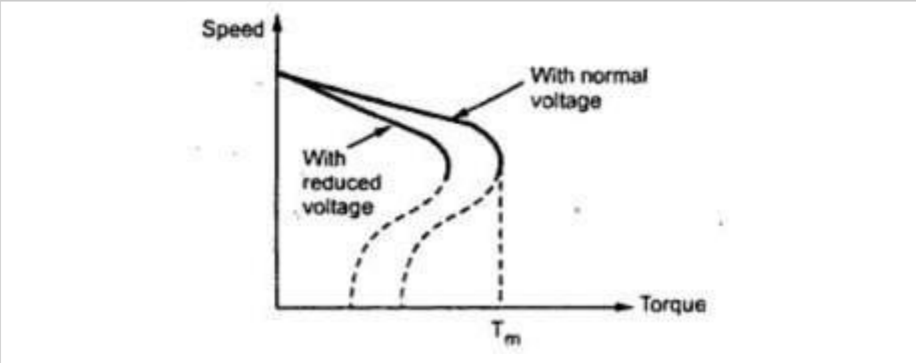


Fig.4.4.3 Speed-torque curves for motor with voltage control

But in this method, due to reduction in voltage, current drawn by the motor increases. Large change in voltage for small change in speed is required is the biggest disadvantage. Due to increased current, the motor may get overheated.

Additional voltage changing equipment is necessary. Hence this method is rarely used in practice. Motors driving fan type of loads use this method of speed control. Due to reduced voltage, E_2 decreases, decreasing the value of maximum torque too.

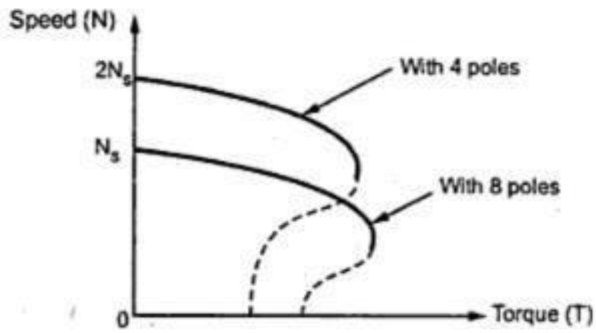
Controlling Number of Poles

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 the 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



$$f(\theta) = F \sin\left(\frac{P}{2}\theta\right)$$

$$f_m(\theta) = M \sin\left(\frac{P_M}{2}\theta\right)$$

In this method, connections of the stator winding are changes 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 speed can be selected.

Consider the pole formation due to single phase of a three phase winding, as shown in the Fig.4.11. There are three tapping points to the stator winding. The supply is given to two of them and third is kept open.

It can be seen that 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. 1. So synchronous speed possible with this arrangement with 50 Hz frequency is N_s = 750 r.p.m.

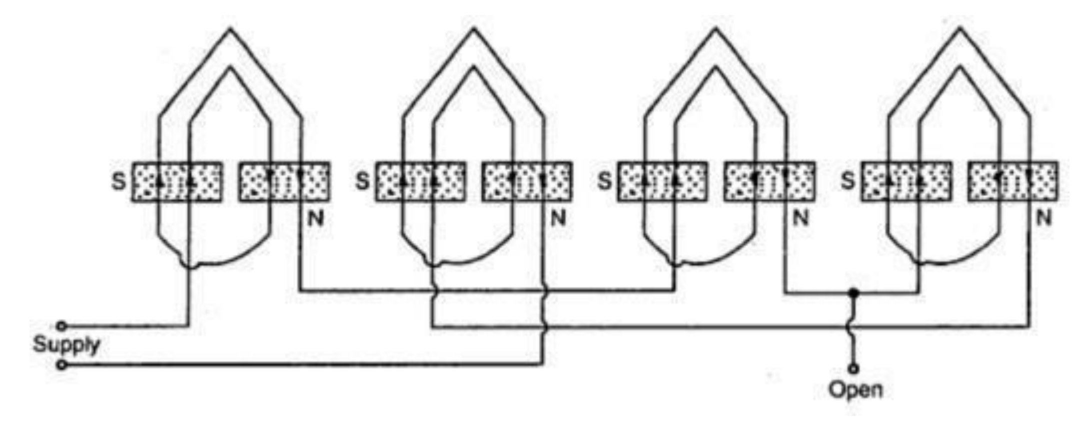


Fig.4.4.4 Pole winding

If now the two terminals to which supply was given either 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. 4.12.

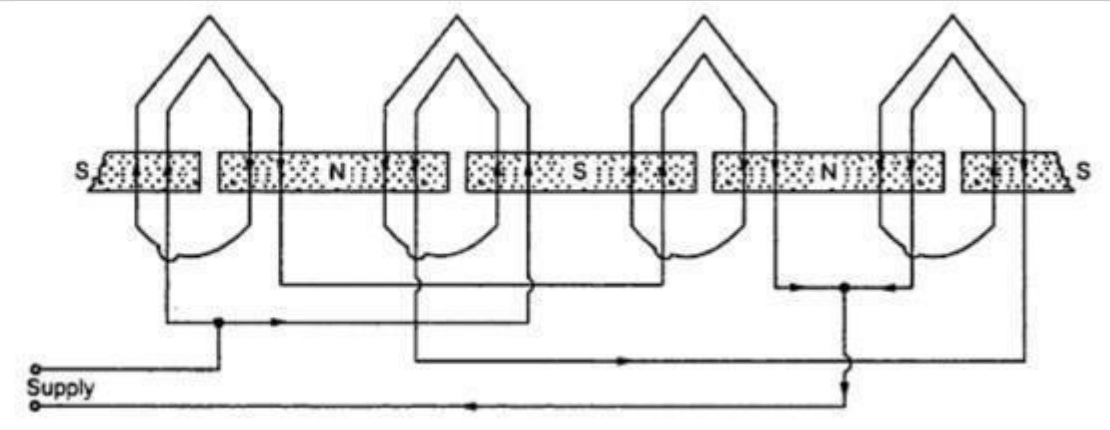


Fig 4.4.5 pole winding

It can be seen that the direction of current through remaining two. Thus upward direction is forming say S pole and downward say N. it can be observed that in this case only 4 poles are formed. So the synchronous speed possible is

1500 r.p.m. for 50 Hz frequency.

Thus series/parallel arrangements of coils can produce the poles in the ratio 2 : 1. But the speed change is in step and smooth speed control is not possible. Similarly the method can be used only for the squirrel cage type motors as squirrel rotor adjusts itself to same number of poles as stator which is not the case in slip ring induction motor.

Multiple Stator Winding Method

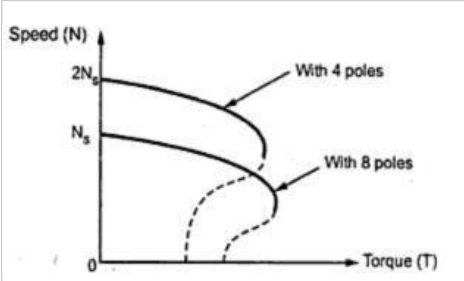
In this method instead of one winding, two separate stator winding are placed in the stator core. he windings are placed in the stator slots only but are electrically isolated from each other. Each winding is divided into coils to which, pole changing with consequent poles, facility is provided.

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.

The various limitations of this method are,

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.

Typical speed-torque characteristics of pole changing induction motor are shown in the Fig. 4.13.



F

POLE AMPLITUDE MODULATION METHOD

The basic disadvantage of other methods which is nonavailability of smooth speed control, is eliminated by this method. The ratio of two speeds in this method, need not be necessarily 2 : 1.

The basic principle of this method is the modulation of two sinusoidally varying m.m.f. waves, with different number of poles.

$$f(\theta) = F \sin\left(\frac{P}{2}\theta\right)$$

Consider sinusoidally distributed m.m.f. wave one phase of the stator as,

where P = Number of poles

and θ = Mechanical angle

This wave is modulated by another sinusoidal m.m.f. wave having P_M number of poles, expressed as,

$$f_m(\theta) = M \sin\left(\frac{P_M}{2}\theta\right)$$

$$f_R(\theta) = FM \sin\left(\frac{P}{2}\theta\right)\sin\left(\frac{P_M}{2}\theta\right)$$

$$= \frac{1}{2} FM \left[\cos\left(\frac{P-P_M}{2}\right)\theta - \cos\left(\frac{P+P_M}{2}\right)\theta\right]$$

The resultant m.m.f. wave after modulation is,

Thus the resultant wave is equivalent to two m.m.f. waves having two separate number of poles as,

$P_1 = P - P_M$ and $P_2 = P + P_M$

This is called suppressed carrier modulation.

If we succeed in suppressing one of the two poles then there exists rotating magnetic field with number of poles as P_1 or P_2. And while suppressing, the method can be used such that the resultant number of poles retained is as required from the speed point of view.

Now if the three stator windings are placed such that angle between their phase axes is $(2\pi/3)r$ radians where r is an integer which is not divisible by 3

$$\left(\frac{P \pm P_M}{P}\right)\left(\frac{2\pi}{3}\right)r = \left(1 \pm \frac{P_M}{P}\right)\left(\frac{2\pi}{3}\right)r$$

then the phase axes angle for modulated poles is given by,

Now to suppress one of the two poles, the angle between its phases axes must be multiple of 2π.

$$\left(1 \pm \frac{P_M}{P}\right)\left(\frac{2\pi}{3}\right)r = 2\pi n \qquad \text{where } n = \text{Integer}$$

$$\therefore \qquad 1 \pm \frac{P_M}{P} = \frac{3n}{r}$$

$$\therefore \qquad \frac{n}{r} = \frac{1}{3}\left[1 \pm \frac{P_M}{P}\right] \qquad \ldots (1)$$

So if r and n are selected so as to satisfy one of the above relations, then either P_1 or P_2 get suppressed and field corresponding to other pole exists.

So speeds corresponding to P poles without modulation and corresponding to either P_1 or $P_2$with modulation, can be achieved. The negative sign in equation (1), gives suppression of P_2 and existence of $P_2 = P + P_M$ while positive sign in equation (1), gives suppression P_2 of and existence of $P_1 = P - P_M$ poles.

For example, stator has 8 poles while values of n and r are selected as 1 and 4 respectively. r is not divisible by 3.

Adding Rheostats in Stator Circuit

We have seen that the reduced voltage can be applied to the stator by adding the rheostats in the stator circuit. The arrangement is shown in the Fig. 1. The part of the voltage gets dropped across the resistances and reduced voltage gets applied across the stator.

The reduction in stator voltage causes reduction in the speed. The rheostats can be varied as per the required change in speed. But the entire line current flows through the rheostats and hence there are large power losses. The method is not efficient from speed control point of view hence used as a starter rather than as a speed control method.

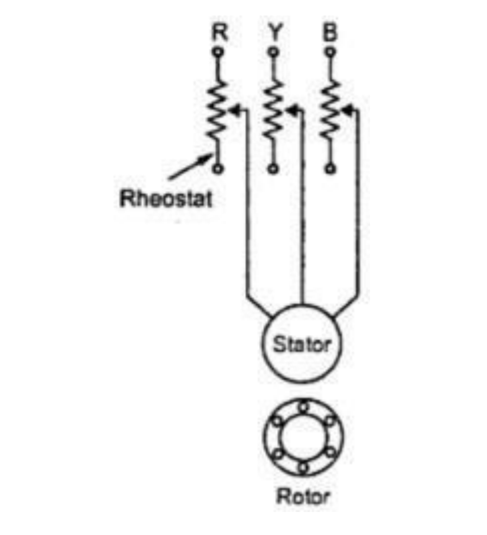


Fig. 4.4.5 Stator resistance control

Adding External Resistance in Rotor Circuit We know, $T \alpha (s E_2^2 R_2)/(R_2^2 + (s X_2)^2)$

For low slip region $(s X_2)^2 << R_2$ and can be neglected and for constant supply voltage is also constant.

$\therefore \quad T \alpha (s R_2)/R_2^2 \alpha s/R_2^2$

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 decreases in T due to R_2 and maintains the load torque constant. So due tot additional rotor resistance R_2, motor slip increases i.e. the speed of the motor decreases. Thus by increasing the rotor resistance R_2, speeds below normal value can be achieved. Another advantage of this method is that the starting torque of the motor increases proportional to rotor resistance.

The Fig. 4.14 shows the torque-speed curves for rotor resistance control.

But this method has following disadvantages :

1. 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 due to reduce the efficiency.
2. The method can not be used for the squirrel cage induction motors.
3. The speeds above the normal values can not be obtained.
4. Large power losses occur due to large loss.
5. Sufficient cooling arrangements are required which make the external rheostats bulky be expensive.
6. Due to large power losses, efficiency is low.

Thus the method is rarely used in the practice.

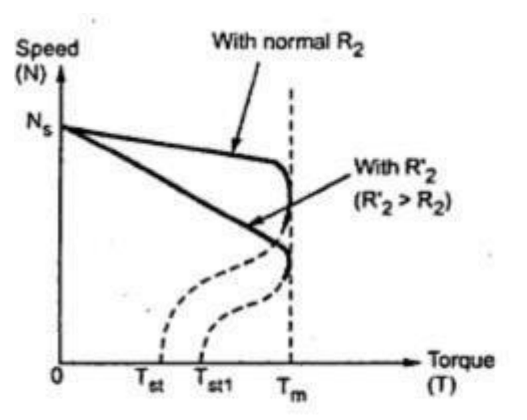


Fig. 4.15

CACADECONTROL

This method is also called concatenation or tandom operation of the induction motors.

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

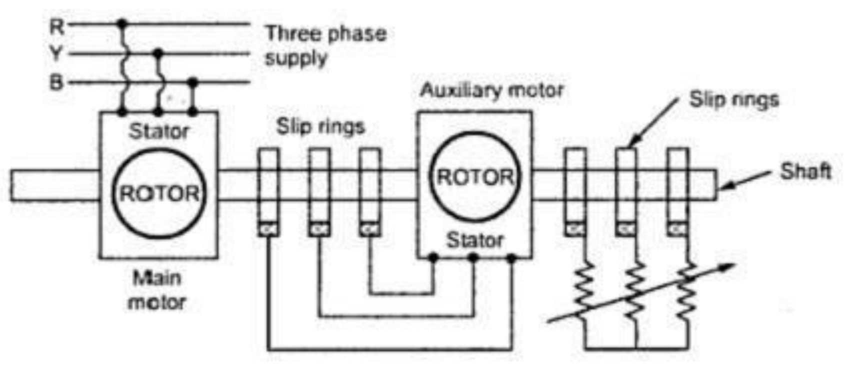


Fig. 4.4.6 Cascade control pf two induction motor

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 torque 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.

Now let, P_A = Number of poles of main motor

P_B = Number of poles of auxiliary motor

f = Supply frequency

$N_{SA} = 120f / P_A$

N = Speed of the set

The speed N is same for both the motors as motors are mounted on the same shaft.

$s_A = (N_{SA} - N)/N_{SA}$

Now f_A = Frequency of rotor induced e.m.f. of motor A

$f_A = s_A f$ ..... as $f_r = s f$

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

$$\therefore \quad N_{sB} = \frac{120 f_B}{P_B} = \frac{120 f_A}{P_B} = \frac{120 \, s_A \, f}{P_B} = \frac{120 (N_{sA} - N) f}{P_B \times N_{sA}}$$

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

$$\therefore \quad N_{sB} = N$$

$$\therefore \quad N = 120\left(\frac{N_{sA} - N}{N_{sA}}\right) \times \frac{f}{P_B}$$

$$\therefore \quad N = \frac{120\,f}{P_B} \times \left[1 - \frac{N}{N_{sA}}\right]$$

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

$$\therefore \quad N = \frac{120\,f}{P_B}\left[1 - \frac{NP_A}{120\,f}\right]$$

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

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

Key Point : Thus the speed N of the set is decided by the total number of poles equal to P_A- P_B. This is possible for cumulatively cascaded motors.

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,

$N_s = 120f/P_A$

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

$N_s = 120f/P_B$

c. Running set as cumulatively cascaded with,

$N = 120f / (P_A + P_B)$

d. Running set as differentially cascaded with,

$N = 120f / (P_A - P_B)$

This method is also rarely used due to following 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 can not be operated if $P_A = P_B$.

INJECTINGSLIP-FREQUENCYE.M.F INTO 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.

It is possible that 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

The Fig.1 shows the scheme of a 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 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 s field regulator.

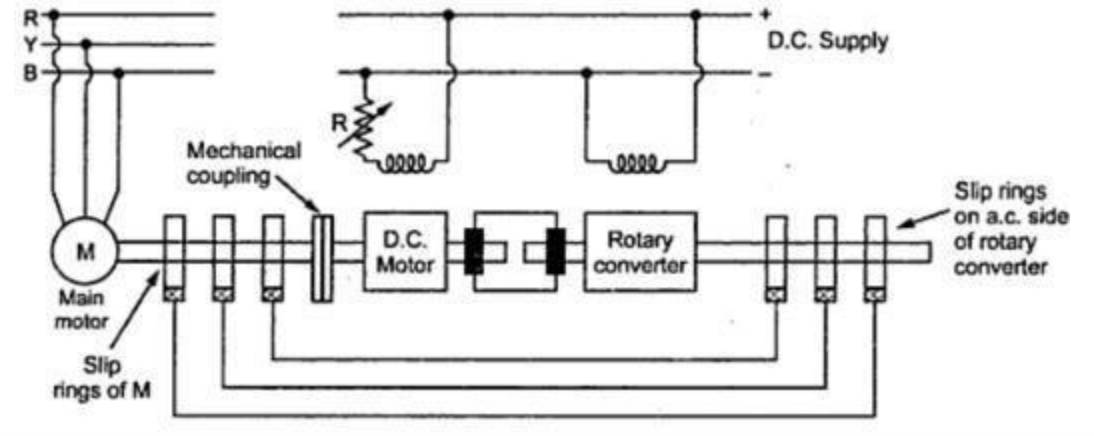


Fig.4.4.7 Kramer system

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.

Very large motors above 4000 kW such as steel rolling mills use such type of speed control. The main advantage of this method is that a smooth speed control is possible. Similarly wide range of speed control is possible. Another advantage of the system is that the design of a rotary converter is practically independent of the speed control required. Similarly if rotary converter is overexcited, it draws leading current and thus power factor improvement is also possible along with the necessary speed control.

Scherbius System

The Fig. 2 shows the scheme of a Scherbius system.

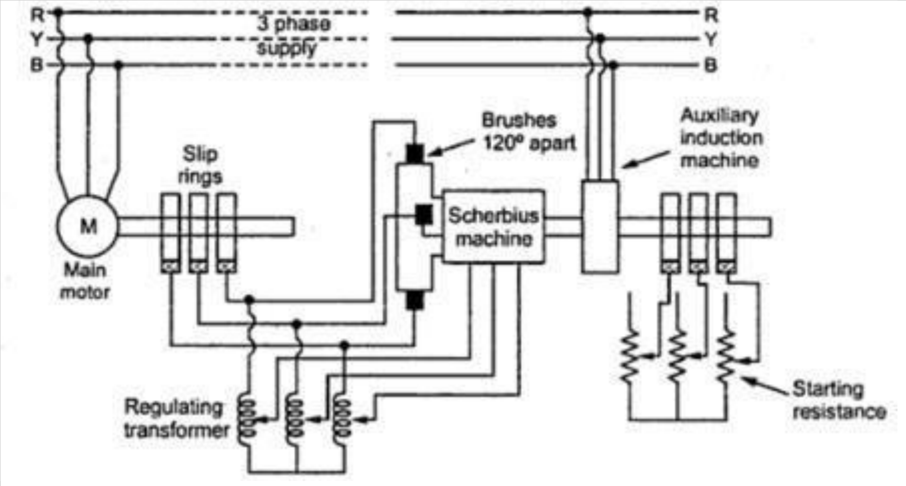


Fig. 4.4.8 Scherbius system

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 is excited at a slip frequency from the rotor of a main motor through a regulation transformer. The taps on the regulating transformer can be varied, this changes the voltage developed in the rotor Scherbius machine, which is injected into the rotor of main motor. This control 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 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.