Module-4
Starting and Speed Control of Three Phase Induction Motors

Necessity of Starter:

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,

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

But 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.

The condition is exactly similar to a transformer with short circuited secondary. Such a transformer when excited by a rated voltage, circulates very high current through short circuited secondary. As secondary current is large, the primary also draws very high current from the supply.

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Similarly in a three phase induction motor, when rotor current is high, consequently 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 current at start there is possibility of damage of the motor winding. Similarly such sudden inrush of current causes large line voltage drop. Thus 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 limit of starting. Such a reduced voltage is applied only for short period and once rotor gets accelerated, full normal rated voltage is applied.

Not only the starter limits the starting current but also provides the protection to the induction motor against overloading loading and low voltage situations. The protection against single phasing is also provided by the starter. The induction motor having rating below 5 h.p. can withstand starting currents hence such motors can be started directly on line. But such motors also need overload, single phasing and low voltage protection which is provided by a starter.

Thus all the three phase induction motors need some or the other type of starter.

Types of Starters:

From the expression of rotor current it can be seen that the current at start can be controlled by reducing E_2 which is possible by supplying reduced voltage at start or by increasing the rotor resistance R_2 at start. The second method is possible only on case of slip ring induction motors.

The various types of starters based on the above two methods of reducing the starting current are,

1. Stator resistance starter
2. Auto-transformer starter
3. Star-delta starter
4. Rotor resistance starter
5. Direct on line starter

Direct on Load Line Starter (D.O.L.):

In case of small capacity motors having rating less than 5 h.p., the starting current is not very high and such motors can withstand such starting current without any starter. Thus there is no need to reduce applied voltage, to control the starting current. Such motors use a type of starter which is used to connect stator directly to the supply lines without any reduction in voltage. Hence the starter is known as direct on line starter.

Though this starter does not reduce the applied voltage, it is used because it protects the motor from various severe abnormal conditions like over loading, low voltage, single phasing etc.

The Fig. 2 shows the arrangement of various components in direct on line starter.

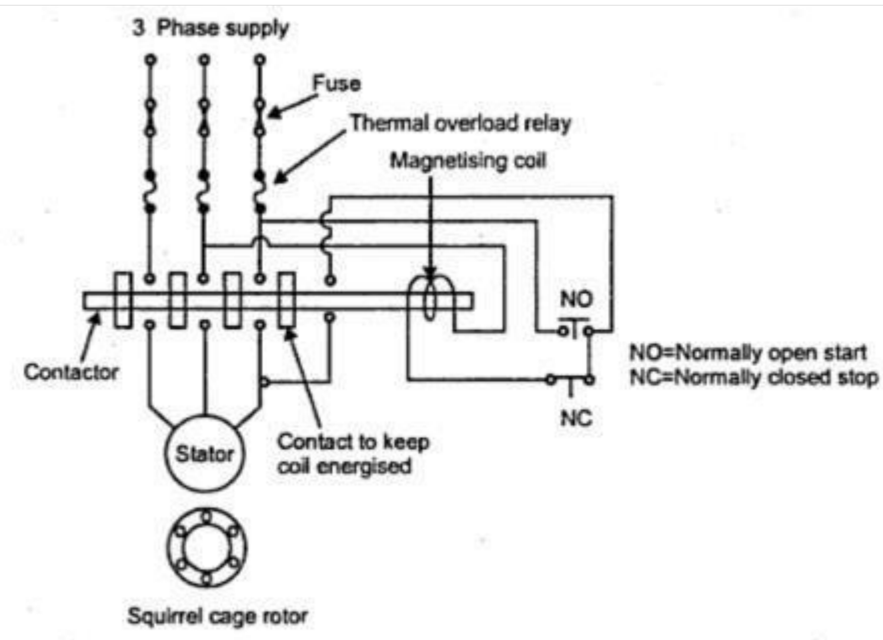


Fig.1 D.O.L. starter

The NO contact is normally open and NC is normally closed. At start, NO is pushed for fraction of second due to which coil gets energized and attracts the contactor. So stator directly gets supply. The additional contact provided, ensures that as long as supply is ON, the coil gets supply and keeps contactor in ON position. When NC is pressed, the coil circuit gets opened due to which coil gets de-energized and motor gets switched OFF from the supply.

Under over load condition, current drawn by the motor increases due to which is an excessive heat produced, which increases temperature beyond limit. Thermal relays get opened due to high temperature, protecting the motor from overload conditions.

Star - Delta Starter:

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 $1/\sqrt{3}$. 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. 1.

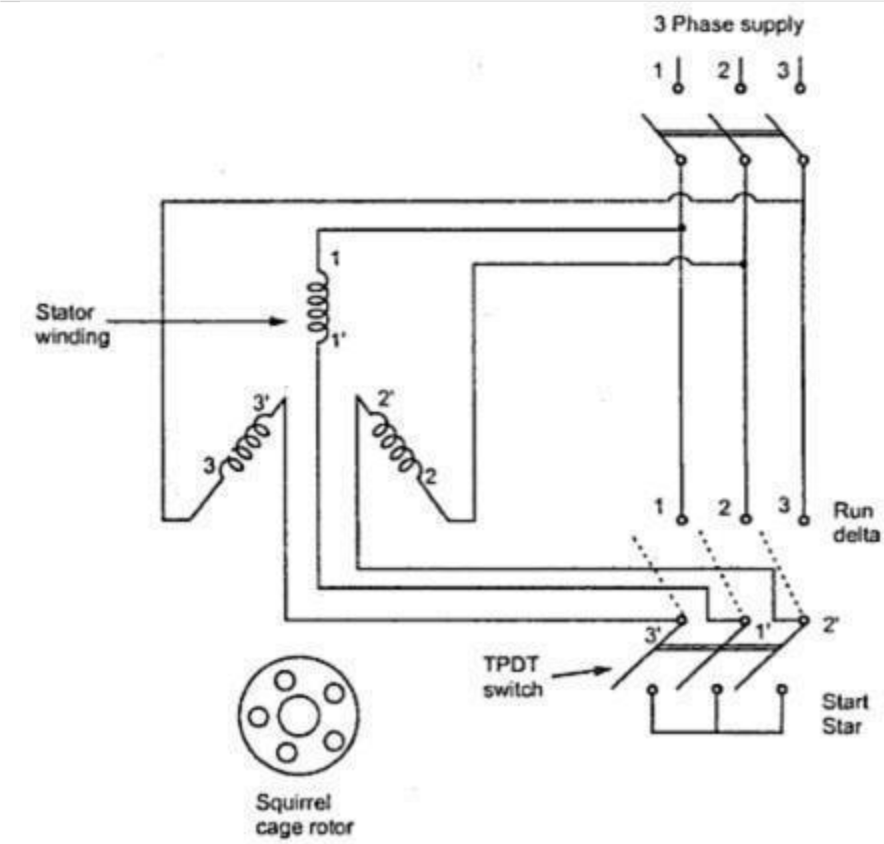


Fig. 1 Star-delta starter

The operation of the switch can be automatic by using relays which ensures that motor will not start with the switch in Run position. The cheapest of all and maintenance free operation are the two important advantages of this starter. While its limitations are, it is suitable for normal delta connected motors and the factor by which voltage changes is 1/√3 which can not be changed.

Ratio of T_{st} to $T_{F.L.}$

We have seen in case of autotransformer that if x is the factor by which the voltage is reduced then,

$$\therefore \quad \boxed{\frac{T_{st}}{T_{F.L.}} = x^2\left[\frac{I_{sc}}{I_{F.L.}}\right]^2 \times s_f}$$

Now the factor x in this type of starter is 1/√3.

$$\therefore \quad \boxed{\frac{T_{st}}{T_{F.L.}} = \frac{1}{3}\left(\frac{I_{sc}}{I_{F.L.}}\right)^2 s_f}$$

where I_{sc} = Starting phase current when delta connection with rated voltage

$I_{F.L.}$ = Full load phase current when delta connection

Example : A three phase induction motor has a ratio of maximum torque to full load torque as 2.5 : 1. Determine the ratio of starting torque to full load torque if star-delta starter is used. The rotor resistance and standstill reactance per phase are 0.4 and 4 respectively.

Solution : The given ratio is, $T_m/T_{F.L.} = 2.5$

The rotor values are, $R_2 = 0.4\Omega$ $X_2 = 4\Omega$

Now $T_m = (kE_2^2)/(2X_2)$

$\therefore$ $T_{F.L.} = T_m/2.5 = (kE_2^2)/(5X_2) = (kE_2^2)/20$ ....(1)

Now $T_{st} = (k E_2^2 R_2)/(R_2^2 + X_2^2)$

With star-delta starter $E_2 = E_2/\sqrt{3}$

$$\therefore \quad T_{st} = \frac{k\left(\frac{E_2}{\sqrt{3}}\right)^2 R_2}{R_2^2 + X_2^2} \quad \ldots (2)$$

Taking ratio of (2) and (1),

$$\frac{T_{st}}{T_{F.L.}} = \frac{k\left(\frac{E_2}{\sqrt{3}}\right)^2 R_2}{R_2^2 + X_2^2} \times \frac{20}{k E_2^2} = \frac{20 \times 0.4}{3[(0.4)^2 + (4)^2]} = \mathbf{0.165}$$

Auto-transformer Starter:

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 auto-transformer starter. The schematic diagram of auto-transformer starter is shown in the Fig..1.

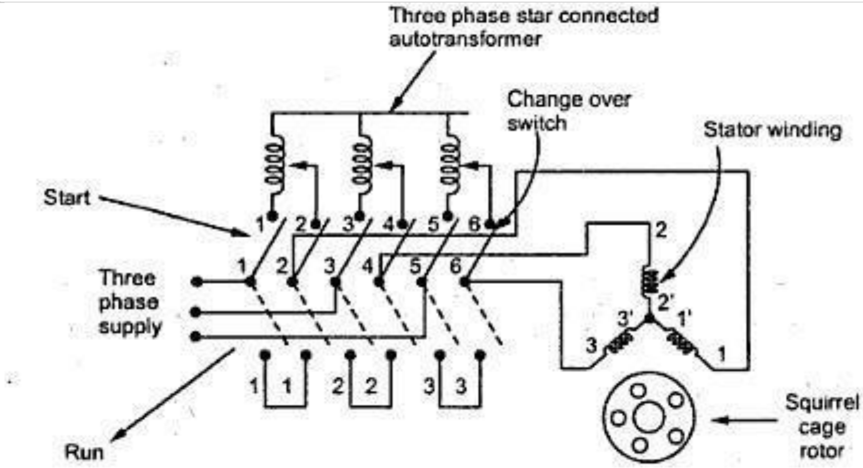


Fig. 1 Auto-transformer starter

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 the Fig. 2.

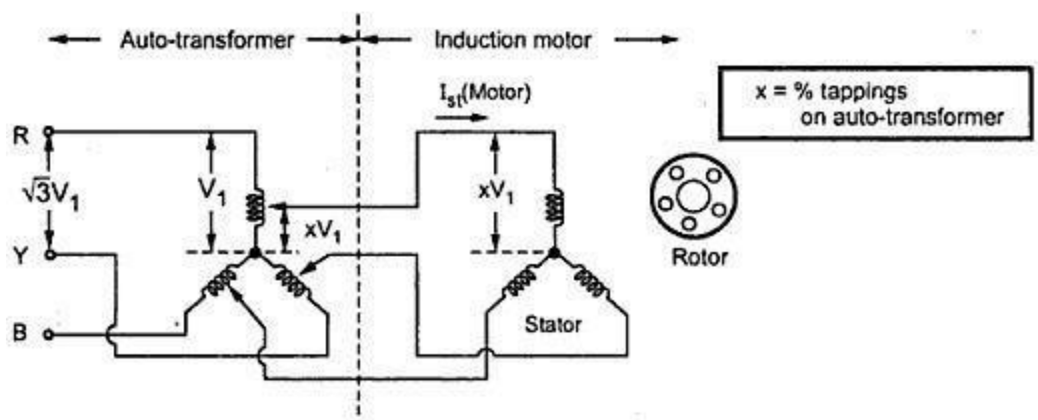


Fig.2 Use of auto-transformer to reduce voltage at start

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.

Relation between T_{st} and $T_{F.L.}$

Let x be the fractional percentage tappings used for an autotransformer to apply reduced voltage to the stator.

So if, I_{sc} = Starting motor current at rated voltage

and I_{st} = Starting motor current with starter

then $I_{st} = x\ I_{sc}$ .....Motor side ....(1)

But there is exists a fixed ratio between starting current drawn from supply I_{st}(supply) and starting moor current I_{st} (motor) due to autotransformer, as shown in the Fig.3.

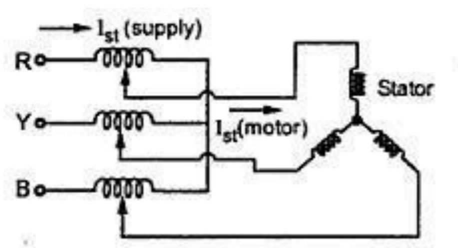


Fig. 3

Autotransformer ratio $x = I_{st}\text{(supply)} / I_{st}\text{(motor)}$

$I_{st}\text{(supply)} = x\ I_{st}\text{(motor)}$ .... (2)

Substituting I_{st} (motor) from equation (1),

$\therefore\ I_{st}\text{(supply)} = x\ .\ x\ I_{sc} = x^2\ I_{sc}$ ....(3)

Now $T_{st}\ \alpha\ I_{st}^2\text{(motor)}\ \alpha\ x^2\ I_{sc}^2$

and $T_{F.L.}\ \alpha\ (I_{F.L.})^2/s_f$

$$\therefore \quad \frac{T_{st}}{T_{F.L.}} = x^2 \left[\frac{I_{sc}}{I_{F.L.}}\right]^2 \times s_f$$

Note : Thus starting torque reduces by x^2 where x is the transformer ratio.

Example : A squirrel cage induction motor has a full load slip of 5%. The motor starting current at rated voltage is 6 times its full load current. Find the tapping on the autotransformer starter which would give full load torque at start. Whet would then be the supply starting current ?

Solution : Starting current at rated voltage = I_{sc}

$\therefore$ $I_{sc} = 6\ I_{F.L.}$ and $s_f = 5\% = 0.05$

Let x = Tapping on autotransformer

$T_{F.L.} = T_{st}$

$$\therefore \quad \frac{T_{st}}{T_{F.L.}} = x^2 \left[\frac{I_{sc}}{I_{F.L.}}\right]^2 \times s_f$$

$$1 = x^2 (6/1)^2 \times 0.05$$
$$x = 0.7453$$

Thus 74.53% tapping is required

Now I_{st} (supply) = x I_{st} (motor) = x (xI_{sc}) = $x^2 I_{sc}$

$= x^2 \times 6 = 3.33\ I_{F.L.}$

Thus supply starting current is 3.33 times the full load current.

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 in the form of 3 phase star connected rheostat. The arrangement is shown in the Fig. 1.

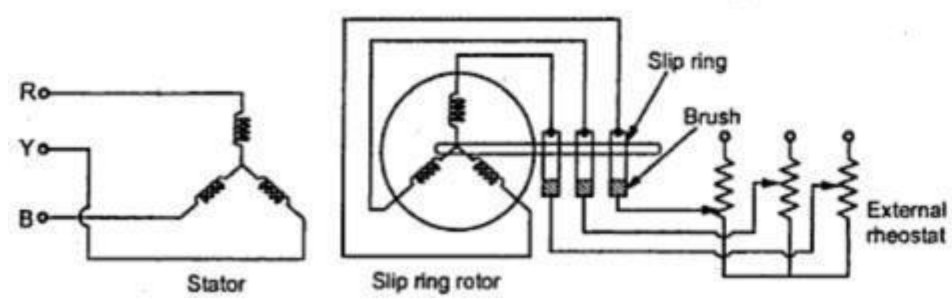


Fig. 1 Rotor resistance starter

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 gather speed, the resistance is gradually cut-off. The operation may be manual or automatic.

We have seen that the starting torque is proportional to the rotor resistance. Hence important advantage of this method is not only the starting current is limited but starting torque of the motor also gets improved.

Note : The only limitation of the starter that it can be used only for slip ring induction motors as in squirrel cage motors, the rotor is permanently short circuited.

Calculation of Steps of Rotor Resistance Starter:

The calculation of steps of rotor resistance starter is based on the assumptions that,

1. The motor starts against a constant torque
2. The rotor current fluctuates between two fixed values, a maximum and a minimum, denoted as I_{2max} and I_{2min}.

The Fig. 2, shows a single phase of a three phase of a three phase rheostat to be inserted in the rotor. The starter has n steps, equally divided into the section AB. The contact point after each step is called stud. The total resistances upto each stud from the star point of star connected rotor as denoted as R_1, R_2, R_{n-1}.

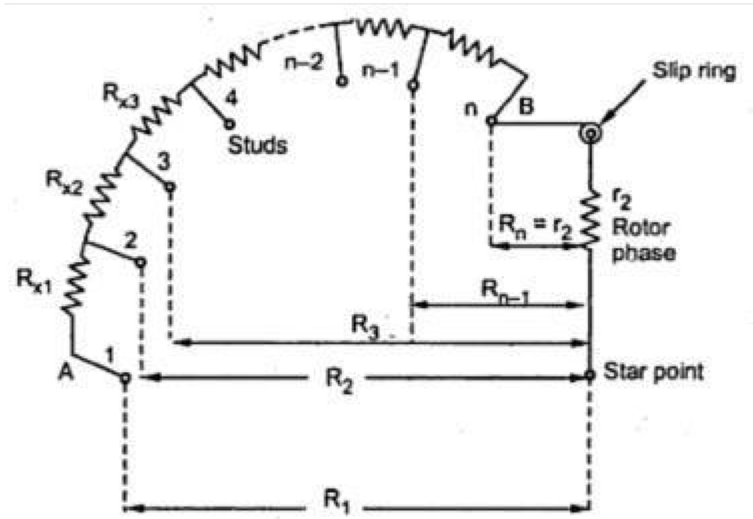
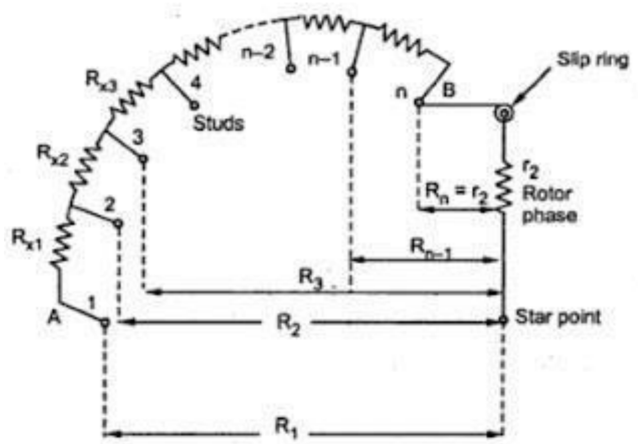


Fig. 2 Steps of rotor resistance starter

It consists of rotor resistance r_2 and the external resistances R_{x1}, R_{x2}...etc. At the time of reaching to the next step, current is maximum . Then motor gathers speed, slip reduces and hence while leaving a stud, the current is I_{2min}.



Let E_2 = Standstill rotor e.m.f. per phase

When handle is moved to stud 1, the current is maximum given by,

$$I_{2max} = \frac{s_1 E_2}{\sqrt{R_1^2 + (s_1 X_2)^2}} = \frac{E_2}{\sqrt{\left(\frac{R_1}{s_1}\right)^2 + X_2^2}}$$

where s_1 = Slip at start = 1

while moving to stud 2, the current reduces to I_{2min} given by,

$$I_{2min} = \frac{E_2}{\sqrt{\left(\frac{R_1}{s_2}\right)^2 + X_2^2}} \qquad \text{where } s_2 < s_1$$

Just reaching to stud 2, the current again increases to I_{2min} as the part of external resistance R_{x1} gets cut-off.

$$\therefore \qquad I_{2max} = \frac{E_2}{\sqrt{\left(\frac{R_2}{s_2}\right)^2 + X_2^2}}$$

While leaving stud 2, the slip changes to s_3 and current again reduces to,

$$I_{2min} = \frac{E_2}{\sqrt{\left(\frac{R_2}{s_3}\right)^2 + X_2^2}}$$

While just reaching to stud 3, R_{x2} gets cut off completely and current again increases to,

$$I_{2max} = \frac{E_2}{\sqrt{\left(\frac{R_3}{s_3}\right)^2 + X_2^2}}$$

Hence at the last n^{th} stud, the maximum current is,

$$I_{2max} = \frac{E_2}{\sqrt{\left(\frac{r_2}{s_n}\right)^2 + X_2^2}}$$

where s_n = Slip under normal running condition
At n^{th} stud no external resistance is in series with rotor.

$$\therefore \qquad I_{2max} = \frac{E_2}{\sqrt{\left(\frac{R_1}{s_1}\right)^2 + X_2^2}} = \frac{E_2}{\sqrt{\left(\frac{R_2}{s_2}\right)^2 + X_2^2}} = \dots \frac{E_2}{\sqrt{\left(\frac{r_2}{s_n}\right)^2 + X_2^2}}$$

i.e. $$\frac{R_1}{s_1} = \frac{R_2}{s_2} = \dots \frac{r_2}{s_n} \qquad \dots (1)$$

And $$I_{2min} = \frac{E_2}{\sqrt{\left(\frac{R_1}{s_2}\right)^2 + X_2^2}} = \frac{E_2}{\sqrt{\left(\frac{R_2}{s_3}\right)^2 + X_2^2}} = \dots \frac{E_2}{\sqrt{\left(\frac{R_{n-1}}{s_n}\right)^2 + X_2^2}}$$

i.e. $$\boxed{\frac{R_1}{s_2} = \frac{R_2}{s_3} = \dots \frac{R_{n-1}}{s_n}} \qquad \dots (2)$$

From (1) and (2) we can write,

$$\frac{s_2}{s_1} = \frac{s_3}{s_2} = \frac{s_4}{s_3} \dots = \frac{R_2}{R_1} = \frac{R_3}{R_2} = \frac{R_4}{R_3} = \dots = \frac{r_2}{R_{n-1}} = K \qquad \dots (3)$$

where K = Constant
From (1), $R_1 = s_1 r_2 / s_n$ but $s_1 = 1$ at start

$$\therefore \quad R_1 = \frac{r_2}{s_n} \qquad \dots (4)$$

Once R_1 is known, other resistances can be calculated.

$R_2 = KR_1$, $\quad R_3 = K\,R_2 = KKR_1 = K^2\,R_1$

$R_4 = K^3\,R_1$, ...$r_2 = K^{n-1}\,R_1$

From last expression of r_2,

$$\boxed{K = \left(\frac{r_2}{R_1}\right)^{\frac{1}{n-1}} = (s_n)^{1/n-1}}$$

where n = Number of starter studs

Thus the resistances of various sections can be obtained as,

$$\boxed{\begin{aligned} R_{x1} &= R_1 - R_2 = R_1 - KR_1 = (1-K)\,R_1 \\ R_{x2} &= R_2 - R_3 = KR_1 - K^2R_1 = K(1-K)\,R_1 = K\,R_{x1} \\ R_{x3} &= K^2\,R_{x1} \dots \dots \end{aligned}}$$

In this way the various steps of rotor resistance starter can be calculated.

Speed Control of Three Phase Induction Motor:

A three phase induction motor is practically a constant speed motor like a d.c. shunt motor. But the speed of d.c. shunt motor can be varied smoothly just by using simple rheostats. This maintains the speed regulation and efficiency of d.c. 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.

For the induction motor we know that,

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

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 Voltage Control:s

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 develop the 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. 1.

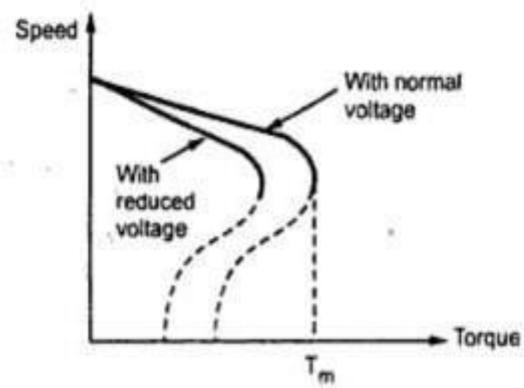


Fig.1 Speed-torque curves for motor with voltage control

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.

Supply Frequency Control or V / f Control:

The synchronous speed is given by,

$N_s = 120f / Ps$

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 (magnetization) 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.

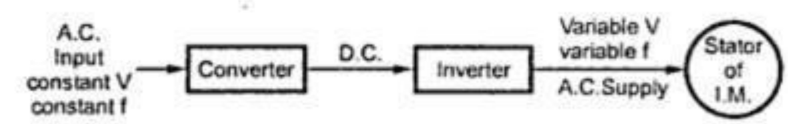


Fig. 1 Electronic scheme for V/f control

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. 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.

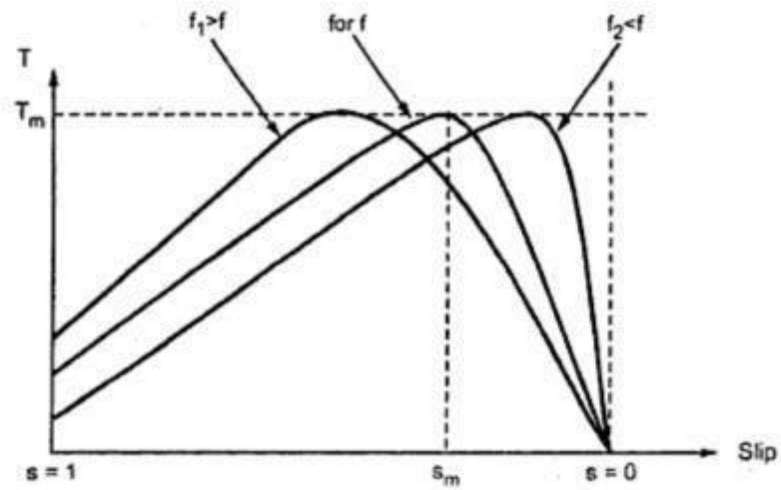


Fig. 2 Torque-slip characteristics with variable f and constant (V/f)

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

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.

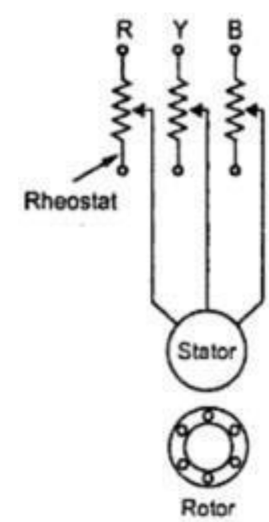


Fig. 1 Stator resistance control

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.

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

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 to the 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. 1 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 cannot be used for the squirrel cage induction motors.
3. The speeds above the normal values cannot 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.

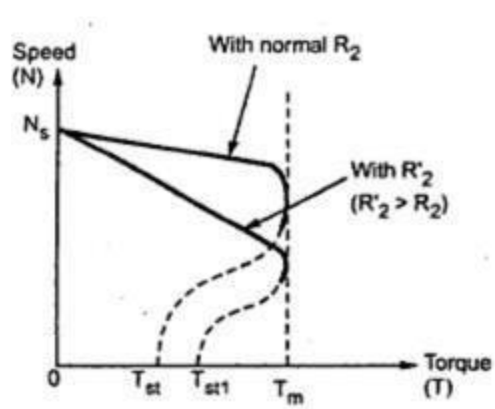


Fig. 1

Single Phase Induction Motors

Introduction:

For general lighting purpose in shops, offices, houses, schools etc. Single phase a.c. supply is commonly used. Hence instead of d.c. motors, the motors which work on single phase a.c. supply are very popularly in use. These a.c. motors are called single phase induction motors. The numerous domestic applications use single phase motors. The power rating of such motors is very small. Some of them are even fractional horse power motors, which are used in applications like small toys, small fans, hair dryers etc. This chapter explains the construction, working principle and applications of various types of single phase induction motors.

Construction of Single Phase Induction Motors

Similar to a d.c. motor, single phase induction motor has basically two main parts. one rotating and other stationary. The stationary part in single phase induction motors is called stator while the rotating part is called rotor.

The stator has laminated construction, made up of stampings. The stampings are slotted on its periphery to carry the winding called stator winding or main winding. This is excited by a single phase a.c. supply. The laminated construction keeps iron losses to minimum. The stampings are made up of material like silicon steel which minimizes the hysteresis loss. The stator winding is wound for certain definite number of poles means when excited by single phase a.c. supply, stator produces the magnetic field which creates the effect of certain definite number of poles. The number of poles for which stator winding is wound, decides the synchronous speed of the motor. The synchronous speed is denoted as N_s and it has a fixed relation with supply frequency f and number of poles P. The relation is given by,

$$\boxed{N_s = \frac{120\,f}{P} \quad \text{r.p.m}}$$

The induction motor never rotates with the synchronous speed but rotates at a speed which is slightly less than the synchronous speed.

The rotor construction is of squirrel cage type. In this type, rotor consists of uninsulated copper or aluminium bars, placed in the slots. The bars are permanently shorted at both the ends with the help of conducting rings called end rings. The entire structure looks like cage hence called squirrel cage rotor. The construction and symbol is shown in the Fig.1

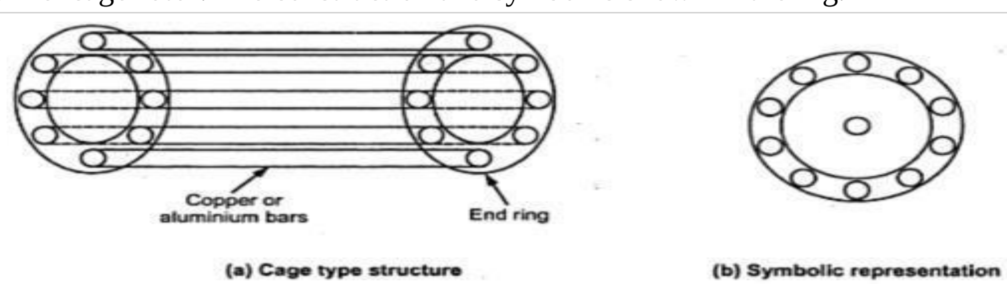


Fig. 1

As the bars are permanently shorted to each other, the resistance of the entire rotor is very very small. The air gap between stator and rotor is kept uniform and as small as possible. The main feature of this rotor is that it automatically adjusts itself for same number of poles as that of the stator winding.

The schematic representation of two pole single phase induction motor is shown in the Fig.2.

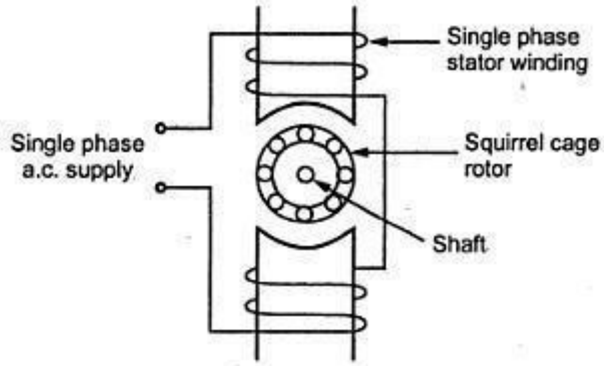


Fig. .2

Working Principle of 1-phase Induction Motor:

For the motoring action, there must exist two fluxes which interact with each other to produce the torque. In d.c. motors, field winding produces the main flux while d.c. supply given to armature is responsible to produce armature flux. The main flux and armature flux interact to produce the torque.

In the single phase induction motor, single phase a.c. supply is given to the stator winding. The stator winding carries an alternating current which produces the flux which is also alternating in nature. This flux is called main flux. This flux links with the rotor conductors and due to transformer action e.m.f. gets induced in the rotor. The induced e.m.f. drives current through the rotor as rotor circuit is closed circuit. This rotor current produces another flux called rotor flux required for the motoring action. Thus second flux is produced according to induction principle due to induced e.m.f. hence the motor is called induction motor. As against this in d.c. motor a separate supply is required to armature to produce armature flux. This is an important difference between d.c. motor and an induction motor.

Another important difference between the two is that the d.c. motors are self starting while single phase induction motors are not self starting.

Let us see why single phase induction motors are not self starting with the help of a theory called double revolving field theory.

Double Revolving Field Theory:

According to this theory, any alternating quantity can be resolved into two rotating components which rotate in opposite directions and each having magnitude as half of the maximum magnitude of the alternating quantity.

In case of single phase induction motors, the stator winding produces an alternating magnetic field having maximum magnitude of Φ_{1m}.

According to double revolving field theory, consider the two components of the stator flux, each having magnitude half of maximum magnitude of stator flux i.e. ($\Phi_{1m}/2$). Both these components are rotating in opposite directions at the synchronous speed N_s which is dependent on frequency and stator poles.

Let Φ_f is forward component rotating in anticlockwise direction while Φ_b is the backward component rotating in clockwise direction. The resultant of these two components at any instant gives the instantaneous value of the stator flux at the instant. So resultant of these two is the original stator flux.

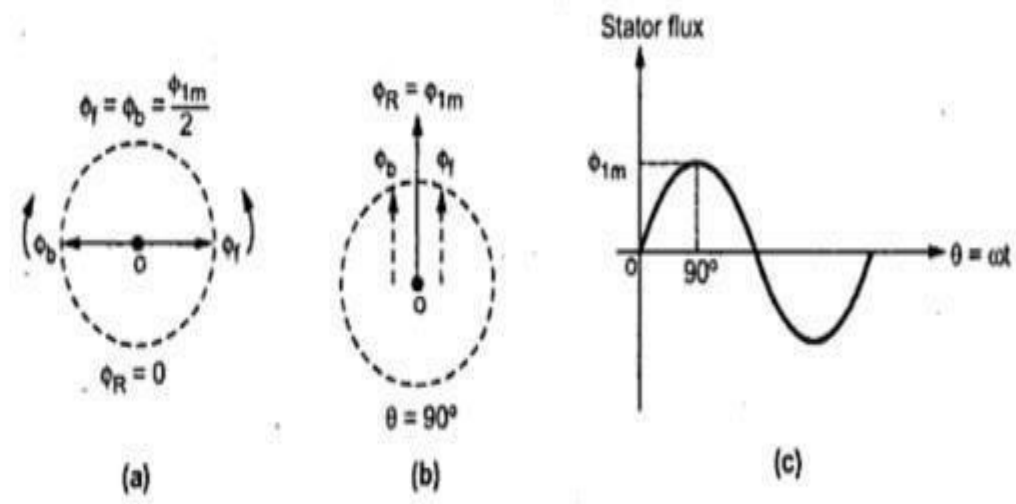


Fig. 1 Stator flux and its two components

The Fig. 1 shows the stator flux and its two components Φ_f and Φ_b. At start both the components are shown opposite to each other in the Fig.1(a). Thus the resultant $\Phi_R = 0$. This is nothing but the instantaneous value of the stator flux at start. After 90°, as shown in the Fig. 1(b), the two components are rotated in such a way that both are pointing in the same direction. Hence the resultant Φ_R is the algebraic sum of the magnitudes of the two components. So $\Phi_R = (\Phi_{1m}/2) + (\Phi_{1m}/2) = \Phi_{1m}$. This is nothing but the instantaneous value of the stator flux at $\theta = 90°$ as shown in the Fig 1(c). Thus continuous rotation of the two components gives the original alternating stator flux.

Both the components are rotating and hence get cut by the motor conductors. Due to cutting of flux, e.m.f. gets induced in rotor which circulates rotor current. The rotor current produces rotor flux. This flux interacts with forward component Φ_f to produce a torque in one particular direction say anticlockwise direction. While rotor flux interacts with backward component Φ_b to produce a torque in the clockwise direction. So if anticlockwise torque is positive then clockwise torque is negative.

At start these two torque are equal in magnitude but opposite in direction. Each torque tries to rotate the rotor in its own direction. Thus net torque experienced by the rotor is zero at start. And hence the single phase induction motors are not self starting.

Torque speed characteristics

The two oppositely directed torques and the resultant torque can be shown effectively with the help of torque-speed characteristics. It is shown in the Fig.2.

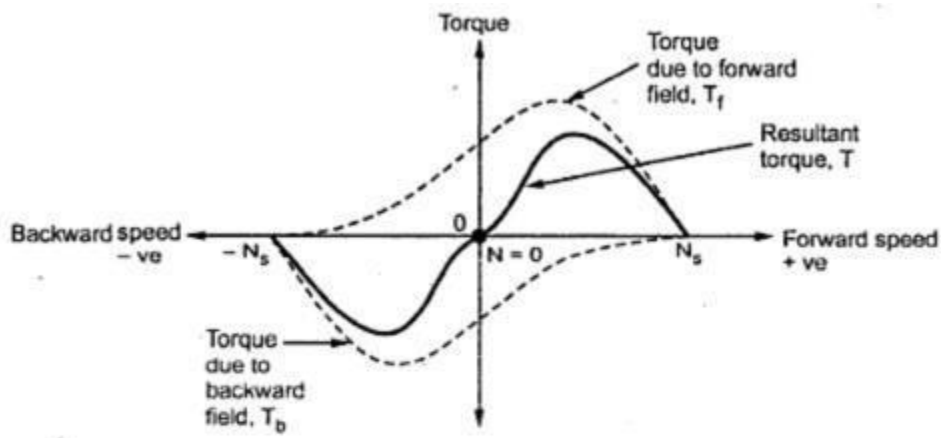


Fig. 2 Torque-speed characteristic

It can be seen that at start N = 0 and at that point resultant torque is zero. So single phase motors are not self starting.

However if the rotor is given an initial rotation in any direction, the resultant average torque increase in the direction in which rotor initially rotated. And motor starts rotating in that direction. But in practice it is not possible to give initial torque to rotor externally hence some modifications are done in the construction of single phase induction motors to make them self starting.

Another theory which can also be used to explain why single phase induction motors is not self starting is cross-field theory.

Types of Single Phase Induction Motors:

In practice some arrangement is provided in the single phase induction motors so as that the stator flux produced becomes rotating type rather than the alternating type, which rotates in particular direction only. So torque produced due to such rotating magnetic field is unidirectional as there is no oppositely directed torque present. Hence under the influence of rotating magnetic field in one direction, the induction motor becomes self starting. It rotates in same direction as that of rotating magnetic field. Thus depending upon the methods of producing rotating stator magnetic flux, the single phase induction motors are classified as,

1. Split phase induction motor
2. Capacitor start induction motor
3. Capacitor start capacitor run induction motor
4. Shaded pole induction motor

To produce rotating magnetic field, it is necessary to have minimum two alternating fluxes having a phase difference between the two. The interaction of such two fluxes produces a resultant flux which is rotating magnetic flux, rotating in space in one particular direction. So an attempt is made in all the single phase induction motors to produce an additional flux other than stator flux, which has a certain phase difference with respect to stator flux.

Such two fluxes are shown in the Fig. 1 having phase difference of between them.

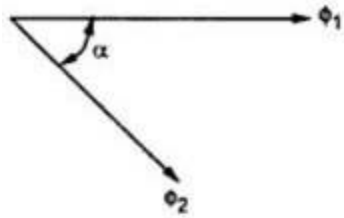


Fig. 1

More the phase difference angle ***α***, more is starting torque produced. Thus production of rotating magnetic field at start is important to make the single phase induction motors self starting. Once the motor starts, then another flux Φ_2 may be removed and motor can continue to rotate under influence of stator flux or main flux alone.

Let us see how the rotating magnetic field is produced in various types of single phase induction motors.

Split Phase Induction Motor:

This type of motor has single phase stator winding called main winding. In addition to this, stator carries one more winding called auxiliary winding or starting winding. The auxiliary winding carries a series resistance such that its impedance is highly resistive in nature. The main winding is inductive in nature.

Let I_m = Current through main winding

and Ist = Current through auxiliary winding

As main winding is inductive, current I_m lags voltage by V by a large angle Φ_m while Ist is almost in phase in V as auxiliary winding is highly resistive. Thus three exists a phase difference of ***α*** between the two currents and hence between the two fluxes produced by the two currents. This is shown in the Fig.1(c). The resultant of these two fluxes is a rotating magnetic field. Due to this, the starting torque, which acts only in one direction is produced.

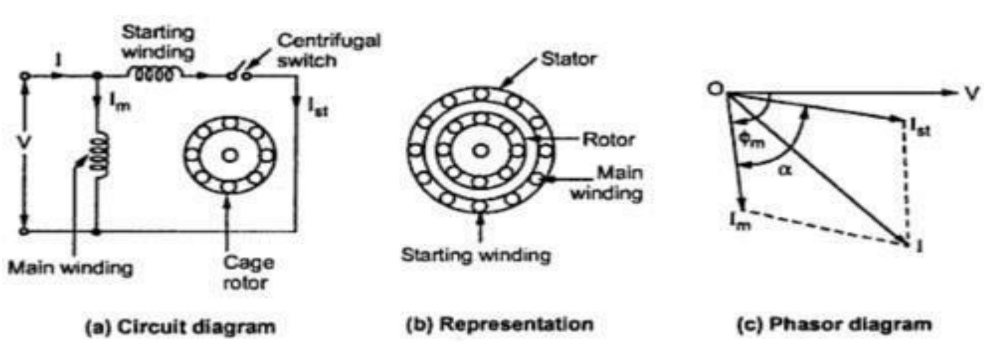


Fig. 1 Split phase induction motor

The auxiliary winding has a centrifugal switch in series with it. When motor gather a speed upto 75 to 80% of the synchronous speed, centrifugal switch gets opened mechanically and in running condition auxiliary winding remains out of the circuit. So motor runs only stator winding. So auxiliary winding is designed for short time use while the main winding is designed for continuous use. As the current I_m and are splitted from each other by angle 'α ' at start, the motor is commonly called split phase motor.

The torque-speed characteristics of split phase motors is shown in the Fig.2.

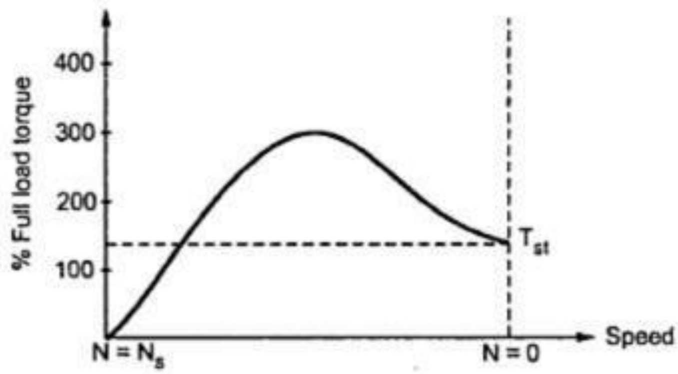


Fig. 2

The starting torque Tst is proportional to the split angle 'α ' but split phase motors give poor starting torque which is 125 to 150% of full load torque.

The direction of rotation of this motor can be reversed by reversing the terminals of either main winding or auxiliary winding. This changes the direction of rotating magnetic field which in turn changes the direction of rotation of the motor.

Applications

These motors have low starting current and moderate starting torque. These are used for easily started loads like fans, blowers, grinders, centrifugal pumps, washing machines, oil burners, office equipments etc. These are available in the range of 1/120 to 1/2 kW.

Capacitor Start Induction Motors:

The construction of this type of motors is similar to the resistance split phase type. The difference is that in series with the auxiliary winding the capacitor is connected. The capacitive circuit draws a leading current, this feature used in this type to increase the split phase angle α between the two currents I_m and Ist.

Depending upon whether capacitor remains in the circuit permanently or is disconnected from the circuit using centrifugal switch, these motors are classified as,

1. Capacitor start motor and
2. Capacitor start capacitor run motors

The connection of capacitor start motor is shown in the Fig. 1(a). The current I_m lags the voltage by angle Φ_m while due to capacitor the current Ist leads the voltage by angle Φ_{st}. Hence there exists a large phase difference between the two currents which is almost 90°, which is an ideal case. The phasor diagram is shown in the Fig.1(b).

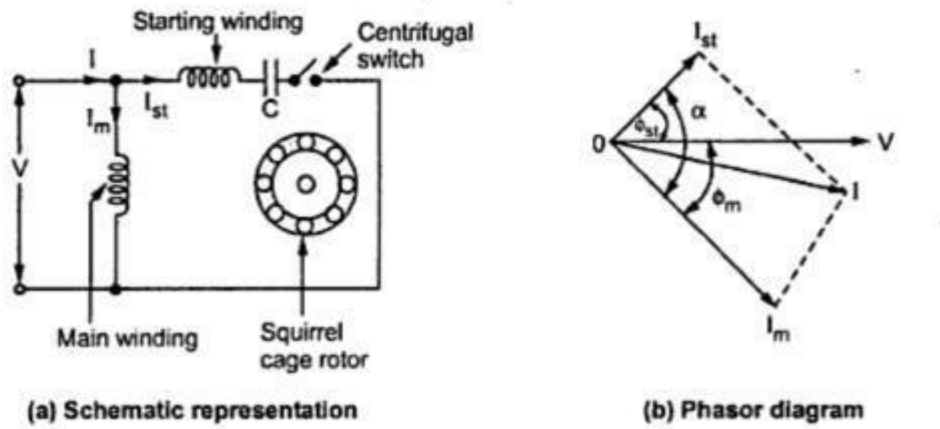


Fig 1. Capacitor start motor

The starting torque is proportional to 'α 'and hence such motors produce very high starting torque When speed approaches to 75 to 80% of the synchronous speed, the starting winding gets disconnected due to operation of the centrifugal switch. The capacitor remains in the circuit only at start hence it is called capacitor start motors.

Key point : In case of capacitor start capacitor run motor, there is no centrifugal switch and capacitor remain permanently in the circuit. This improves the power factor.

The schematic representation of such motor is shown in the Fig. 2.

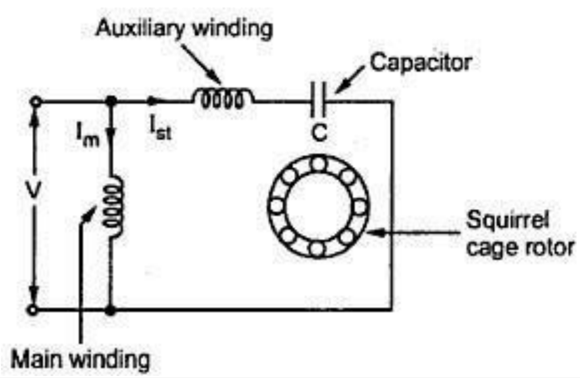


Fig. 2 Capacitor start capacitor run motor

The phasor diagram remains same as shown in the Fig.1(b). The performance not only at start but in running condition also depends on the capacitor C hence its value is to be designed so as to compromise between best starting and best running condition. Hence the starting torque available in such type of motor is about 50 to 100% of full load torque.

The direction of rotation, in both the types can be changed by interchanging the connection of main winding or auxiliary winding. The capacitor permanently in the circuit improves the power factor. These motors are more costly than split phase type motors.

The capacitor value can be selected as per the requirement of starting torque, the starting torque can be as high as 350 to 400 % of full load torque. The torque-speed characteristics is as shown in the Fig.3.

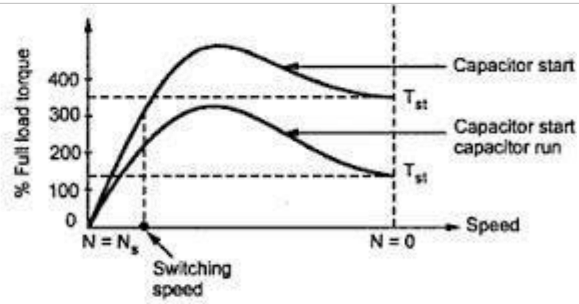


Fig.3 Torque speed characteristic of capacitor split phase motor

Applications

These motors have high starting torque and hence are used for hard starting loads. These are used for compressors, conveyors, grinders, fans, blowers, refrigerators, air conditions etc. These are most commonly used motors. The capacitor start capacitor run motors are used in celling fans, blowers and air-circulations. These motors are available upto 6 kW.

Example : A 250 W, 230 V, 50 Hz capacitor start motor has the following impedances at standstill.

Main winding, $Z_m = 7 + j5\ \Omega$

Auxiliary winding, $Z_a = 11.5 + j5\ \Omega$

Find the value of capacitor to be connected in series with the auxiliary winding to give a phase displacement between the currents in two windings. Draw the circuit and phasor diagram for motor.

Solution : Let X_c be the capacitive reactance to be connected with auxiliary winding at start, as shown in the Fig. 1(a).

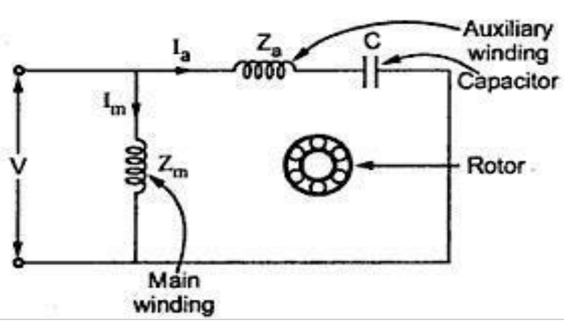


Fig. 1(a)

$\therefore \quad Z_a = 11.5 + j\,(5 - X_c)\ \Omega$

$\quad = 7 + j5\ \Omega = 8.6023$

Now I_a and I_m must have a phase difference of 90^o. I_m will lag the voltage by 35.5376^o hence I_a must lead the voltage by $(90^o - 35.5376^o)$ i.e. 53.4624^o , as shown in the Fig 1(b).

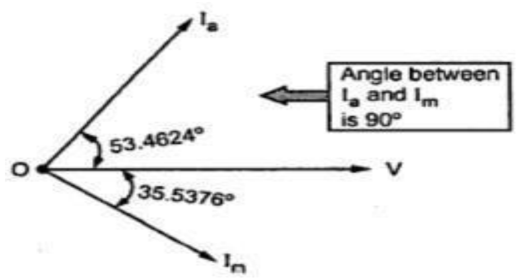


Fig. 1(b)

The phase angle of Z_a is,

$\Phi_a = \tan^{-1}((5 - X_c)/11.5) = -53.4624^o$

Key point :As leads, the phase angle of i.e. must be negative hence taken as

$\tan(-53.4624^o) = (5 - X_c)/11.5$ i.e.

$-1.34956 = (5 - X_c)/11.5$

$\therefore \quad X_c = 20.52\ \Omega = 1/(2\pi fC)$

$\therefore \quad C = 1/(2\pi \times 50 \times 20.52) = 155.1217\mu F$

Shaded Pole Induction Motor:

This type of motor consists of a squirrel cage rotor and stator consisting of salient poles i.e. projected poles. The poles are shaded i.e. each pole carries a copper band on one of its unequally divided part called shading ban Fig.1(a) shows 4 pole shaded pole construction while Fig. 1(b) shows a single pole consisting of copper shading band.

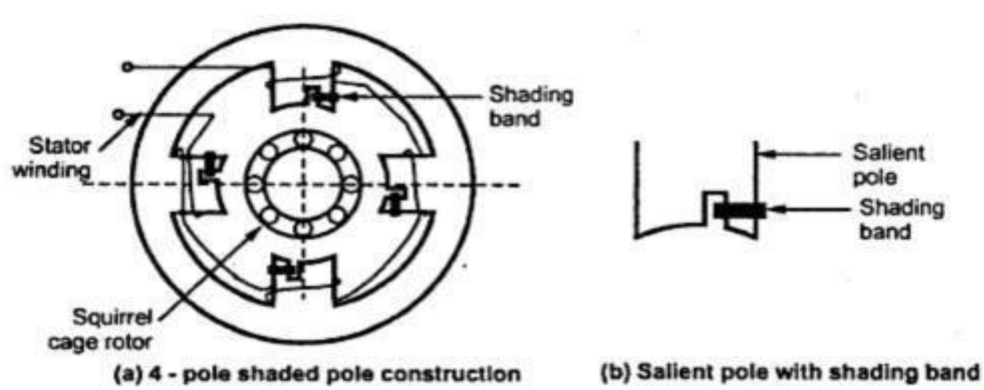


Fig 1

Key point : When single phase a.c. supply is given to the stator winding, due to shading provided to the poles, a rotating magnetic field is generated.

The production of rotating magnetic field can be explained as below :

The current carried by the stator winding is alternating and produces alternating flux. The waveform of the flux is shown in the Fig. 2(a). The distribution of this flux in the pole area is greatly influenced by the role of copper shading band. Consider the three instants say t_1, t_2 and t_3 during first half cycle of the flux as shown, in the Fig 2(a).

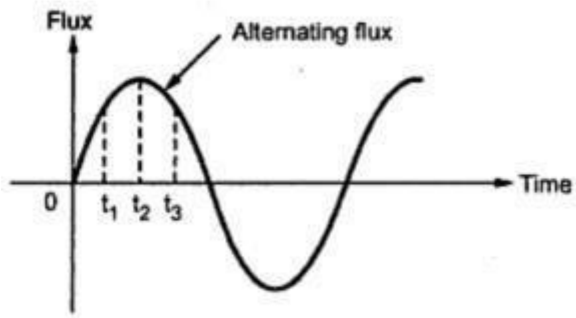


Fig. 2 (a) Waveform of stator flux

At instant $t = t_1$, rate of rise of current and hence the flux is very high. Due to the transformer action, large e.m.f. gets induced in the copper shading band. This circulates current through shading band as it is short circuited, producing its own flux. According to lenz's law, the direction of this current is so as to oppose the cause i.e. rise in current. Hence shading ring flux is opposing to the main flux. Hence there is crowding of flux in non-shaded part while weakening of flux in shaded part. Overall magnetic axis shifts in non-shaded part as shown in the Fig. 2(b).

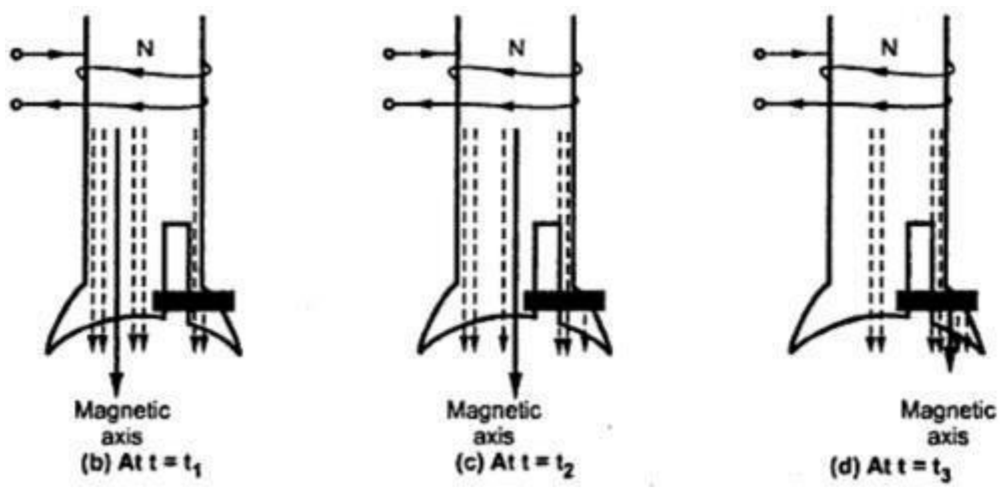


Fig. 2 Production of rotating magnetic field

At instant $t = t_2$, rate of rise of current and hence the rate of change of flux is almost zero as flux almost reaches to its maximum value. So $d\Phi/dt = 0$. Hence there is very little induced e.m.f. in the shading ring. Hence the shading ring flux is also negligible, hardly affecting the distribution of the main flux. Hence the main flux distribution is uniform and magnetic axis lies at the centre of the pole face as shown in the Fig. 2(c).

At the instant $t = t_3$, the current and the flux is decreasing. The rate of decrease is high which again induces a very large e.m.f. in the shading ring. This circulates current through the ring which produces its own flux. Now direction of the flux produced by the shaded ring current is so as to oppose the cause which is decrease in flux. So it oppose the decrease in flux means its direction is same as that of main flux, strengthening it. So there is crowding of flux in the shaded part as compared to non-shaded part. Due to this the magnetic axis shifts to the middle of the shaded part of the pole. This is shown in the Fig. 2(d).

This sequence keeps on repeating for negative half cycle too. Consequently this produces an effect of rotating magnetic field, the direction of which is from non-shaded part of the pole to the shaded part of the pole. Due to this, motor produces the starting torque is low which is about 40 to 50% of the full load torque for this type of motor. The torque speed characteristics is shown in the Fig. 3.

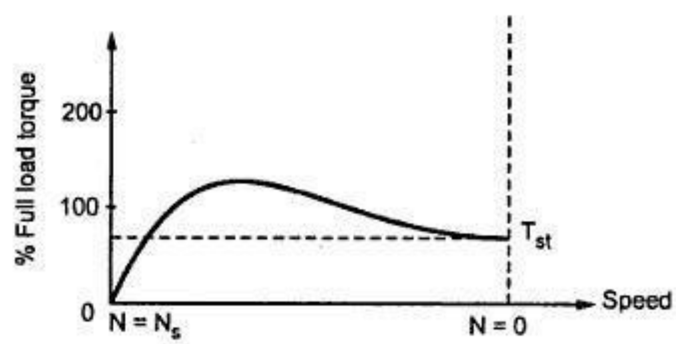


Fig. 3 Torque-speed characteristics of shaded pole motor

Due to absence of centrifugal switch the construction is simple and robust but this type of motor has a lot of lamination as :

1. The starting torque is poor.
2. The power factor is very low.
3. Due to I^2R, copper losses in the shading ring the efficiency is very low.
4. The speed reversal is very difficult. To achieve the speed reversal, the additional set of shading rings is required. By opening one set and closing other, direction can be reversed but the method is complicated and expensive.
5. The size and power rating of these motors is very small. These motors are usually available in a range of 1/300 to 1/20 kW.

Application

These motors are cheap but have very low starting torque, low power factor and low efficiency. These motors are commonly used for the small fans, by motors, advertising displays, film projectors, record players, gramophones, hair dryers, photo copying machines etc.