UNIT – 3

SINGLE PHASE INDUCTION MOTOR

SINGLE PHASE INDUCTION MOTOR

The single-phase induction machine is the most frequently used motor for refrigerators, washing machines, clocks, drills, compressors, pumps, and so forth.

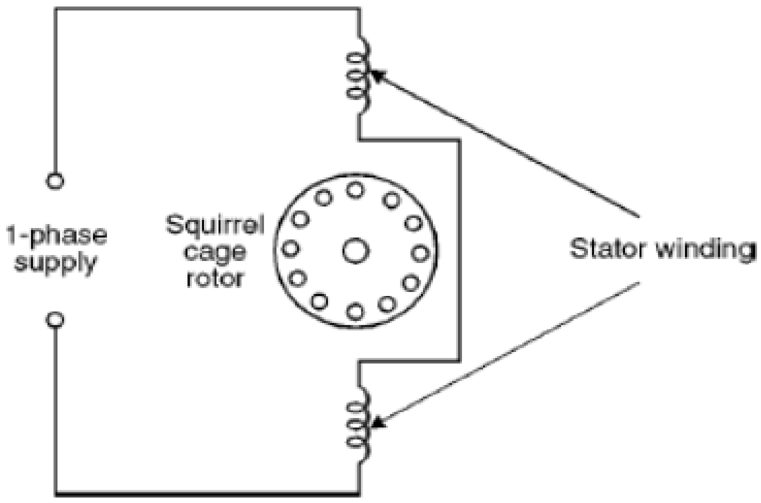


Fig. 1. Elementary Single – phase induction motor

<u>Construction:</u> A Single Phase induction motor has two parts--- stator and rotor. The single-phase motor stator has a laminated iron core with two windings arranged perpendicularly, One is the main and the other is the auxiliary winding or starting winding as showing in the fig 1. (a).

The motor uses a squirrel cage rotor, which has a laminated iron core with slots as shown in fig1 (b). Aluminum bars are molded on the slots and short-circuited at both ends with a ring.

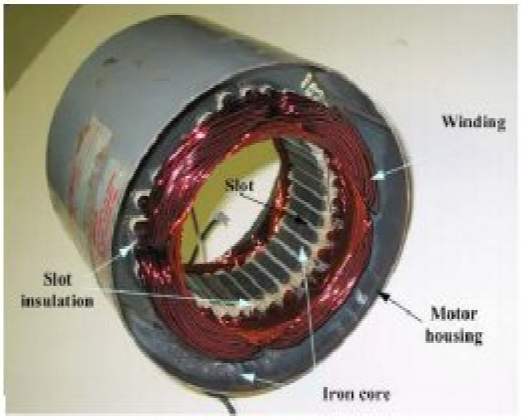


Fig. 1(a) Stator

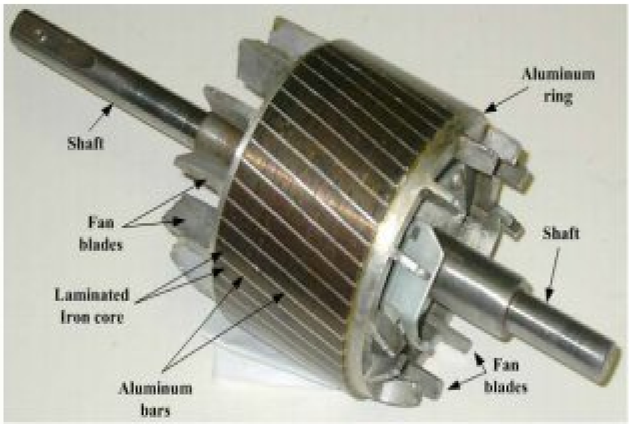


Fig. 1(b) Rotor

Working Principle: When 1-phase AC supply is given to stator winding of 1-phase IM, the alternating electric current flows through the stator or main winding. This alternating current produces an alternating flux which is known as main flux. This main flux links with rotor conductors & hence cut the rotor conductors.

According to faraday law of electromagnetic induction emf gets induced in rotor. Since rotor circuit is closed hence electric current starts flowing in rotor. This rotor current produces its own flux called rotor flux. Now there are two fluxes, one is the main flux & another is rotor flux. By the interaction of these two fluxes, desired torque is produced which is required by the motor to rotate.

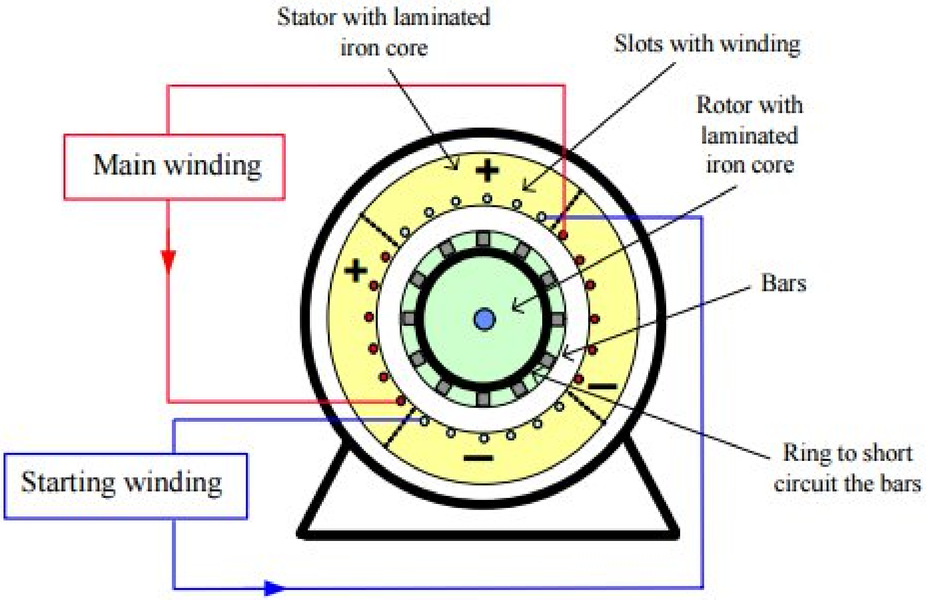


Fig. 2. Single – phase induction motor

DOUBLE REVOLVING FIELD THEORY: According to double field revolving theory, any alternating quantity can be resolved into two components, each component have magnitude equal to the half of the maximum magnitude of the alternating quantity and both these component rotates in opposite direction to each other. For example - a flux, φ can be resolved into two components

$$\frac{\phi_m}{2}\ and\ -\frac{\phi_m}{2}$$

Each of these components rotates in opposite direction i. e if one φ_m / 2 is rotating in clockwise direction then the other φ_m / 2 rotates in anticlockwise direction.

When a single phase ac supply is given to the stator winding of single phase induction motor, it produces its flux of magnitude, φ_m. According to the double field revolving theory, this alternating flux, φ_m is divided into two components of magnitude φ_m /2. Each of these components will rotate in opposite direction, with the synchronous speed, N_s. Let these two components of flux as forward component of flux, φ_f and backward component of flux, φ_b. The resultant of these two components of flux at any instant of time, gives the value of instantaneous stator flux at that particular instant.

$$i.e.\phi_r = \frac{\phi_m}{2} + \frac{\phi_m}{2} \ or \ \phi_r = \phi_f + \phi_b$$

At starting, both the forward and backward components of flux are exactly opposite to each other. Also both of these components of flux are equal in magnitude. So, they cancel each other and hence the net torque experienced by the rotor at starting is zero.

Both components are rotating & hence get cuts by rotor conductors. Due to cutting of flux emf gets induced in rotor which circulates rotor current. The rotor current produces rotor flux. This flux interacts with forward component to produce a torque in clockwise direction. When rotor flux interacts with backward component, it produces a torque in anticlockwise direction. Hence net torque experienced by rotor is zero at start because each torque tries to rotate the rotor in its own direction.So, the single phase induction motors are not self starting motors.

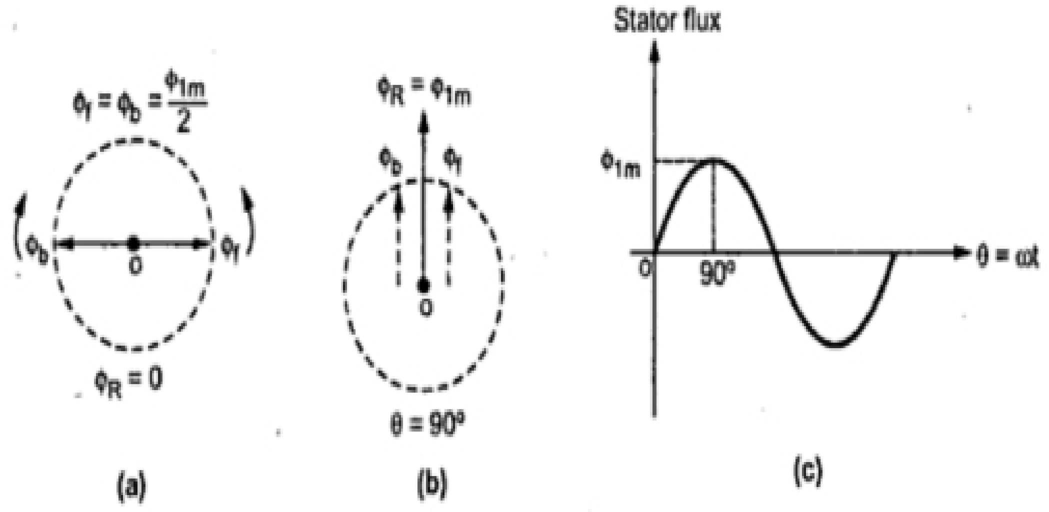


Fig.3. Stator Flux and its two components.

CROSS-FIELD THEORY: The principle of operation of a single-phase induction motor can be explained from the cross-field theory. As soon as the rotor begins to turn, a speed emf E is induced in the rotor conductors, as they cut the stator flux F_s. This voltage increases as the rotor speed increases. It causes current I_R to flow in the rotor bars facing the stator poles as shown in Fig. 4

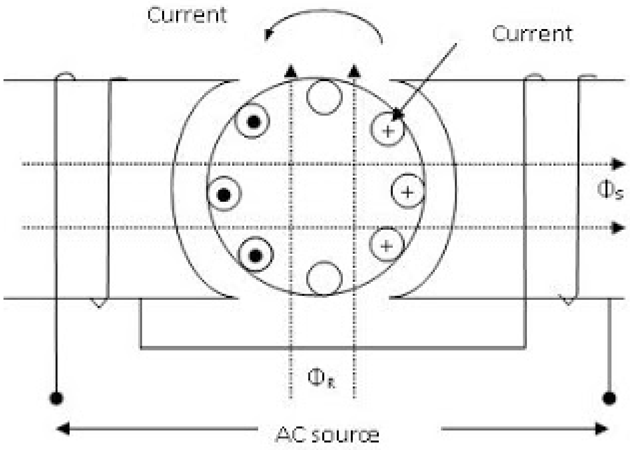


Fig. 4. Current induced in the rotor bars due to rotation

These currents produce an ac flux F_R which act at right angle to the stator flux F_s. Equally important is the fact that F_R does not reach its maximum value at the same time as F_S does, in effect, F_R lags almost 90^o behind F_S, owing to the inductance of the rotor

The combined action of F_s and F_R produces a revolving magnetic field, similar to that in a three-phase motor. The value of F_R increases with increasing speed, becoming almost equal to F_s at synchronous speed. The flux rotates counterclockwise in the same direction as the rotor and it rotates at synchronous speed irrespective of the actual speed of the rotor. As the motor approaches synchronous speed, F_R becomes almost equal to F_s and a nearly perfect revolving field is produces.

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.5.

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.

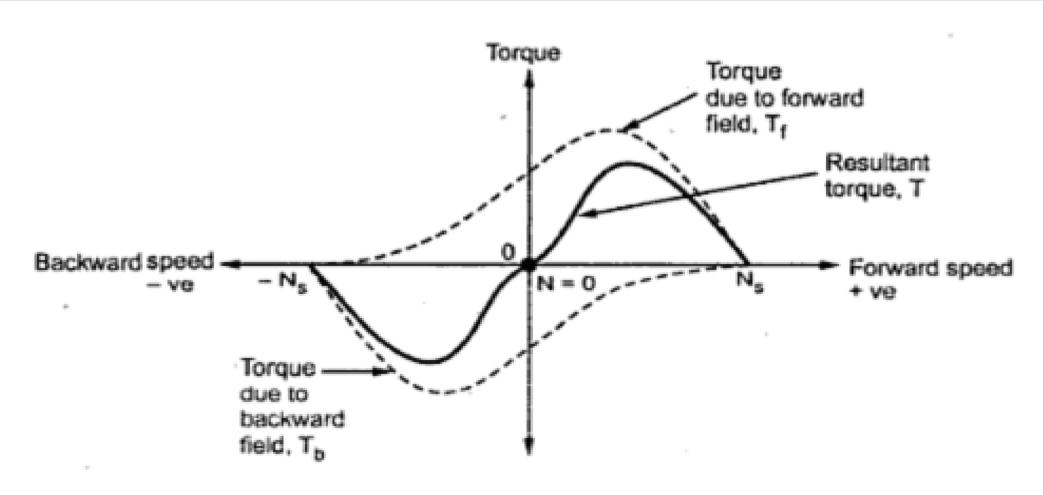


Fig. 5. Torque-speed characteristic

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.

TYPES OF SINGLE PHASE INDUCTION MOTOR

The single phase induction motors are made self starting by providing an additional flux by some additional means. Now depending upon these additional means the single phase induction motors are classified as:

1. Split Phase or Resistance Start.
2. Capacitor start inductor motor.
    - Capacitor Start
    - Permanent Split Capacitor
    - Capacitor Start Capacitor Run
3. Shaded pole induction motor

1. <u>Split – phase Induction Motor:</u>

The stator of a split – phase induction motor has two windings, the main winding and the auxiliary winding. These windings are displaced in space by 90 electric degrees as shown in fig.6. The auxiliary winding is made of thin wire so that it has a high R/X ratio as compared to the main winding which has thick super enamel copper wire. When the two stator windings are energized from a single – phase supply, the current Im and Ia in the main winding and auxiliary winding lag behind the supply voltage V, and Ia leading the current Im as shown in fig. 7.Hence phase difference exist between two currents. This phase difference produces rotating magnetic field. Once motor had reached 70-80% of synchronous speed, auxiliary winding is removed by switch.

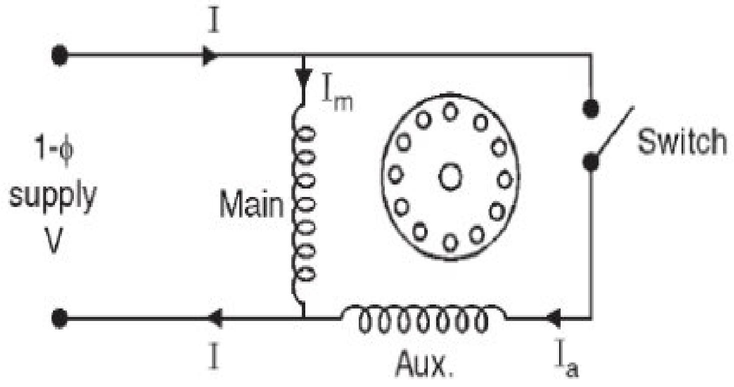


Fig.6. Schematic Diagram of Split – phase Induction Motor

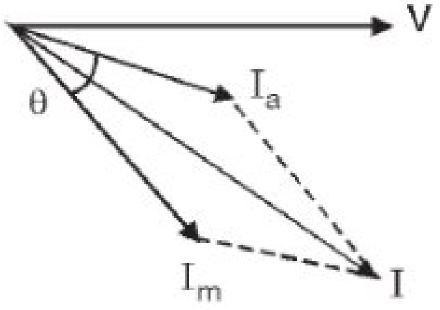


Fig 7. Phasor Diagram

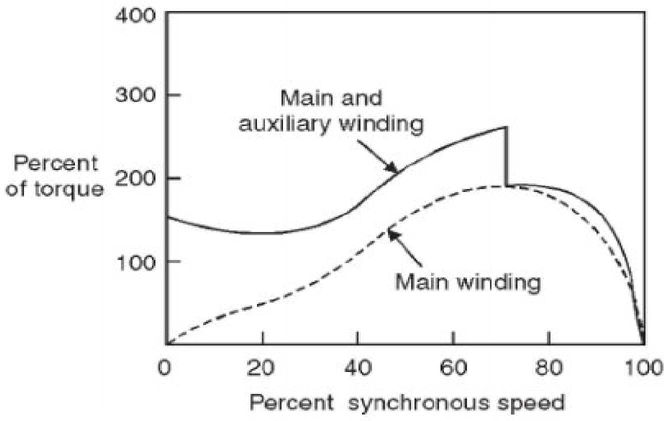


Fig 8. Torque Speed Characteristic

2. Capacitor – Start Motor:

Capacitors are used to improve the starting and running performance of the single phase inductions motors. Its stator has two windings, main winding & auxiliary winding and are displaced by 90° in space. A capacitor C & a centrifugal switch is also connected in series with auxiliary winding.

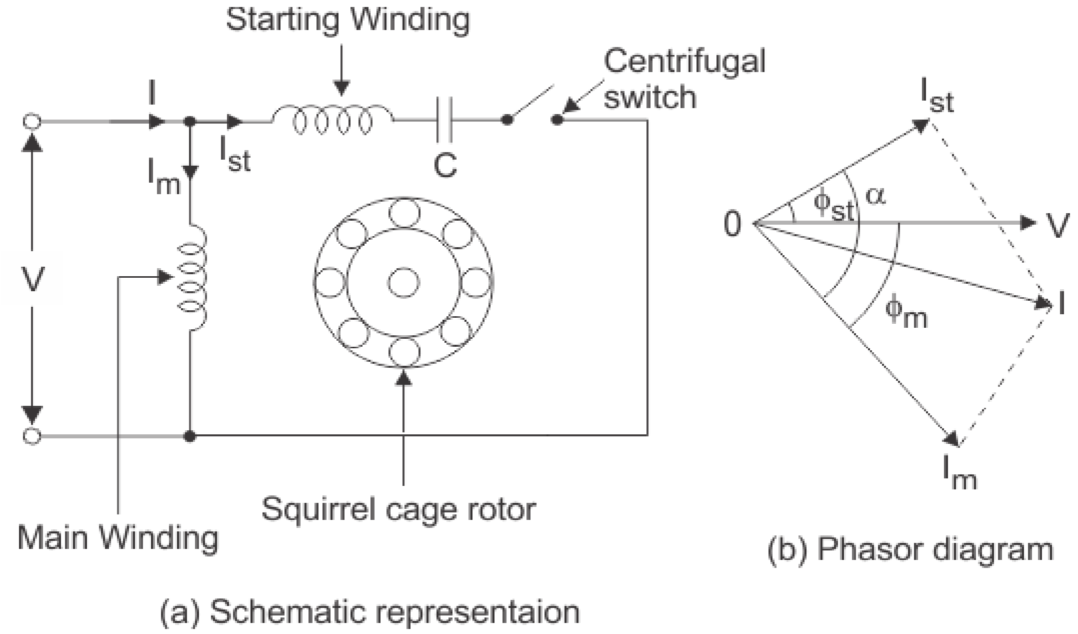


Fig. 9. Capacitor Start motor

3. Permanent – Split Capacitor Motor:

Its stator has two windings, main winding & auxiliary winding and are displaced by 90° in space. A capacitor C is connected in series with auxiliary winding permanently at starting and running conditions.

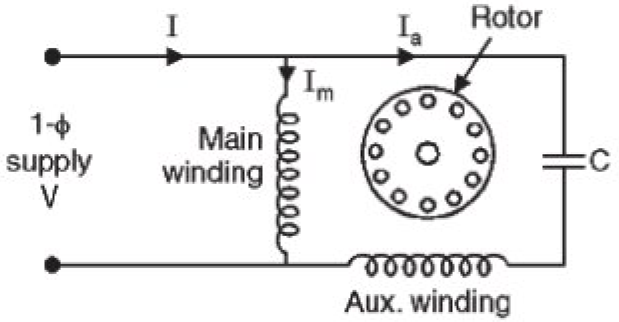


Fig. 10. Schematic Diagram of Permanent – Split Capacitor Motor

4. Capacitor - Start Capacitor - Run:

In this method two capacitors are used, one for starting and one for running as shown in fig. (11). The features of the capacitor start and PSC methods can be combined with this method. The run capacitor is connected in series with the start winding or auxiliary winding, and a start capacitor is connected in the circuit using a normally closed switch while starting the motor. Start capacitor provides starting boost to motor and PSC provides high running to the motor. It is more costly, but still facilitates high starting and breakdown torque along with smooth running characteristics at high horsepower ratings.

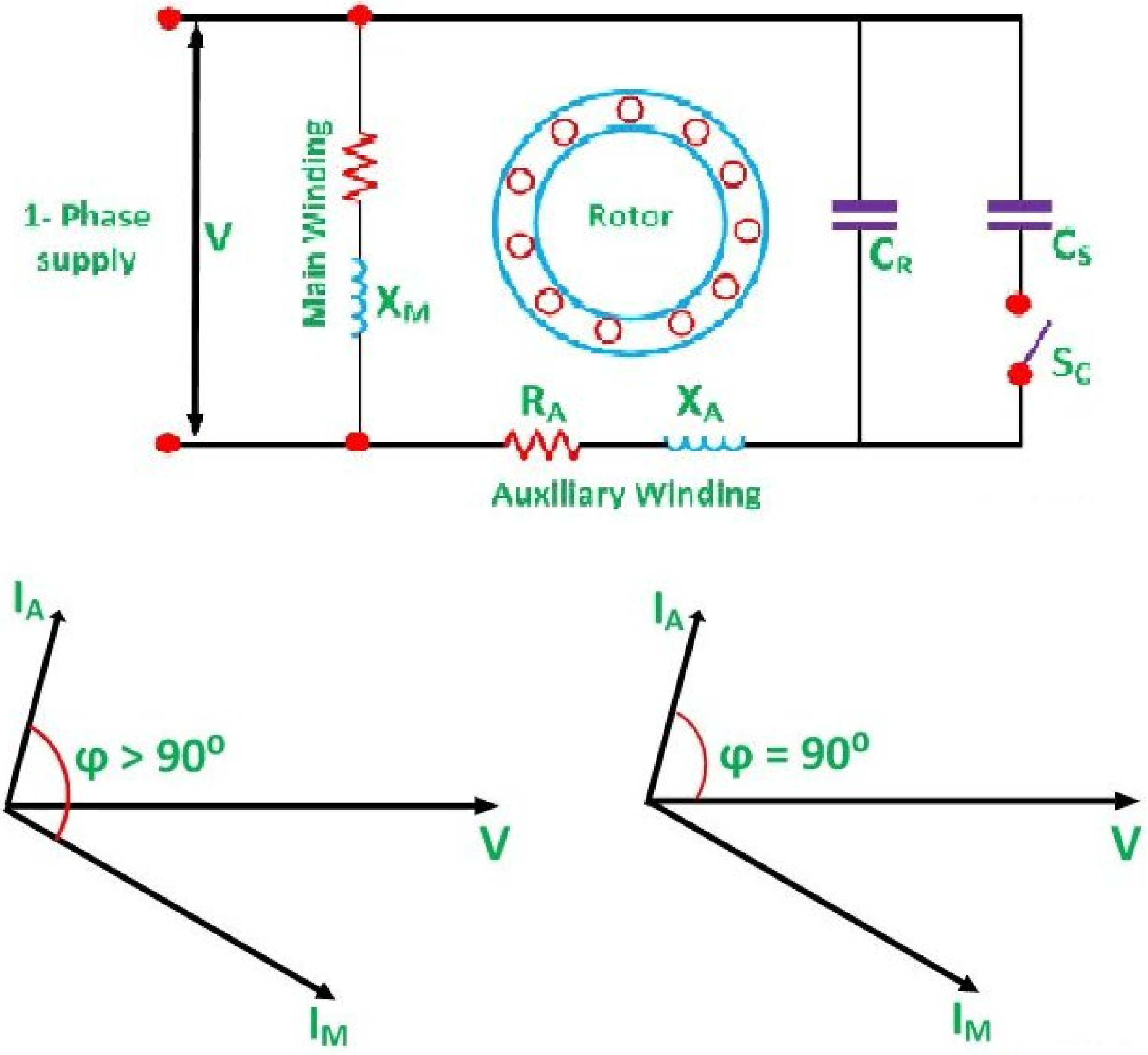
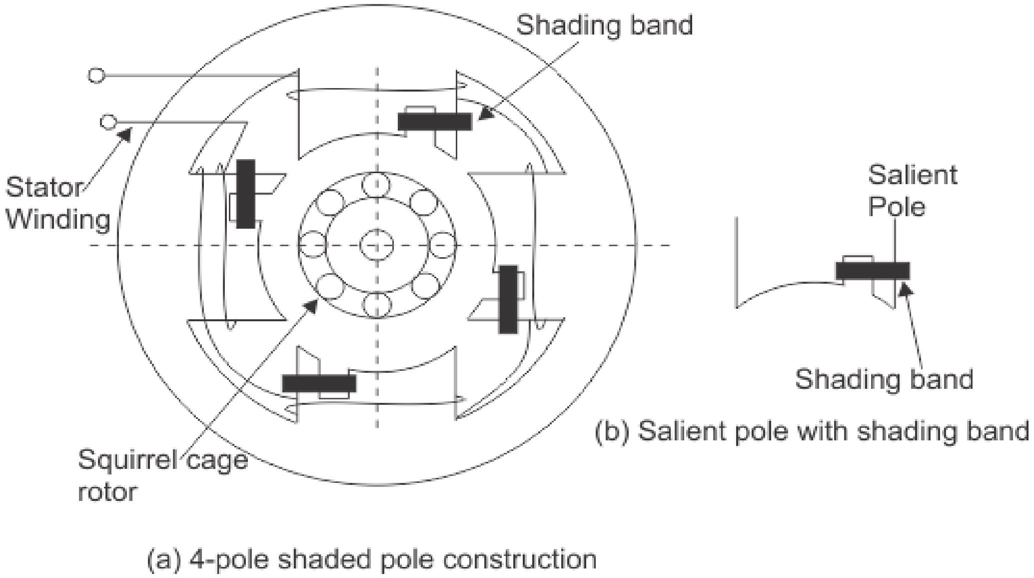


Fig.11. Schematic Diagram and Phasor of Capacitor - Start Capacitor – Run

5. Shaded Pole Induction Motor:

The stator of the shaded pole single phase induction motor has salient or projected poles. These poles are shaded by copper band or ring which is inductive in nature. The poles are divided into two unequal halves. The smaller portion carries the copper band and is called as shaded portion of the pole.

ACTION: When a single phase supply is given to the stator of shaded pole induction motor an alternating flux is produced. This flux links with shading coil which induces an emf in the shaded coil. Since this shaded coil is short-circuited hence a current is produced in it in such a direction to oppose the main flux. The flux in shaded pole lags behind the flux in the unshaded pole. The phase difference between these two fluxes produces resultant rotating flux.



(a) 4-pole shaded pole construction

(b) Salient pole with shading band

Fig. 12. Schematic Diagram of Shaded Pole Induction Motor

DETERMINATION OF EQUIVALENT CIRCUIT PARAMETERS

The parameter of the equivalent circuit of single – phase induction motor can be determined from the blocked – rotor and no – load tests. These tests are performed with auxiliary winding kept open, except for the capacitor – run motor.

1. Blocked – rotor test:

In this test the rotor is at rest (blocked). A low voltage is applied to the stator so that rated current flows in the main winding. The voltage, current and power input are measured. With the rotor blocked, s =1 the impedance in the equivalent circuit is so large compared with that it may be neglected from the equivalent circuit. Therefore the equivalent circuit at s=1 is shown in fig.(13).

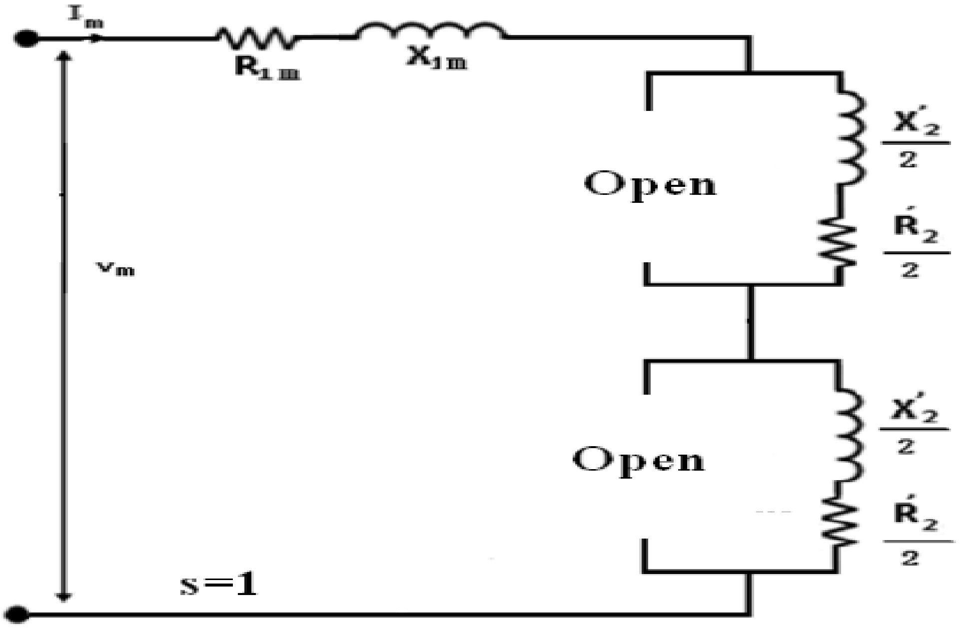


Fig. 13. Blocked rotor Test of 1-φ Induction Motor

$$Z_e = V_{sc}/ I_{sc}$$

$$R_e = P_{sc} /(I_{sc})^2$$

But $R_e = R_{1m} + R_2'$

∴ $R_2' = R_e - R_{1m}$

= rotor resistance referred to stator

$$X_e = X_{1m} + X_2'$$

we get, $X_e = \sqrt{(Z_{eq}^{\,2} - R_e^{\,2})}$

Since $X_{1m} = X_2'$ (Assumption)

$$X_{1m} = 1/2\sqrt{(Z_{eq}^{\,2} - R_e^{\,2})}$$

Hence, from blocked rotor test the parameters R_2', X_{1m}, X_2' can be found if R_{1m} is known.

2. No Load Test:

The motor is run without load at rated voltage and rated frequency. The voltage, current and input power are measured. At no load, the slip s is very small close to zero and $R'_2/2s$ is very large as compared to $X_m/2$.The resistance $R'_2/2(2\text{-}s)$ associated with the backward rotating field is so small as compared to $X_m/2$, that the backward magnetizing current is negligible. Therefore, under no load conditions, the equivalent circuit becomes as shown in fig.(14).

$$P_o = V_o I_o \cos\Phi$$

$$\cos \Phi = P_o / V_o I_o$$

The equivalent reactance at no load is given by

$$X_o = X_{1m} + X_m/2 + X_2'/2$$

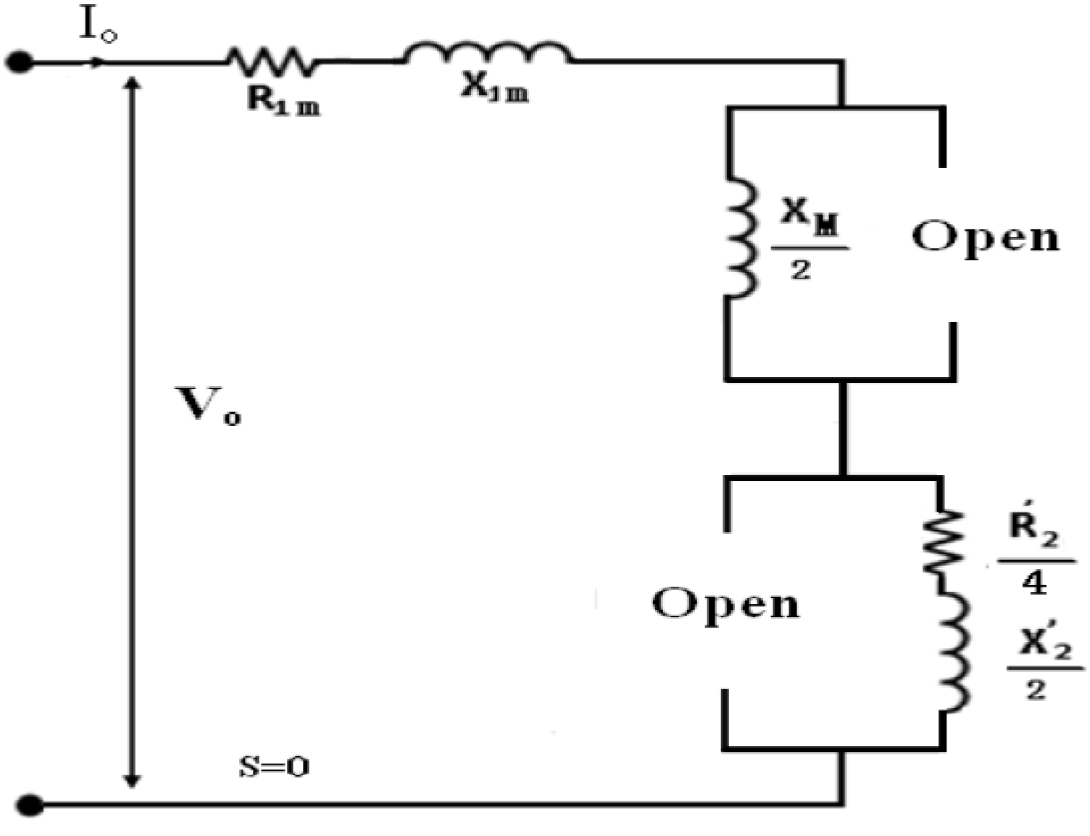


Fig. 14. No Load Test of 1-φ Induction Motor

Since X_{1m} and X_2' are already known from the blocked rotor test, the magnetizing reactance X_m can be calculated from above equation.

And $$Z_o = V_o / I_o$$

$$X_o = Z_o \sin\Phi_o$$

$$X_o = Z_o \sqrt{(1 - \cos^2\Phi_o)}$$

EQUIVALENT CIRCUIT OF SINGLE – PHASE INDUCTION MOTOR

When the stator of single phase induction motor is connected to single – phase supply, the stator current produces a pulsating flux. According to the double – revolving field theory,the pulsating air – gap flux in the motor at standstill can be resolved into two equal and opposite fluxes with the motor. Since the magnitude of each rotating flux is one – half of the alternating flux, it is convenient to assume that the two rotating fluxes are acting on two separate rotors.

Thus, a single – phase induction motor may be considered as consisting of two motors having a common stator winding and two imaginary rotors, which rotate in opposite directions. The standstill impedance of each rotor referred to the main stator winding is $(\frac{R_2'}{2} + j\,\frac{X_2'}{2})$. The equivalent circuit of single – phase induction motor at standstill is shown in fig.(15).

R_{1m} = resistance of stator winding
X_{1m} = leakage reactance of stator winding
X_M = total magnetizing reactance
$R2'$ = resistance of rotor referred to the stator
$X2'$ = leakage reactance of rotor referred to the stator

The forward flux induces a voltage Emf in the main stator winding. The backward rotating flux induces a voltage Emb in the main stator winding. The resultant induced voltage in the main stator winding is Em ,

where **Em = Emf + Emb**

At standstill, **Emf = Emb**

Now suppose that the motor is started with the help of an auxiliary winding. The auxiliary winding is switched out after the motor gains it normal speed. The effective rotor resistance of an induction motor depends on the slip of the rotor. The slip of the rotor with respect to the forward rotating flux is S. The slip the rotor with respect to the backward rotating flux is (2-S).When the forward and backward slips are taken in account, the result is the equivalent circuit shown in fig.(16) which represent the motor running on the main winding alone.

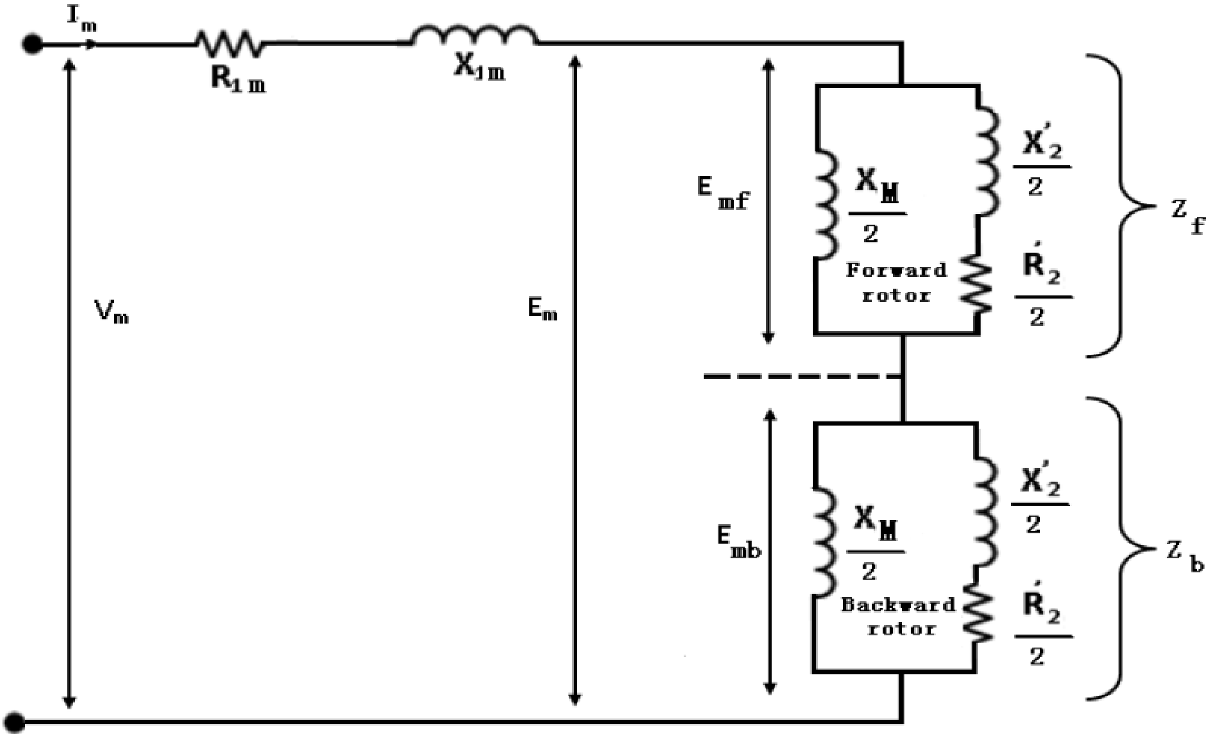


Fig. 15. Equivalent Circuit of 1-φ Induction Motor at Standstill.

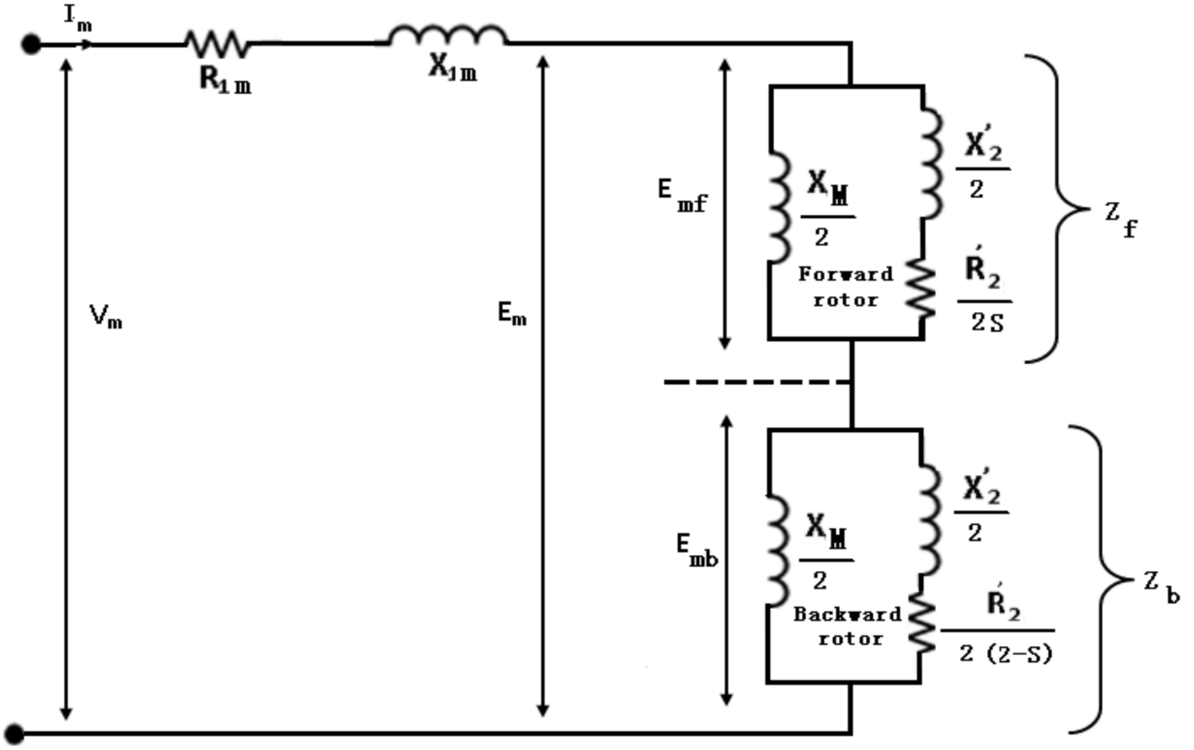


Fig. 16. Running Detail Circuit of 1-φ Induction Motor.

The rotor impedance representing the effect of forward field referred to the stator winding m is given by an impedance $(\frac{\acute{R}_2}{2S} + j\frac{\acute{X}_2}{2})$ in parallel with $j\frac{X_M}{2}$.

$$Z_f = R_f + jX_f = (\frac{\acute{R}_2}{2S} + j\frac{\acute{X}_2}{2}) \parallel (j\frac{X_M}{2})$$

$$Z_f = \frac{(\frac{\acute{R}_2}{2S} + j\frac{\acute{X}_2}{2})(j\frac{X_M}{2})}{\frac{\acute{R}_2}{2S} + j\frac{\acute{X}_2}{2} + j\frac{X_M}{2}}$$

Similarly, the rotor impedance representing the effect of backward field referred to the stator winding m is given by impedance $(\frac{\acute{R}_2}{2(2-S)} + j\frac{\acute{X}_2}{2})$ in parallel with $j\frac{X_M}{2}$.

$$Z_b = R_b + jX_b = (\frac{\acute{R}_2}{2(2-S)} + j\frac{\acute{X}_2}{2}) \parallel (j\frac{X_M}{2})$$

$$Z_b = \frac{(\frac{\acute{R}_2}{2(2-S)} + j\frac{\acute{X}_2}{2})(j\frac{X_M}{2})}{\frac{\acute{R}_2}{2(2-S)} + j\frac{\acute{X}_2}{2} + j\frac{X_M}{2}}$$

The simplified equivalent circuit of single – phase induction motor with only main winding energized is shown in fig.(17).

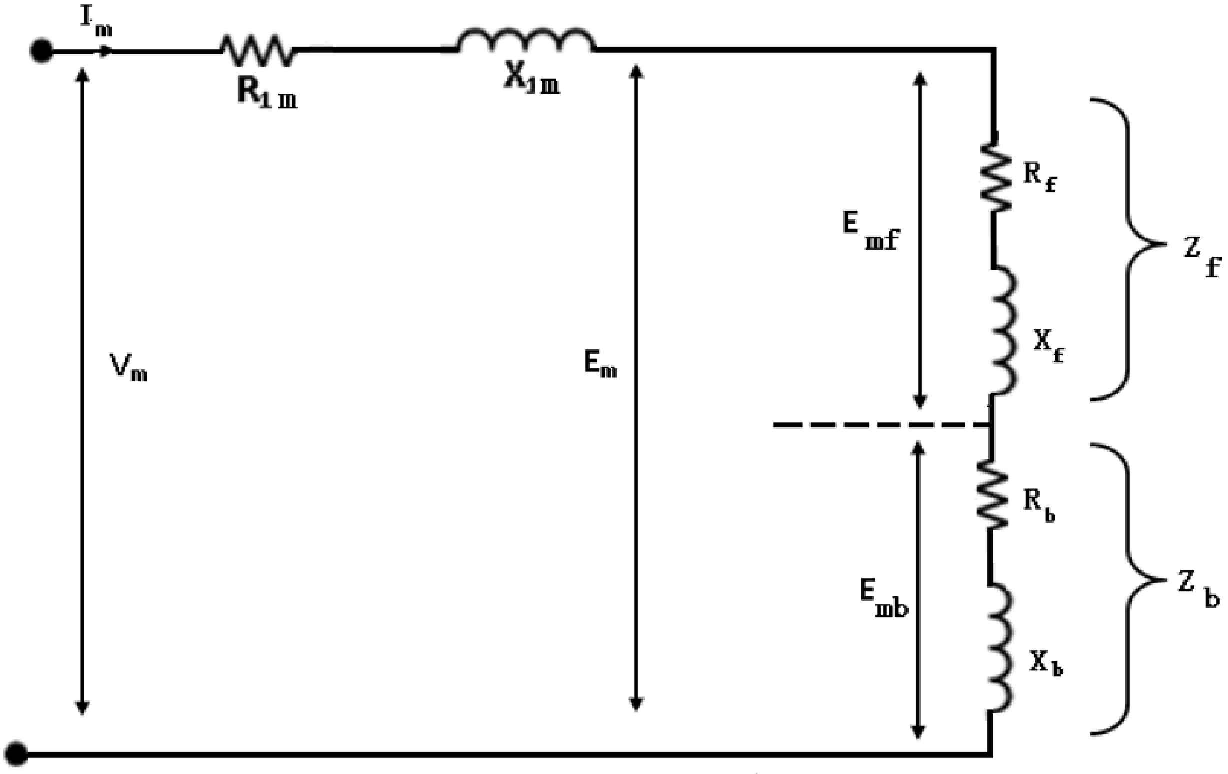


Fig. 17. Simplified Equivalent Circuit of 1-φ Induction Motor.

The current in the stator winding is--

$$I_m = \frac{V_m}{Z_{1m} + Z_f + Z_b}$$

The torque of the backward field is in opposite direction to that of the forward field, and therefore the total air – gap power in a single phase induction motor is

$$P_g = P_{gf} - P_{gb}$$

Where P_{gf} = air – gap power for forward field

$$P_{gf} = I_m^2 R_f$$

Where P_{gb} = air – gap power for backward field

$$P_{gb} = I_m^2 R_b$$

∴

$$P_g = I_m^2 R_f - I_m^2 R_b = I_m^2 (R_f - R_b)$$

The torque produced by the forward field

$$T_f = \frac{1}{\omega_s} P_{gf} = \frac{P_{gf}}{2\pi n_s}$$

The torque produced by the backward field

$$T_b = \frac{1}{\omega_s} P_{gb} = \frac{P_{gb}}{2\pi n_s}$$

The resultant electromagnetic or induced torque T_{int} is the difference between the torque T_f and T_b:

$$T_{int} = T_f - T_b$$

As in the case of the 3 - phase I.M., the induced torque is equal to the air gap power divided by synchronous angular velocity.

$$T_{int} = \frac{P_g}{\omega_s} = \frac{1}{\omega_s}(P_{gf} - P_{gb}) = \frac{I_m^2}{\omega_s}(R_f - R_b)$$

The total copper loss is the sum of rotor copper loss due to the forward field and the rotor copper loss due to the backward field.

$$P_{cr} = P_{crf} + P_{crb}$$

And rotor copper loss in a 3 – phase induction motor

$$P_{cr} = \text{slip} * \text{air gap power}$$

$$P_{cr} = sP_{gf} + (2 - s)P_{gb}$$

The power converted from electrical to mechanical form in a single phase induction motor is given by

$$P_{mech} = P_{conv} = \omega T_{ind}$$

$$P_{mech} = (1 - s)\omega_s T_{ind}$$

$$= (1 - s)P_g = (1 - s)(P_{gf} - P_{gb})$$

Or

$$P_{mech} = I_m^2(R_f - R_b)(1 - s)$$

UNIVERSAL MOTOR - CONSTRUCTION, WORKING

A universal motor is a special type of motor which is designed to run on either DC or single phase AC supply. These motors are generally series wound (armature and field winding are in series), and hence produce high starting torque. They run at lower speed on AC supply than they run on DC supply of same voltage, due to the reactance voltage drop which is present in AC and not in DC.

There are two basic types of universal motor:

(i) compensated type and
(ii) uncompensated type

CONSTRUCTION OF UNIVERSAL MOTOR: Construction of a universal motor is very similar to the construction of a DC machine.

- It consists of a stator on which field poles are mounted. Field coils are wound on the field poles.
- However, the whole magnetic path (stator field circuit and also armature) is laminated. Lamination is necessary to minimize the eddy currents which induce while operating on AC.
  The rotary armature is of wound type having straight or skewed slots and commutator with brushes resting on it.
- The commutation on AC is poorer than that for DC. Because of the current induced in the armature coils. For that reason brushes used are having high resistance.

WORKING OF UNIVERSAL MOTOR

- A universal motor works on either DC or single phase AC supply. When the universal motor is fed with a DC supply, it works as a DC series motor. When current flows in the field winding, it produces an electromagnetic field. The same current also flows from the armature conductors. When a current carrying conductor is placed in an electromagnetic field, it experiences a mechanical force. Due to this mechanical force, or torque, the rotor starts to rotate. The direction of this force is given by Fleming's left hand rule.
- When fed with AC supply, it still produces unidirectional torque. Because, armature winding and field winding are connected in series, they are in same phase. Hence, as polarity of AC changes periodically, the direction of current in armature and field winding reverses at the same time.
  Thus, direction of magnetic field and the direction of armature current reverse in such a way that the direction of force experienced by armature conductors remains same. Thus, regardless of AC or DC supply, universal motor works on the same principle that DC series motor works.
- In a normal d.c. motor if direction of both field and armature current is reversed, the direction of torque remains unchanged. So when normal d.c. series motor is connected to an a.c. supply, both field and armature current get reversed and unidirectional torque gets produced in the motor hence motor can work on a.c. supply.

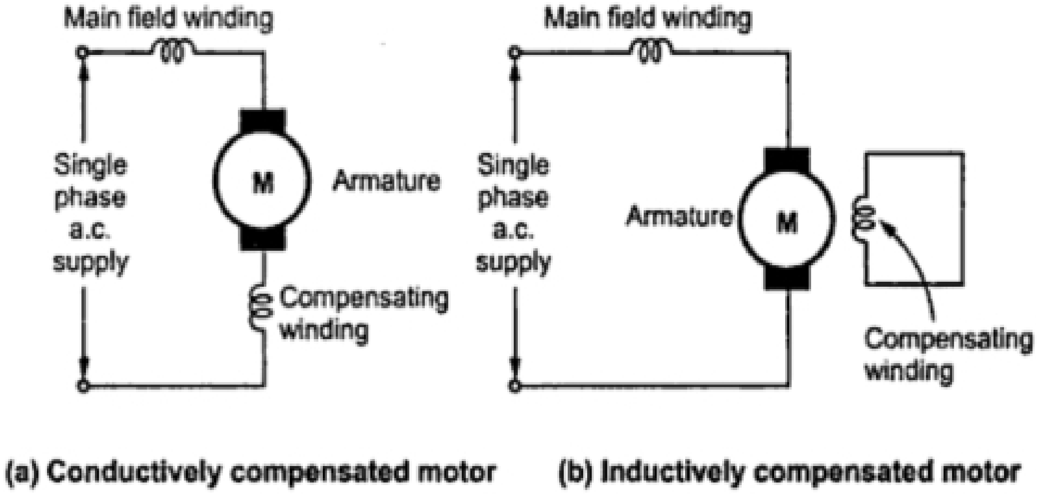
But performance of such motor is not satisfactory due to the following reasons :
i) There are tremendous eddy current losses in the yoke and field cores, which causes overheating.
ii) Armature and field winding offer high reactance to a.c. due to which operating power factor is very low.
iii) The sparking at brushes is a major problem because of high voltage and current induced in the short circuited armature coils during the commutation period.
Some modifications are required to have the satisfactory performance of d.c. series motor on a.c. supply, when it is called a.c. series motor. The modifications are:

i) To reduce the eddy current losses, yoke and pole core construction is laminated.

ii) The power factor can be improved by reducing the magnitudes of field and armature reactance. Field reactance can be decreased by reducing the number of turns. But this reduces the field flux. But this reduction in flux (N α 1/Φ), increases the speed and reduce the torque. To keep the torque same it is necessary to increase the armature turns proportionately. This increases the armature inductance.

Now to compensate for increased armature flux which produce severe armature reaction, it is necessary to use compensating winding. The flux produced by this winding is opposite to that produced by armature and effectively neutralizes the armature reaction.

If such a compensating winding is connected in series with the armature as shown in the Fig.1 (a), the motor is said to be 'conductively compensated'. For motors to be operated on a.c. and d.c. both, the compensation should be conductive. If compensating winding is short circuited on its self as shown in the Fig. 1(b), the motor is said to be 'inductively compensated'. In this compensating winding acts as a secondary of transformer and armature as its primary. The ampere turns produced by compensating winding neutralize the armature ampere turns.



(a) Conductively compensated motor (b) Inductively compensated motor

Fig.18. Universal Motor

REPULSION MOTOR

Repulsion motor works on the principle of repulsion between two magnetic fields. Consider a 2-pole salient pole motor with vertical magnetic axis (basic functioning of salient pole and non-salient pole the construction is same). The armature is connected to commutator and brush. The brushes are short circuited using a low-resistance jumper. When alternating current is supplied to field or stator winding, it induces an emf in the armature. The direction of alternating current is such that it creates North Pole at the top and south pole at the bottom. The direction of induced emf is given by Lenz law, according to which the direction of induced emf is so as to oppose the cause producing it. the induced emf induces the current in the armature conductors. The direction of induced current in the armature conductors depends on the position of the brush.

If the brush axis is along the direction of the field (or) if the brush axis is collinear with the magnetic field, the armature behaves like an electromagnet and so an N-pole is formed directly below the N-pole of the stator and S-pole is formed directly above the S-pole of the stator. The net torque at this condition is zero. Both the N-poles repel each other and Both the S-poles repel each other. The two repulsion forces are in direct opposition to each other and hence no torque will be developed in this condition. Also if we consider that the brushes are shifted through 90 degree, so that the magnetic axis is perpendicular to the brush axis, so torque also at this condition is zero.

Now consider a situation when brush axis is neither along the magnetic axis nor perpendicular to the magnetic axis. The brush axis is displaced at an angle α to magnetic axis. Now a net voltage is induced at the brush terminals which will produce a current in armature. Due to current in armature circuit it will produce its own magnetic field with N & S pole. But in this condition N pole is not directly under the N-pole of magnetic field and S pole is not directly above the S-pole of magnetic axis. The poles of armature are slightly displaced from that of the poles of the magnetic field.

During this condition the N pole of main field will repel the N pole of rotor and similarly S pole of main field will repel S pole of rotor. Hence rotor starts rotating in a particular direction. Rotation of rotor is determined by position of brushes w.r.t magnetic field of rotor.

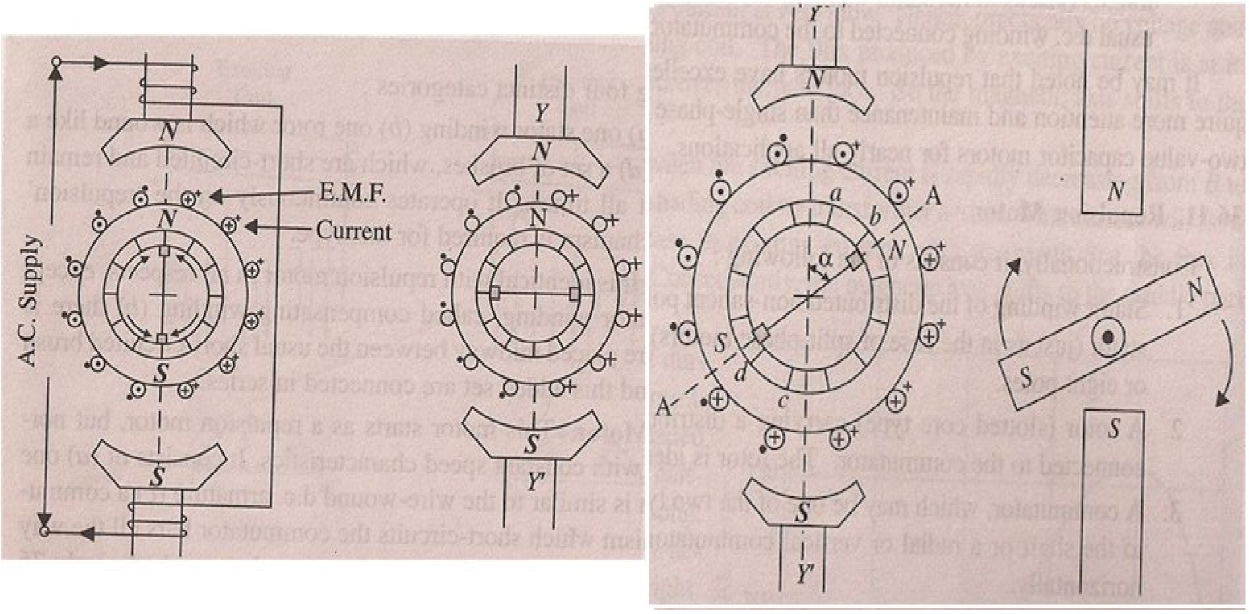


Fig.19. Universal Motor