Chapter (9)

Single-Phase Motors

Introduction

As the name suggests, these motors are used on single-phase supply. Single-phase motors are the most familiar of all electric motors because they are extensively used in home appliances, shops, offices etc. It is true that single-phase motors are less efficient substitute for 3-phase motors but 3-phase power is normally not available except in large commercial and industrial establishments. Since electric power was originally generated and distributed for lighting only, millions of homes were given single-phase supply. This led to the development of single-phase motors. Even where 3-phase mains are present, the single-phase supply may be obtained by using one of the three lines and the neutral. In this chapter, we shall focus our attention on the construction, working and characteristics of commonly used single-phase motors.

9.1 Types of Single-Phase Motors

Single-phase motors are generally built in the fractional-horsepower range and may be classified into the following four basic types:

1. Single-phase induction motors
   (i) split-phase type (ii) capacitor type
   (iii) shaded-pole type

2. A.C. series motor or universal motor

3. Repulsion motors
   (i) Repulsion-start induction-run motor
   (ii) Repulsion-induction motor

4. Synchronous motors
   (i) Reluctance motor (ii) Hysteresis motor

9.2 Single-Phase Induction Motors

A single phase induction motor is very similar to a 3-phase squirrel cage induction motor. It has (i) a squirrel-cage rotor identical to a 3-phase motor and (ii) a single-phase winding on the stator.

Unlike a 3-phase induction motor, a single-phase induction motor is not self-starting but requires some starting means. The single-phase stator winding produces a magnetic field that pulsates in strength in a sinusoidal manner. The field polarity reverses after each half cycle but the field does not rotate. Consequently, the alternating flux cannot produce rotation in a stationary squirrel-cage rotor. However, if the rotor of a single-phase motor is rotated in one direction by some mechanical means, it will continue to run in the direction of rotation. As a matter of fact, the rotor quickly accelerates until it reaches a speed slightly below the synchronous speed. Once the motor is running at this speed, it will continue to rotate even though single-phase current is flowing through the stator winding. This method of starting is generally not convenient for large motors. Nor can it be employed fur a motor located at some inaccessible spot.

Fig. (9.1) shows single-phase induction motor having a squirrel cage rotor and a single-phase distributed stator winding. Such a motor inherently docs not develop any starting torque and, therefore, will not start to rotate if the stator winding is connected to single-phase a.c. supply. However, if the rotor is started by auxiliary means, the motor will quickly attain me final speed. This strange behaviour of single-phase induction motor can be explained on the basis of double-field revolving theory.

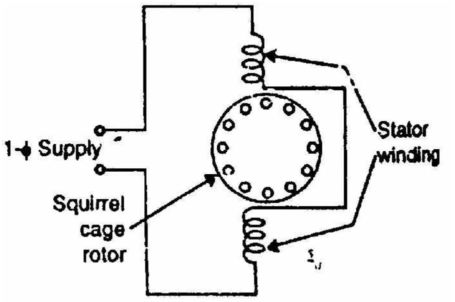


Fig.(9.1)

9.3 Double-Field Revolving Theory

The double-field revolving theory is proposed to explain this dilemma of no torque at start and yet torque once rotated. This theory is based on the fact that an alternating sinusoidal flux ($\phi = \phi_m \cos \omega t$) can be represented by two revolving fluxes, each equal to one-half of the maximum value of alternating flux (i.e., $\phi_m/2$) and each rotating at synchronous speed ($N_s = 120\ f/P$, $\omega = 2\pi f$) in opposite directions.

The above statement will now be proved. The instantaneous value of flux due to the stator current of a single-phase induction motor is given by;

$$\phi = \phi_m \cos \omega t$$

Consider two rotating magnetic fluxes ϕ_1 and ϕ_2 each of magnitude $\phi_m/2$ and rotating in opposite directions with angular velocity ω [See Fig. (9.2)]. Let the two fluxes start rotating from OX axis at

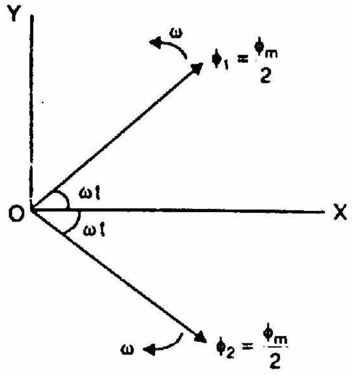


Fig.(9.2)

t = 0. After time t seconds, the angle through which the flux vectors have rotated is at. Resolving the flux vectors along-X-axis and Y-axis, we have,

$$\text{Total X-component} = \frac{\phi_m}{2}\cos\omega t + \frac{\phi_m}{2}\cos\omega t = \phi_m \cos\omega t$$

$$\text{Total Y-component} = \frac{\phi_m}{2}\sin\omega t - \frac{\phi_m}{2}\sin\omega t = 0$$

$$\text{Resultant flux, } \phi = \sqrt{(\phi_m \cos\omega t)^2 + 0^2} = \phi_m \cos\omega t$$

Thus the resultant flux vector is $\phi = \phi_m \cos\omega t$ along X-axis. Therefore, an alternating field can be replaced by two relating fields of half its amplitude rotating in opposite directions at synchronous speed. Note that the resultant vector of two revolving flux vectors is a stationary vector that oscillates in length with time along X-axis. When the rotating flux vectors are in phase [See Fig. (9.3 (i))], the resultant vector is $\phi = \phi_m$; when out of phase by 180° [See Fig. (9.3 (ii))], the resultant vector $\phi = 0$.

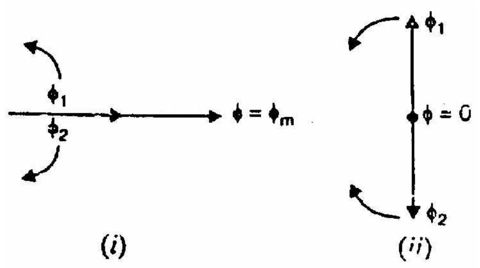


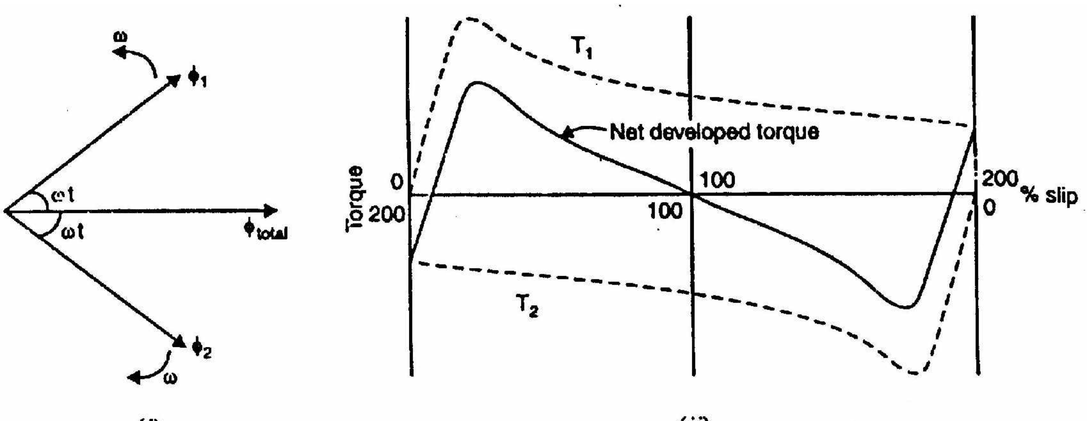
Fig.(9.3)

Let us explain the operation of single-phase induction motor by double-field revolving theory.

(i) Rotor at standstill

Consider the case that the rotor is stationary and the stator winding is connected to a single-phase supply. The alternating flux produced by the stator winding can be presented as the sum of two rotating fluxes ϕ_1 and ϕ_2, each equal to one half of the maximum value of alternating flux and each rotating at synchronous speed ($N_s = 120\ f/P$) in opposite directions as shown in Fig. (9.4 (i)). Let the flux ϕ_1 rotate in anti clockwise direction and flux ϕ_2 in clockwise direction. The flux ϕ_1 will result in the production of torque T_1 in the anti clockwise direction and flux ϕ_2 will result in the production of torque T_2 In the clockwise direction. At standstill, these two torques are equal and opposite and the net torque developed is zero. Therefore, single-phase induction motor is not self-starting. This fact is illustrated in Fig. (9.4 (ii)).

Note that each rotating field tends to drive the rotor in the direction in which the field rotates. Thus the point of zero slip for one field corresponds to 200% slip for the other as explained later. The value of 100% slip (standstill condition) is the same for both the fields.



(i) (ii)

Fig.(9.4)

(ii) Rotor running

Now assume that the rotor is started by spinning the rotor or by using auxiliary circuit, in say clockwise direction. The flux rotating in the clockwise direction is the forward rotating flux (ϕ_f) and that in the other direction is the backward rotating flux (ϕ_b). The slip w.r.t. the forward flux will be

$$s_f = \frac{N_s - N}{N_s} = s$$

where N_s = synchronous speed
N = speed of rotor in the direction of forward flux

The rotor rotates opposite to the rotation of the backward flux. Therefore, the slip w.r.t. the backward flux will be

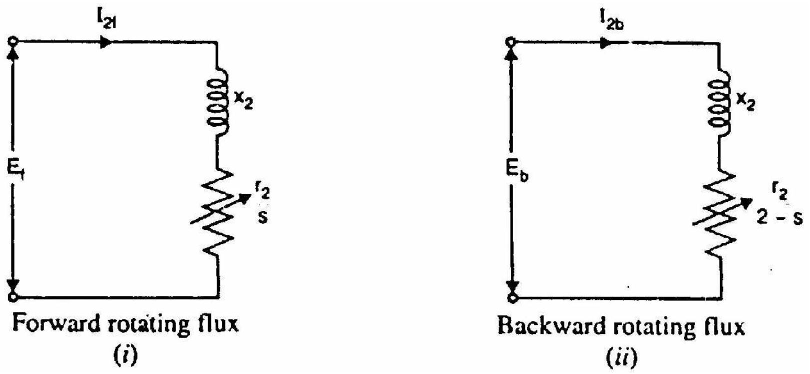
$$s_b = \frac{N_s - (-N)}{N_s} = \frac{N_s + N}{N_s} = \frac{2N_s - N_s + N}{N_s}$$

$$= \frac{2N_s}{N_s} - \frac{(N_s - N)}{N_s} = 2 - s$$

$$\therefore \quad s_b = 2 - s$$

Thus fur forward rotating flux, slip is s (less than unity) and for backward rotating flux, the slip is 2 – s (greater than unity). Since for usual rotor resistance/reactance ratios, the torques at slips of less than unity arc greater than those at slips of more than unity, the resultant torque will be in the direction of the rotation of the forward flux. Thus if the motor is once started, it will develop net torque in the direction in which it has been started and will function as a motor.

Fig. (9.5) shows the rotor circuits for the forward and backward rotating fluxes. Note that $r_2 = R_2/2$, where R_2 is the standstill rotor resistance i.e., r_2 is equal to half the standstill rotor resistance. Similarly, $x_2 = X_2/2$ where X_2 is the standstill rotor reactance. At standstill, s = 1 so that impedances of the two circuits are equal. Therefore, rotor currents are equal i.e., $I_{2f} = I_{2b}$. However, when the rotor rotates, the impedances of the two rotor circuits are unequal and the rotor current I_{2b} is higher (and also at a lower power factor) than the rotor current I_{2f}. Their m.m.f.s, which oppose the stator m.m.f.s, will result in a reduction of the backward rotating flux. Consequently, as speed increases, the forward flux increases, increasing the driving torque while the backward flux decreases, reducing the opposing torque. The motor-quickly accelerates to the final speed.



Forward rotating flux (*i*)

Backward rotating flux (*ii*)

Fig.(9.5)

9.4 Making Single-Phase Induction Motor Self-Starting

The single-phase induction motor is not self-starting and it is undesirable to resort to mechanical spinning of the shaft or pulling a belt to start it. To make a single-phase induction motor self-starting, we should somehow produce a revolving stator magnetic field. This may be achieved by converting a single-phase supply into two-phase supply through the use of an additional winding. When the motor attains sufficient speed, the starting means (i.e., additional winding) may be removed depending upon the type of the motor. As a matter of fact, single-phase induction motors are classified and named according to the method employed to make them self-starting.

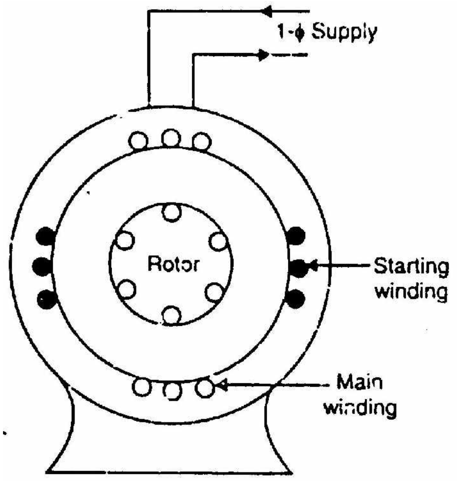


Fig.(9.6)

(i) **Split-phase motors**-started by two phase motor action through the use of an auxiliary or starting winding.

(ii) **Capacitor motors**-started by two-phase motor action through the use of an auxiliary winding and a capacitor.

(iii) **Shaded-pole motors**-started by the motion of the magnetic field produced by means of a shading coil around a portion of the pole structure.

9.5 Rotating Magnetic Field From 2-Phase Supply

As with a 3-phase supply, a 2-phase balanced supply also produces a rotating magnetic field of constant magnitude. With the exception of the shaded-pole motor, all single-phase induction motors are started as 2-phase machine. Once so started, the motor will continue to run on single-phase supply.

Let us see how 2-phase supply produces a rotating magnetic field of constant magnitude. Fig. (9.10 (i)) shows 2-pole, 2-phase winding. The phases X and Y are energized from a two-phase source and currents in these phases arc indicated as I_x and I_y [See Fig. (9.10 (ii))]. Referring to Fig. (9.10 (ii)), the fluxes produced by these currents arc given by;

$$\phi_Y = \phi_m \sin \omega t \qquad \text{and} \qquad \phi_X = \phi_m \sin(\omega t + 90°) = \phi_m \cos \omega t$$

Here ϕ_m is the maximum flux due to either phase. We shall now prove that this 2-phase supply produces a rotating magnetic field of constant magnitude equal to ϕ_m.

(i) At instant 1 [See (Fig. 9.10 (ii)) and Fig. (9.10 (iii))], the current is zero in phase Y and maximum in phase X. With the current in the direction shown, a resultant flux is established toward the right. The magnitude of the resultant flux is constant and is equal to ϕ_m as proved under:

$$\text{At instant 1, } \omega t = 0° \qquad \therefore \quad \phi_Y = 0 \quad \text{and} \quad \phi_X = \phi_m$$

$$\therefore \quad \text{Resultant flux, } \phi_r = \sqrt{\phi_X^2 + \phi_Y^2} = \sqrt{(\phi_m)^2 + (0)^2} = \phi_m$$

Fig.(9.7)

(ii) At instant 2 [See Fig. (9.10 (ii)) and Fig. (9.10 (iii))], the current is still in the same direction in phase X and an equal current flowing in phase Y. This establishes a resultant flux of the same value (i.e., $\phi_r = \phi_m$) as proved under:

$$\text{At instant 2, } \omega t = 45° \qquad \therefore \quad \phi_Y = \frac{\phi_m}{\sqrt{2}} \quad \text{and} \quad \phi_X = \frac{\phi_m}{\sqrt{2}}$$

$$\therefore \quad \text{Resultant flux, } \phi_r = \sqrt{(\phi_X)^2 + (\phi_Y)^2}$$

$$= \sqrt{\left(\frac{\phi_m}{\sqrt{2}}\right)^2 + \left(\frac{\phi_m}{\sqrt{2}}\right)^2} = \phi_m$$

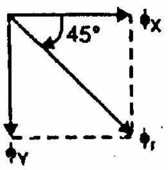


Fig.(9.8)

Note that resultant flux has the same value (i.e. ϕ_m) but turned 45° clockwise from position 1.

(iii) At instant 3 [See Fig. (9.10 (ii)) and Fig. (9.10 (iii))], the current in phase. X has decreased to zero and current in phase Y has increased to maximum. This establishes a resultant flux downward as proved under:

Fig.(9.9)

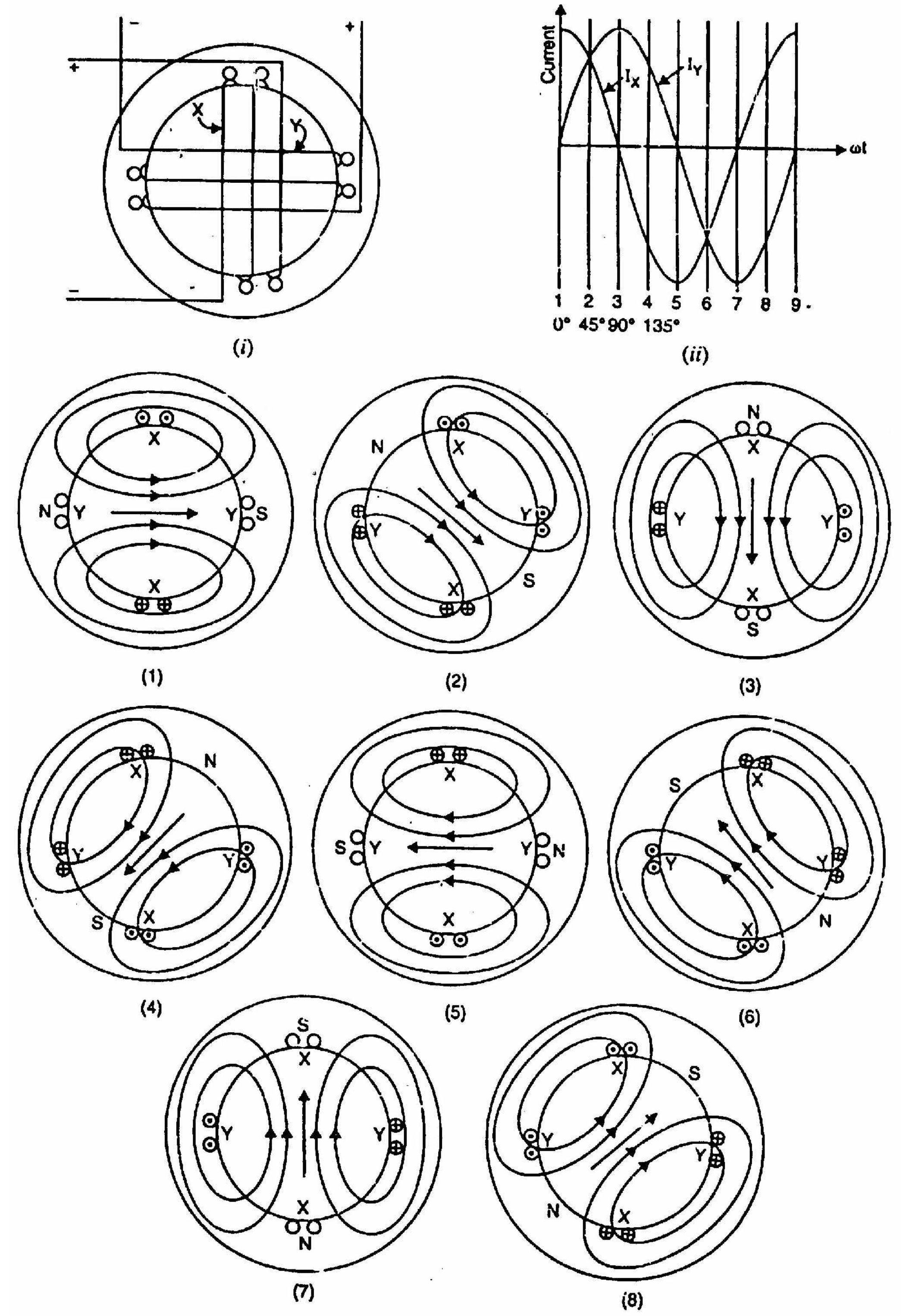


Fig.(9.10)

At instant 3, $\omega t = 90^\circ \quad \therefore \quad \phi_Y = \phi_m$ and $\phi_X = 0$

$$\therefore \quad \phi_r = \sqrt{\phi_X^2 + (\phi_Y)^2} = \sqrt{(0)^2 + (\phi_m)^2} = \phi_m$$

Note that resultant flux has now turned 90° clockwise from position 1.
The reader may note that in the three instants considered above, the resultant flux is constant and is equal to ϕ_m. However, this constant resultant flux is shining its position (clockwise in this case). In other words, the rotating flux is produced. We shall continue to consider other instants to prove this fact.

(iv) At instant 4 [See Fig. (9.10 (ii)) and Fig. (9.10 (iii))], the current in phase X has reversed and has the same value as that of phase Y. This establishes a resultant flux equal to ϕ_m turned 45° clockwise from position 3.

At instant 4, $\omega t = 135^\circ \quad \therefore \quad \phi_Y = \dfrac{\phi_m}{\sqrt{2}}$ and $\phi_X = \dfrac{\phi_m}{\sqrt{2}}$

$$\therefore \quad \phi_r = \sqrt{\phi_X^2 + \phi_Y^2} = \sqrt{\left(-\frac{\phi_m}{\sqrt{2}}\right)^2 + \left(\frac{\phi_m}{\sqrt{2}}\right)^2} = \phi_m$$

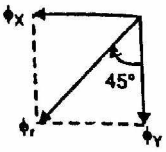


Fig.(9.11)

(v) At instant 5 [See Fig. (9.10 (ii)) and Fig. (9.10 (iii))], the current in phase X is maximum and in phase Y is zero. This establishes a resultant flux equal to ϕ_m toward left (or 90° clockwise from position 3).

At instant 5, $\omega t = 180^\circ \quad \therefore \quad \phi_Y = 0$ and $\phi_X = -\phi_m$

$$\therefore \quad \phi_r = \sqrt{\phi_X^2 + \phi_Y^2} = \sqrt{(-\phi_m)^2 + (0)^2} = \phi_m$$

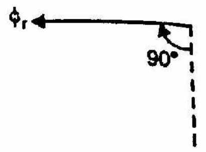


Fig.(9.12)

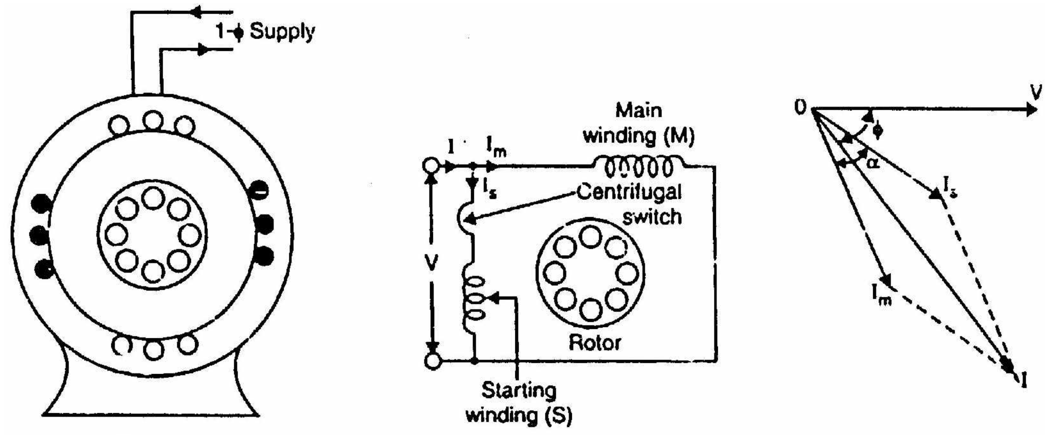
(vi) Diagrams 6, 7, and 8 [See Fig. (9.10 (iii))] indicate the direction of the resultant flux during the remaining successive instants.

It follows from the above discussion that a 2-phase supply produces a rotating magnetic field of constant value (= ϕ_m the maximum value of one of the fields).

Note: If the two windings arc displaced 90° electrical but produce fields that are not equal and that are not 90° apart in time, the resultant field is still rotating but is not constant in magnitude. One effect of this nonuniform rotating field is the production of a torque that is non-uniform and that, therefore, causes noisy operation of the motor. Since 2-phase operation ceases once the motor is started, the operation of the motor then becomes smooth.

9.6 Split-Phase Induction Motor

The stator of a split-phase induction motor is provided with an auxiliary or starting winding S in addition to the main or running winding M. The starting winding is located 90° electrical from the main winding [See Fig. (9.13 (i))] and operates only during the brief period when the motor starts up. The two windings are so resigned that the starting winding S has a high resistance and relatively small reactance while the main winding M has relatively low resistance and large reactance as shown in the schematic connections in Fig. (9.13 (ii)). Consequently, the currents flowing in the two windings have reasonable phase difference c (25° to 30°) as shown in the phasor diagram in Fig. (9.13 (iii)).



(i) (ii) (iii)

Fig.(9.13)

Operation

(i) When the two stator windings are energized from a single-phase supply, the main winding carries current I_m while the starting winding carries current I_s.

(ii) Since main winding is made highly inductive while the starting winding highly resistive, the currents I_m and I_s have a reasonable phase angle a (25° to 30°) between them as shown in Fig. (9.13 (iii)). Consequently, a weak revolving field approximating to that of a 2-phase machine is produced which starts the motor. The starting torque is given by;

$$T_s = kI_m I_s \sin\alpha$$

where k is a constant whose magnitude depends upon the design of the motor.

(iii) When the motor reaches about 75% of synchronous speed, the centrifugal switch opens the circuit of the starting winding. The motor then operates as a single-phase induction motor and continues to accelerate till it reaches the normal speed. The normal speed of the motor is below the synchronous speed and depends upon the load on the motor.

Characteristics

(i) The sinning torque is 15 to 2 times the full-loud torque mid (lie starting current is 6 to 8 times the full-load current.

(ii) Due to their low cost, split-phase induction motors are most popular single-phase motors in the market.

(iii) Since the starting winding is made of fine wire, the current density is high and the winding heats up quickly. If the starting period exceeds 5 seconds, the winding may burn out unless the motor is protected by built-in-thermal relay. This motor is, therefore, suitable where starting periods are not frequent.

(iv) An important characteristic of these motors is that they are essentially constant-speed motors. The speed variation is 2-5% from no-load to full-load.

(v) These motors are suitable where a moderate starting torque is required and where starting periods are infrequent e.g., to drive:
    (a) fans (b) washing machines (c) oil burners (d) small machine tools etc.

The power rating of such motors generally lies between 60 W and 250 W.

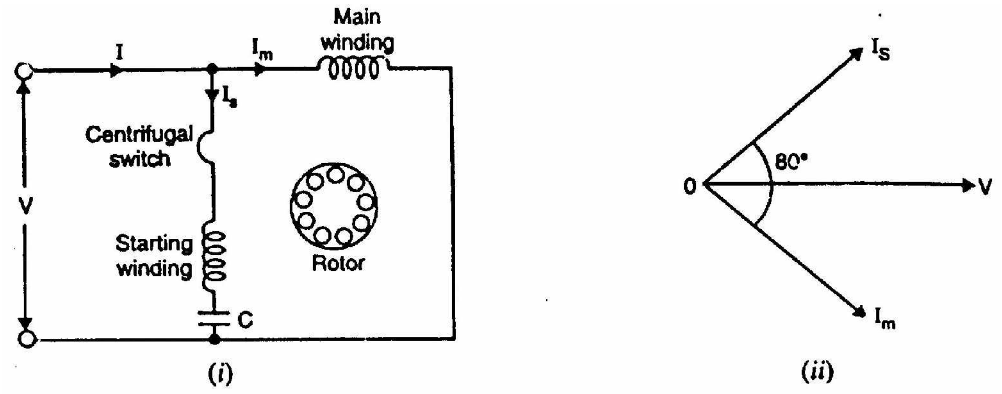
9.7 Capacitor-Start Motor

The capacitor-start motor is identical to a split-phase motor except that the starting winding has as many turns as the main winding. Moreover, a capacitor C is connected in series with the starting winding as shown in Fig. (9.14 (i)). The value of capacitor is so chosen that I_s leads I_m by about 80° (i.e., $\alpha \simeq 80°$) which is considerably greater than 25° found in split-phase motor [See Fig. (9.14 (ii))]. Consequently, starting torque ($T_s = k\, I_m\, I_s \sin \alpha$) is much more than that of a split-phase motor Again, the starting winding is opened by the centrifugal switch when the motor attains about 75% of synchronous speed. The motor then operates as a single-phase induction motor and continues to accelerate till it reaches the normal speed.

Characteristics

(i) Although starting characteristics of a capacitor-start motor are better than those of a split-phase motor, both machines possess the same running characteristics because the main windings are identical.

(ii) The phase angle between the two currents is about 80° compared to about 25° in a split-phase motor. Consequently, for the same starting torque, the current in the starting winding is only about half that in a split-phase motor. Therefore, the starting winding of a capacitor start motor heats up less quickly and is well suited to applications involving either frequent or prolonged starting periods.



(*i*) (*ii*)

Fig.(9.14)

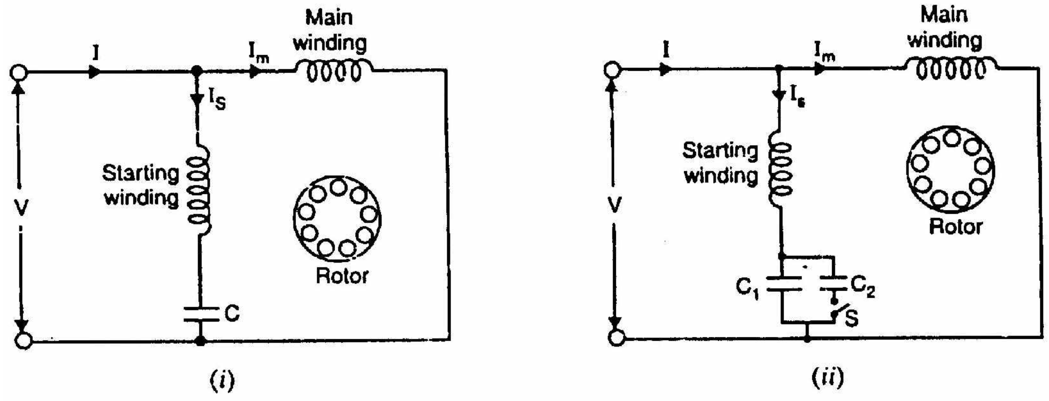
(iii) Capacitor-start motors are used where high starting torque is required and where the starting period may be long e.g., to drive:
  (a) compressors (b) large fans (c) pumps (d) high inertia loads

The power rating of such motors lies between 120 W and 7-5 kW.

9.8 Capacitor-Start Capacitor-Run Motor

This motor is identical to a capacitor-start motor except that starting winding is not opened after starting so that both the windings remain connected to the supply when running as well as at starting. Two designs are generally used.

(i) In one design, a single capacitor C is used for both starting and running as shown in Fig.(9.15 (i)). This design eliminates the need of a centrifugal switch and at the same time improves the power factor and efficiency of the motor.



(*i*) (*ii*)

Fig.(9.15)

(ii) In the other design, two capacitors C_1 and C_2 are used in the starting winding as shown in Fig. (9.15 (ii)). The smaller capacitor C_1 required for optimum running conditions is permanently connected in series with the starting winding. The much larger capacitor C_2 is connected in parallel with C_1 for optimum starting and remains in the circuit during starting. The starting capacitor C_1 is disconnected when the motor approaches about 75% of synchronous speed. The motor then runs as a single-phase induction motor.

Characteristics

(i) The starting winding and the capacitor can be designed for perfect 2-phase operation at any load. The motor then produces a constant torque and not a pulsating torque as in other single-phase motors.

(ii) Because of constant torque, the motor is vibration free and can be used in: (a) hospitals (6) studios and (c) other places where silence is important.

9.9 Shaded-Pole Motor

The shaded-pole motor is very popular for ratings below 0.05 H.P. ($\simeq$ 40 W) because of its extremely simple construction. It has salient poles on the stator excited by single-phase supply and a squirrel-cage rotor as shown in Fig. (9.16). A portion of each pole is surrounded by a short-circuited turn of copper strip called shading coil.

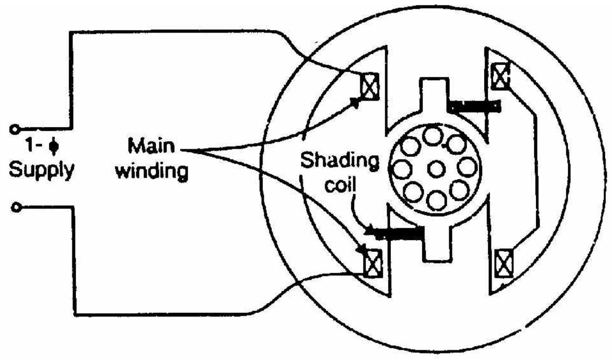


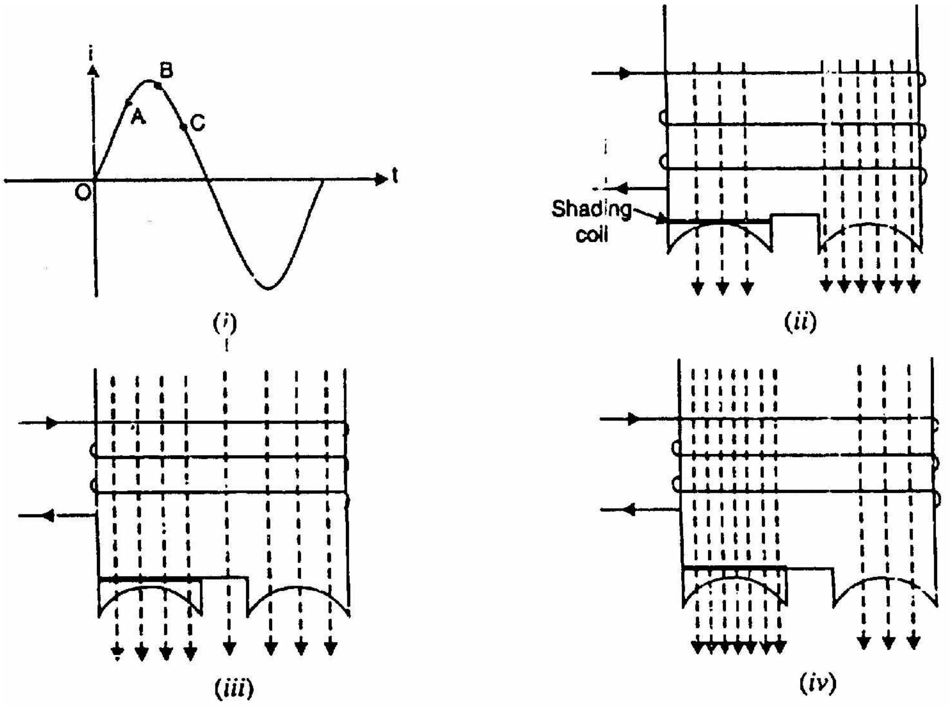
Fig.(9.16)

Operation

The operation of the motor can be understood by referring to Fig. (9.17) which shows one pole of the motor with a shading coil.

(i) During the portion OA of the alternating-current cycle [See Fig. (9.17)], the flux begins to increase and an e.m.f. is induced in the shading coil. The resulting current in the shading coil will be in such a direction (Lenz's law) so as to oppose the change in flux. Thus the flux in the shaded portion of the pole is weakened while that in the unshaded portion is strengthened as shown in Fig. (9.17 (ii)).

(ii) During the portion AB of the alternating-current cycle, the flux has reached almost maximum value and is not changing. Consequently, the flux distribution across the pole is uniform [See Fig. (9.17 (iii))] since no current is flowing in the shading coil. As the flux decreases (portion BC of the alternating current cycle), current is induced in the shading coil so as to oppose the decrease in current. Thus the flux in the shaded portion of the pole is strengthened while that in the unshaded portion is weakened as shown in Fig. (9.17 (iv)).



(i) (ii) (iii) (iv)

Fig.(9.17)

(iii) The effect of the shading coil is to cause the field flux to shift across the pole face from the unshaded to the shaded portion. This shifting flux is like a rotating weak field moving in the direction from unshaded portion to the shaded portion of the pole.

(iv) The rotor is of the squirrel-cage type and is under the influence of this moving field. Consequently, a small starting torque is developed. As soon as this torque starts to revolve the rotor, additional torque is produced by single-phase induction-motor action. The motor accelerates to a speed slightly below the synchronous speed and runs as a single-phase induction motor.

Characteristics

(i) The salient features of this motor are extremely simple construction and absence of centrifugal switch.

(ii) Since starting torque, efficiency and power factor are very low, these motors are only suitable for low power applications e.g., to drive:
    (a) small fans (6) toys (c) hair driers (d) desk fans etc.

The power rating of such motors is upto about 30 W.

9.10 Equivalent Circuit of Single-Phase Induction Motor

It was stated earlier that when the stator of a single-phase induction motor is con heeled to single-phase supply, the stator current produces a pulsating flux that is equivalent to two-constant-amplitude fluxes revolving in opposite directions at the synchronous speed (double-field revolving theory). Each of these fluxes induces currents in the rotor circuit and produces induction motor action similar to that in a 3-phase induction motor Therefore, a single-phase induction motor can to imagined to be consisting of two motors, having a common stator winding but with their respective rotors revolving in opposite directions. Each rotor has resistance and reactance half the actual rotor values.

Let R_1 = resistance of stator winding
X_1 = leakage reactance of stator winding
X_m = total magnetizing reactance
R'_2 = resistance of the rotor referred to the stator
X'_2 = leakage reactance of the rotor referred to the stator

revolving theory.

(i) **At standstill**. At standstill, the motor is simply a transformer with its secondary short-circuited. Therefore, the equivalent circuit of single-phase motor at standstill will be as shown in Fig. (9.18). The double-field revolving theory suggests that characteristics associated with each revolving field will be just one-half of the characteristics associated with the actual total flux. Therefore, each rotor has resistance and reactance equal to $R'_2/2$ and $X'_2/2$ respectively. Each rotor is associated with half the

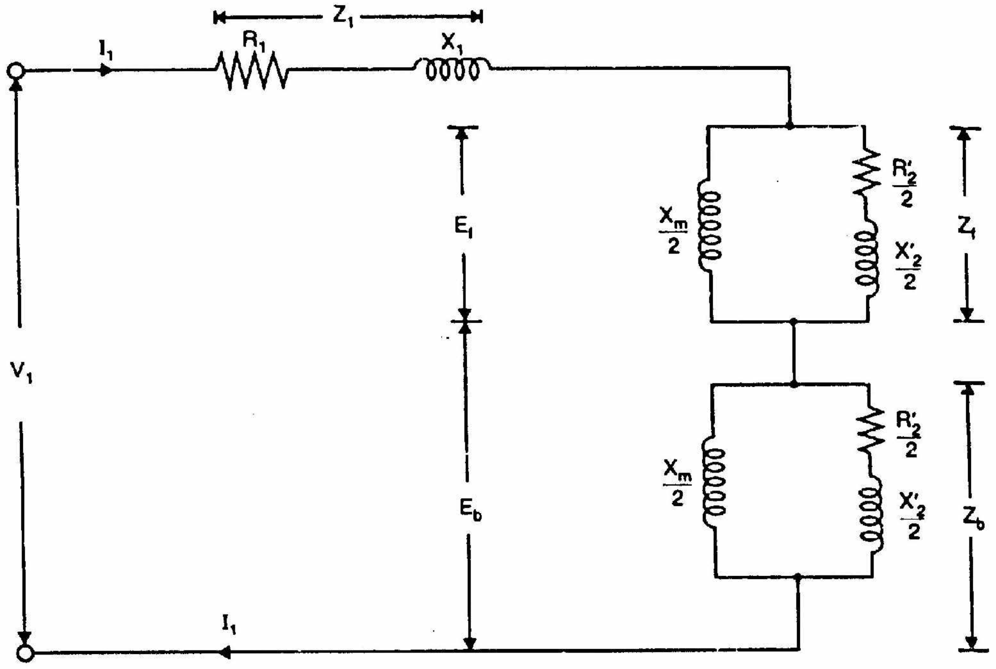


Fig.(9.18)

total magnetizing reactance. Note that in the equivalent circuit, the core loss has been neglected. However, core loss can be represented by an equivalent resistance in parallel with the magnetizing reactance.

Now $E_f = 4.44\ f\ N\ \phi_f$; $E_b = 4.44\ f\ N\ \phi_b$

At standstill, $\phi_f = \phi_b$. Therefore, $E_f = E_b$.

$$V_1 \simeq E_f + E_b = I_1Z_f + I_1Z_b$$

where Z_f = impedance of forward parallel branch
Z_b = impedance of backward parallel branch

(ii) **Rotor running**. Now consider that the motor is pinning at some speed in the direction of the forward revolving field, the slip being s. The rotor current produced by the forward field will have a frequency sf where f is the stator frequency. Also, the rotor current produced by the backward field will have a frequency of (2 – s)f. Fig. (9.19) shows the equivalent circuit of a single-phase induction motor when the rotor is rotating at slip s. It is clear, from the equivalent circuit that under running conditions, E_f becomes much greater than E_b because the term $R'_2/2s$ increases very much as s tends towards zero. Conversely, E^ falls because the term $R'_2/2(2 - s)$ decreases since (2 – s) tends toward 2. Consequently, the forward field increases, increasing the driving torque while the backward field decreases reducing the opposing torque.

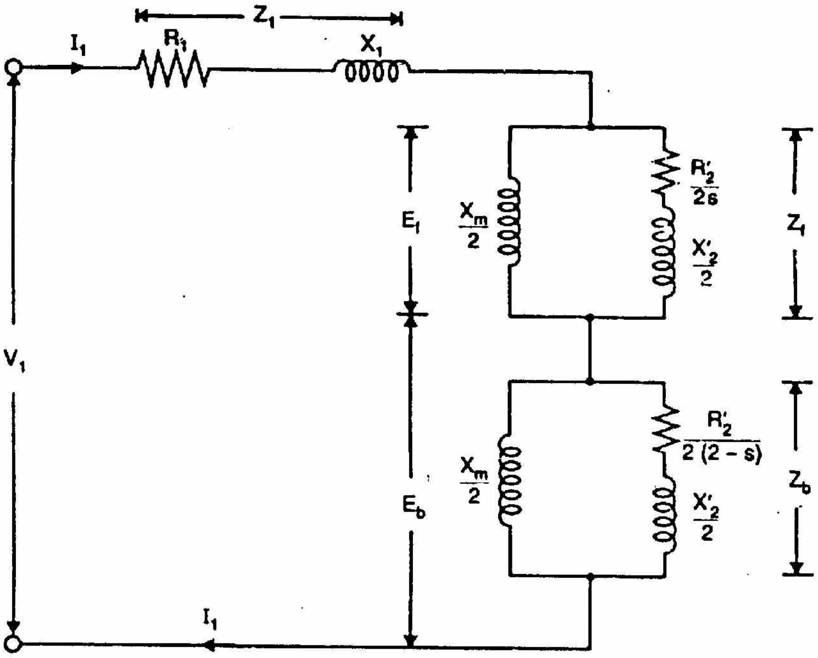


Fig.(9.19)

Total impedance of the circuit .is given by;

$$Z_r = Z_1 + Z_f + Z_b$$

where $Z_1 = R_1 + j\,X_1$

$$Z_f = \frac{j\frac{X_m}{2}\left(\frac{R'_2}{2s} + j\frac{X'_2}{2}\right)}{\frac{R'_2}{2s} + j\left(\frac{X_m}{2} + \frac{X'_2}{2}\right)}$$

$$Z_b = \frac{j\frac{X_m}{2}\left(\frac{R'_2}{2(2-s)} + j\frac{X'_2}{2}\right)}{\frac{R'_2}{2(2-s)} + j\left(\frac{X_m}{2} + \frac{X'_2}{2}\right)}$$

$$\therefore \quad I_1 = V_1 / Z_r$$

9.11 A.C. Series Motor or Universal Motor

A d.c. series motor will rotate in the same direction regardless of the polarity of the supply. One can expect that a d.c. series motor would also operate on a single-phase supply. It is then called an a.c. series motor. However, some changes must be made in a d.c. motor that is to operate satisfactorily on a.c. supply. The changes effected are:

(i) The entire magnetic circuit is laminated in order to reduce the eddy current loss. Hence an a.c. series motor requires a more expensive construction than a d.c. series motor.

(ii) The series field winding uses as few turns as possible to reduce the reactance of the field winding to a minimum. This reduces the voltage drop across the field winding.

(iii) A high field flux is obtained by using a low-reluctance magnetic circuit.

(iv) There is considerable sparking between the brushes and the commutator when the motor is used on a.c. supply. It is because the alternating flux establishes high currents in the coils short-circuited by the brushes. When the short-circuited coils break contact from the commutator, excessive sparking is produced. This can be eliminated by using high-resistance leads to connect the coils to the commutator segments.

Construction

The construction of en a.c. series motor is very similar to a d.c. series motor except that above modifications are incorporated [See Fig. (9.20)]. Such a motor can be operated either on a.c. or d.c. supply and the resulting torque-speed curve is about the same in each case. For this reason, it is sometimes called a universal motor.

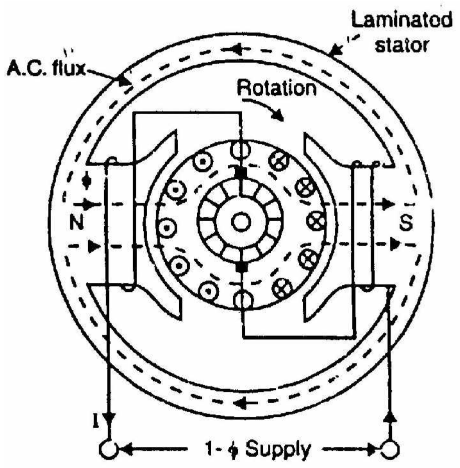


Fig.(9.20)

Operation

When the motor is connected to an a.c. supply, the same alternating current flows through the field and armature windings. The field winding produces an alternating flux ϕ that reacts with the current flowing in the armature to produce a torque. Since both armature current and flux reverse simultaneously, the torque always acts in the same direction. It may be noted that no rotating flux is produced in this type of machines; the principle of operation is the same as that of a d.c. series motor.

Characteristics

The operating characteristics of an a.c. series motor are similar to those of a d.c. series motor.

(i) The speed increases to a high value with a decrease in load. In very small series motors, the losses are usually large enough at no load that limit the speed to a definite value (1500 - 15,000 r.p.m.).

(ii) The motor torque is high for large armature currents, thus giving a high starting torque.

(iii) At full-load, the power factor is about 90%. However, at starting or when carrying an overload, the power factor is lower.

Applications

The fractional horsepower a.c. series motors have high-speed (and corresponding small size) and large starting torque. They can, therefore, be used to drive:

(a) high-speed vacuum cleaners
(b) sewing machines
(c) electric shavers
(d) drills
(e) machine tools etc.

9.12 Single-Phase Repulsion Motor

A repulsion motor is similar to an a.c. series motor except that:

(i) brushes are not connected to supply but are short-circuited [See Fig. (9.21)]. Consequently, currents are induced in the armature conductors by transformer action.

(ii) the field structure has non-salient pole construction.

By adjusting the position of short-circuited brushes on the commutator, the starting torque can be developed in the motor.

Construction

The field of stator winding is wound like the main winding of a split-phase motor and is connected directly to a single-phase source. The armature or rotor is similar to a d.c. motor armature with drum type winding connected to a commutator (not shown in the figure). However, the brushes are not connected to supply but are connected to each other or short-circuited. Short-circuiting the brushes effectively makes the rotor into a type of squirrel cage. The major difficulty with an ordinary single-phase induction motor is the low starting torque. By using a commutator motor with brushes short-circuited, it is possible to vary the starting torque by changing the brush axis. It has also better power factor than the conventional single-phase motor.

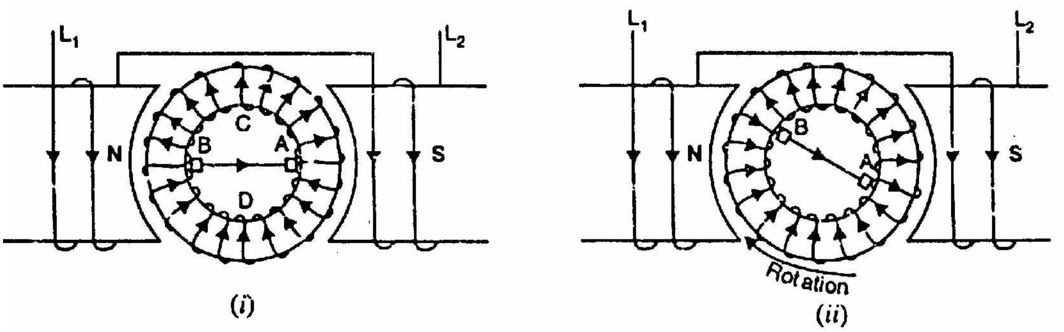


Fig.(9.21)

Principle of operation

The principle of operation is illustrated in Fig. (9.21) which shows a two-pole repulsion motor with its two short-circuited brushes. The two drawings of Fig. (9.21) represent a time at which the field current is increasing in the direction shown so that the left-hand pole is N-pole and the right-hand pole is S-pole at the instant shown.

(i) In Fig. (9.21 (i)), the brush axis is parallel to the stator field. When the stator winding is energized from single-phase supply, e.m.f. is induced in the armature conductors (rotor) by induction. By Lenz's law, the direction of the e.m.f. is such that the magnetic effect of the resulting armature currents will oppose the increase in flux. The direction of current in armature conductors will be as shown in Fig. (9.21 (i)). With the brush axis in the position shown in Fig. (9.21 (i)), current will flow from brush B to brush A where it enters the armature and flows back to brush B through the two paths ACB and ADB. With brushes set in this position, half of the armature conductors under the N-pole carry current inward and half carry current outward. The same is true under S-pole. Therefore, as much torque is developed in one direction as in the other and the armature remains stationary. The armature will also remain stationary if the brush axis is perpendicular to the stator field axis. It is because even then net torque is zero.

(ii) If the brush axis is at some angle other than 0° or 90° to the axis of the stator field, a net torque is developed on the rotor and the rotor accelerates to its final speed. Fig. (9.21 (ii)) represents the motor at the same instant as that in Fig. (9.21 (i)) but the brushes have been shifted clockwise through some angle from the stator field axis. Now e.m.f. is still induced in the direction indicated in Fig. (9.21 (i)) and current flows through the two paths of the armature winding from brush A to brush B. However, because of the new brush positions, the greater part of the conductors under the N-pole carry current in one direction while the greater part of conductors under S-pole carry current in the opposite direction. With brushes in the position shown in Fig. (9.21 (ii), torque is developed in the clockwise direction and the rotor quickly attains the final speed.

(iii) The direction of rotation of the rotor depends upon the direction in which the brushes are shifted. If the brushes are shifted in clockwise direction from the stator field axis, the net torque acts in the clockwise direction and the rotor accelerates in the clockwise direction. If the brushes are shifted in anti-clockwise direction as in Fig. (9.22). the armature current under the pole faces is reversed and the net torque is developed in the anti-clockwise direction. Thus a repulsion motor may be made to rotate in either direction depending upon the direction in which the brushes are shifted.

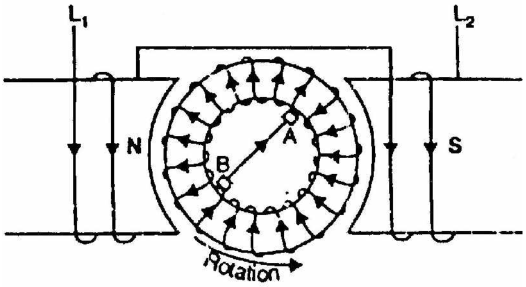


Fig.(9.22)

(iv) The total armature torque in a repulsion motor can be shown to be

$$T_a \propto \sin 2\alpha$$

where α = angle between brush axis and stator field axis
For maximum torque, $2\alpha = 90°$ or $\alpha = 45°$

Thus adjusting α to 45° at starting, maximum torque can be obtained during the starting period. However, α has to be adjusted to give a suitable running speed.

Characteristics

(i) The repulsion motor has characteristics very similar to those of an a.c. series motor i.e., it has a high starting torque and a high speed at no load.
(ii) The speed which the repulsion motor develops for any given load will depend upon the position of the brushes.
(iii) In comparison with other single-phase motors, the repulsion motor has a high starring torque and relatively low starting current.

9.13 Repulsion-Start Induction-Run Motor

Sometimes the action of a repulsion motor is combined with that of a single-phase induction motor to produce repulsion-start induction-run motor (also called repulsion-start motor). The machine is started as a repulsion motor with a corresponding high starting torque. At some predetermined speed, a centrifugal device short-circuits the commutator so that the machine then operates as a single-phase induction motor.

The repulsion-start induction-run motor has the same general construction of a repulsion motor. The only difference is that in addition to the basic repulsion-motor construction, it is equipped with a centrifugal device fitted on the armature shaft. When the motor reaches 75% of its full pinning speed, the centrifugal device forces a short-circuiting ring to come in contact with the inner surface of the commutator. This snort-circuits all the commutator bars. The rotor then resembles squirrel-cage type and the motor runs as a single-phase induction motor. At the same time, the centrifugal device raises the brushes from the commutator which reduces the wear of the brushes and commutator as well as makes the operation quiet.

Characteristics

(i) The starting torque is 2.5 to 4.5 times the full-load torque and the starting current is 3.75 times the full-load value.
(ii) Due to their high starting torque, repulsion-motors were used to operate devices such as refrigerators, pumps, compressors etc.

However, they posed a serious problem of maintenance of brushes, commutator arid the centrifugal device. Consequently, manufacturers have stopped making them in view of the development of capacitor motors which are small in size, reliable and low-priced.

9.14 Repulsion-Induction Motor

The repulsion-induction motor produces a high starting torque entirely due to repulsion motor action. When running, it functions through a combination of induction-motor and repulsion motor action.

Construction

Fig. (9.23) shows the connections of a 4-pole repulsion-induction motor for 230 V operation. It consists of a stator and a rotor (or armature).

(i) The stator carries a single distributed winding fed from single-phase supply.

(ii) The rotor is provided with two independent windings placed one inside the other. The inner winding is a squirrel-cage winding with rotor bars permanently short-circuited. Placed over the squirrel cage winding is a repulsion commutator armature winding. The repulsion winding is connected to a commutator on which ride short-circuited brushes. There is no centrifugal device and the repulsion winding functions at all times.

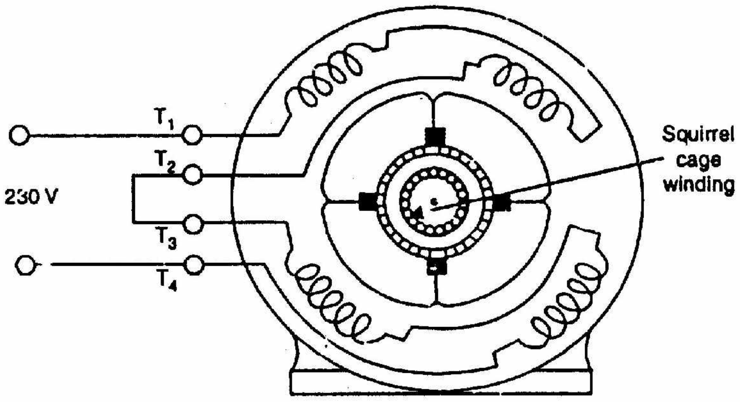


Fig.(9.23)

Operation

(i) When single-phase supply is given to the stator winding, the repulsion winding (i.e., outer winding) is active. Consequently, the motor starts as a repulsion motor with a corresponding high starting torque.

(ii) As the motor speed increases, the current shifts from the outer to inner winding due to the decreasing impedance of the inner winding with increasing speed. Consequently, at running speed, the squirrel cage winding carries the greater part of rotor current. This shifting of repulsion-motor action to induction-motor action is thus achieved without any switching arrangement.

(iii) It may be seen that the motor starts as a repulsion motor. When running, it functions through a combination of principle of induction and repulsion; the former being predominant.

Characteristics

(i) The no-load speed of a repulsion-induction motor is somewhat above the synchronous speed because of the effect of repulsion winding. However, the speed at full-load is slightly less than the synchronous speed as in an induction motor.

(ii) The speed regulation of the motor is about 6%.

(iii) The starting torque is 2.25 to 3 times the full-load torque; the lower value being for large motors. The starting current is 3 to 4 times the full-load current.

This type of motor is used for applications requiring a high starting torque with essentially a constant running speed. The common sizes are 0.25 to 5 H.P.

9.15 Single-Phase Synchronous Motors

Very small single-phase motors have been developed which run at true synchronous speed. They do not require d.c. excitation for the rotor. Because of these characteristics, they are called unexcited single-phase synchronous motors. The most commonly used types are:

(i) Reluctance motors (ii) Hysteresis motors

The efficiency and torque-developing ability of these motors is low; The output of most of the commercial motors is only a few watts.

9.16 Reluctance Motor

It is a single-phase synchronous motor which does not require d.c. excitation to the rotor. Its operation is based upon the following principle:

Whenever a piece of ferromagnetic material is located in a magnetic field; a force is exerted on the material, tending to align the material so that reluctance of the magnetic path that passes through the material is minimum.

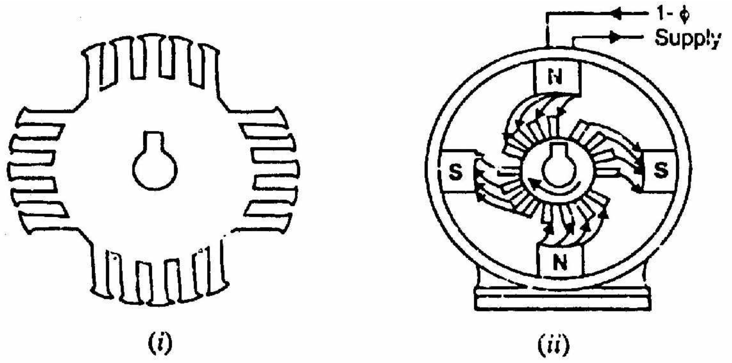


Fig.(9.24)

Construction

A reluctance motor (also called synchronous reluctance motor) consists of:

(i) **a stator** carrying a single-phase winding along with an auxiliary winding to produce a synchronous-revolving magnetic field.

(ii) **a squirrel-cage rotor** having unsymmetrical magnetic construction. This is achieved by symmetrically removing some of the teeth from the squirrel-cage rotor to produce salient poles on the rotor. As shown in Fig. (9.24 (i)), 4 sailent poles have been produced on me rotor. The salient poles created on the rotor must be equal to the poles on the stator.

Note that rotor salient poles offer low reductance to the stator flux and, therefore, become strongly magnetized.

Operation

(i) When single-phase stator having an auxiliary winding is energized, a synchronously-revolving field is produced. The motor starts as a standard squirrel-cage induction motor and will accelerate to near its synchronous speed.

(ii) As the rotor approaches synchronous speed, the rotating stator flux will exert reluctance torque on the rotor poles tending to align the salient-pole axis with the axis of the rotating field. The rotor assumes a position where its salient poles lock with the poles of the revolving field [See Fig. (9.24 (ii))]. Consequently, the motor will continue to run at the speed of revolving flux i.e., at the synchronous speed.

(iii) When we apply a mechanical load, the rotor poles fall slightly behind the stator poles, while continuing to turn at synchronous speed. As the load on the motor is increased, the mechanical angle between the poles increases progressively. Nevertheless, magnetic attraction keeps the rotor locked to the rotating flux. If the load is increased beyond the amount under which the reluctance torque can maintain synchronous speed, the rotor drops out of step with the revolving field. The speed, then, drops to some value at which the slip is sufficient to develop the necessary torque to drive the load by induction-motor action.

Characteristics

(i) These motors have poor torque, power factor and efficiency.
(ii) These motors cannot accelerate high-inertia loads to synchronous speed.
(iii) The pull-in and pull-out torques of such motors are weak.

Despite the above drawbacks, the reluctance motor is cheaper than any other type of synchronous motor. They are widely used for constant-speed applications such as timing devices, signalling devices etc.

9.17 Hysteresis Motor

It is a single-phase motor whose operation depends upon the hysteresis effect i.e., magnetization produced in a ferromagnetic material lags behind the magnetizing force.

Construction It consists of:

(i) **a stator** designed to produce a synchronously-revolving field from a single-phase supply. This is accomplished by using permanent-split capacitor type construction. Consequently, both the windings (i.e., starting as well as main winding) remain connected in the circuit during running operation as well as at starting. The value of capacitance is so adjusted as to result in a flux revolving at synchronous speed.

(ii) **a rotor** consisting of a smooth cylinder of magnetically hard steel, without winding or teeth.

Operation

(i) When the stator is energized from a single-phase supply, a synchronously-revolving field (assumed in anti-clockwise direction) is produced due to split-phase operation.

(ii) The revolving stator flux magnetizes the rotor. Due to hysteresis effect, the axis of magnetization of rotor will lag behind the axis of stator field by hysteresis lag angle a as shown in Fig. (9.25). Thus the rotor and stator poles are locked. If the rotor is stationary, the starting torque produced is given by:

$$T_s \propto \phi_s \phi_r \sin\alpha$$

where ϕ_s = stator flux.
ϕ_r = rotor flux.

From now onwards, the rotor accelerates to synchronous speed with a uniform torque.

(iii) After reaching synchronism, the motor continues to run at synchronous speed and adjusts its torque angle so as to develop the torque required by the load.

Characteristics

(i) A hysteresis motor can synchronize any load which it can accelerate, no matter how great the inertia. It is because the torque is uniform from standstill to synchronous speed.

(ii) Since the rotor has no teeth or salient poles or winding, a hysteresis motor is inherently quiet and produces smooth rotation of the load.

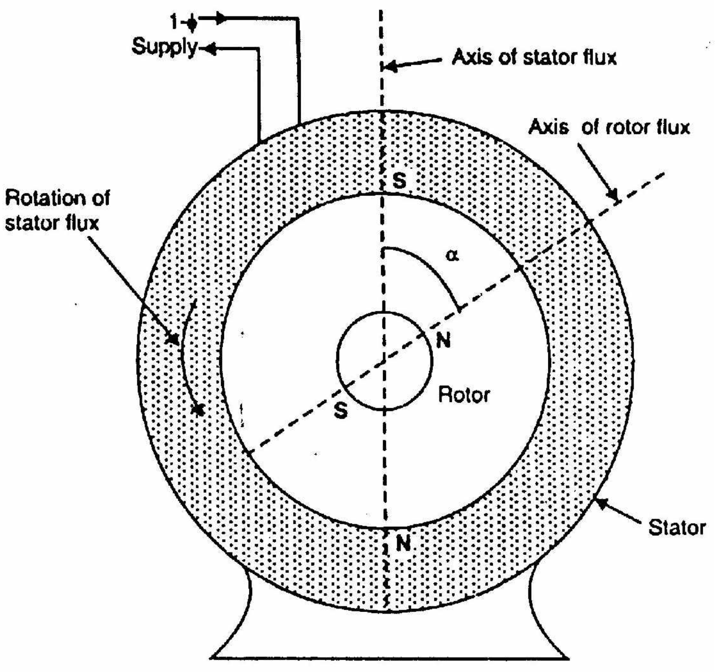


Fig.(9.25)

(iii) The rotor takes on the same number of poles as the stator field. Thus by changing the number of stator poles through pole-changing connections, we can get a set of synchronous speeds for the motor.

Applications

Due to their quiet operation and ability to drive high-inertia toads, hysteresis motors are particularly well suited for driving (i) electric clocks (ii) timing devices (iii) tape-decks (iv)from-tables and other precision audio-equipment.