Introduction to Electrical Circuits

Final Term
Week: 12

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Reference Book:

[1] Principles of Electrical Machines -V.K. Mehta, Rohit Mehta

[2] A Textbook of Electrical Technology , Volume- II, - B.L. Theraja, A.K. Theraja

Introduction to Induction Motor

Induction motor: General Principle

- Conversion of electrical power into mechanical power takes place in the ***rotating*** part of an electrical motor.
- In D.C. motors, the electric power is ***conducted*** directly to the armature (i.e. rotating part through brushes and commutator. Hence, D.C. motor can be called ***conduction*** motor.
- In A.C. motors, the rotor does not receive electric power by conduction but by ***induction*** in exactly the same way as the secondary of a 2-winding transformer receives its power from the primary.
- Hence, A.C. motors are known as ***Induction Motors***. It can be treated as ***rotating transformer*** i.e. one in which the primary winding is stationary but the secondary is free to rotate.

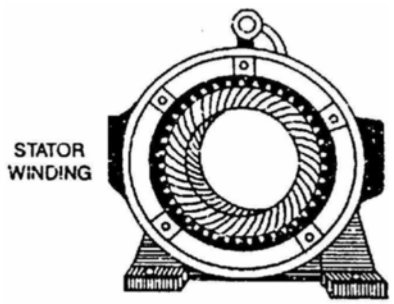


Fig: Stator

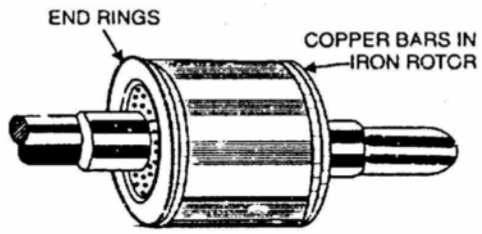


Fig: Squirrel cage rotor

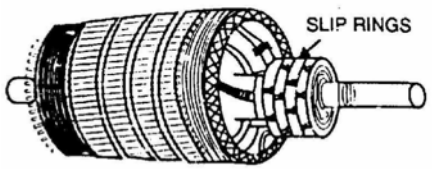


Fig: Wound rotor

A 3-phase induction motor has two main parts -

(i) Stator

(ii) Rotor

The rotor is separated from the stator by a small air-gap which ranges from 0.4 mm to 4 mm, depending on the power of the motor.

Single-Phase Motor

- The single-phase motor, designed to operate from a single-phase supply, are generally built in the ***fractional-horsepower range*** to perform a wide variety of useful services in home, offices, factories, workshops and in a business establishments etc.
- Single-phase motors 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

Single-Phase Induction Motor

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.

- A single-phase motor is not ***self-starting***.
- This type of motor inherently does 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, it will continue to run in the direction of rotation and quickly accelerates until it reaches a speed slightly below the synchronous speed.
- This strange behavior of the single phase motor can be explained in two ways:
  (i) by double-field revolving theory, and
  (ii) by cross-field theory.

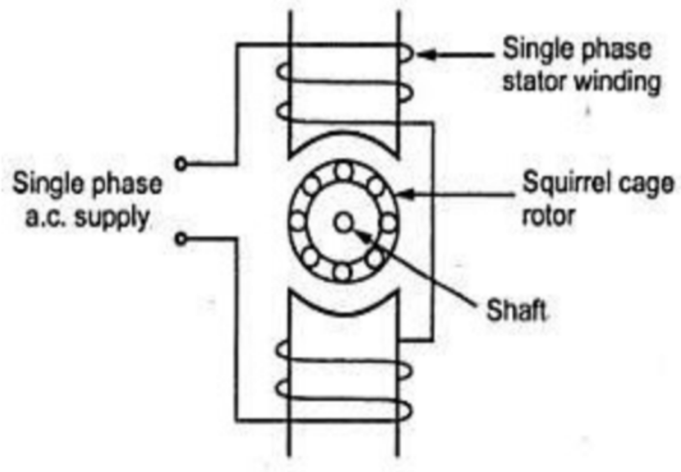


Fig: Single-phase induction motor

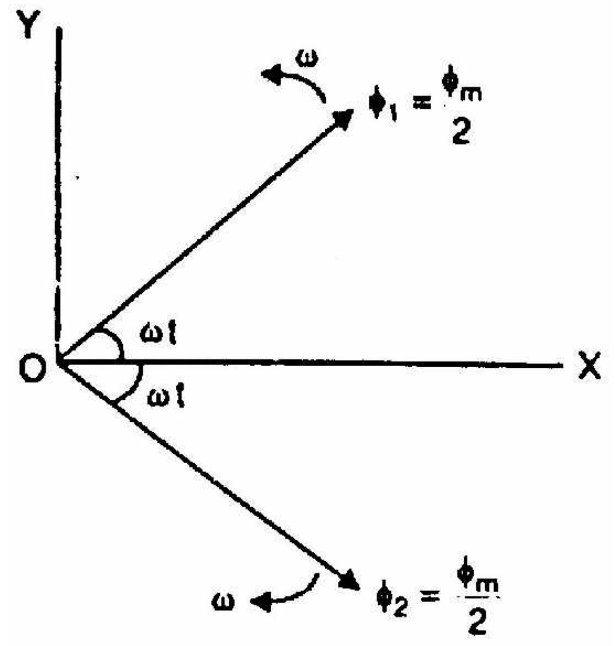
Double-Field Revolving Theory

This theory based on the fact that the **alternating sinusoidal flux ($\Phi = \Phi_m \cos \omega t$)** produced by the stator winding 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 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, each be equal to $\Phi_m/2$ start revolving from OX axis at t = 0 in anti-clockwise and clockwise directions respectively, with angular velocity ω.

Double-Field Revolving Theory

- After time t seconds, the angle through which the flux vectors have rotated is $\boldsymbol{\theta = \omega t}$. Resolving the flux vectors along-X-axis and Y-axis, we have,

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

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

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

- When the rotating flux vectors are in phase the resultant vector is $\phi = \phi_m$; when out of phase by 180°, the resultant vector $\phi = 0$ [Fig.-2].

- At standstill, two torques produced by opposite revolving fluxes are equal and opposite and the net torque developed is zero. Therefore, single-phase induction motor is not self-starting [Fig.-3].

- 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.-3].

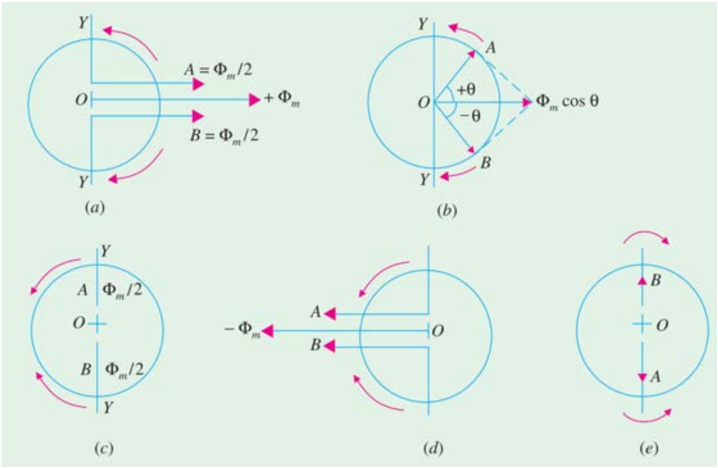


Fig. 1

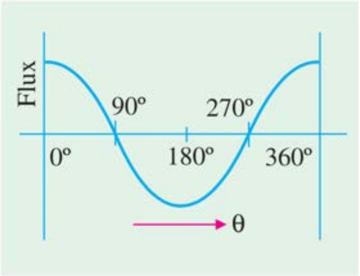


Fig. 2

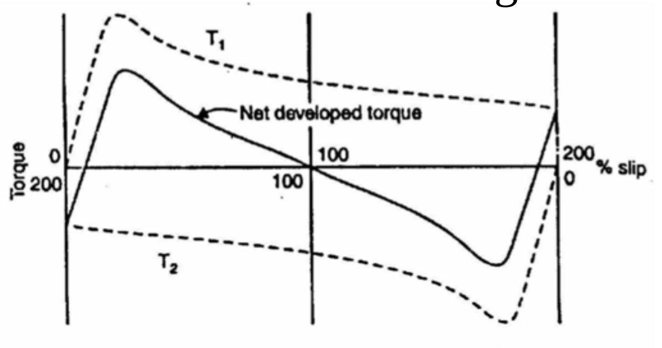


Fig. 3

Cross-Field Theory

- The quadrature pulsating rotor field reacts against the pulsating main field to produce a resultant magnetic field. The resultant magnetic field is a fairly constant rotating magnetic field that rotates in the same direction as the direction of the rotation of the rotor.

- A squirrel- cage induction motor will continue to rotate, producing induction motor torque in a rotating magnetic field, once a rotational emf has been initiated.

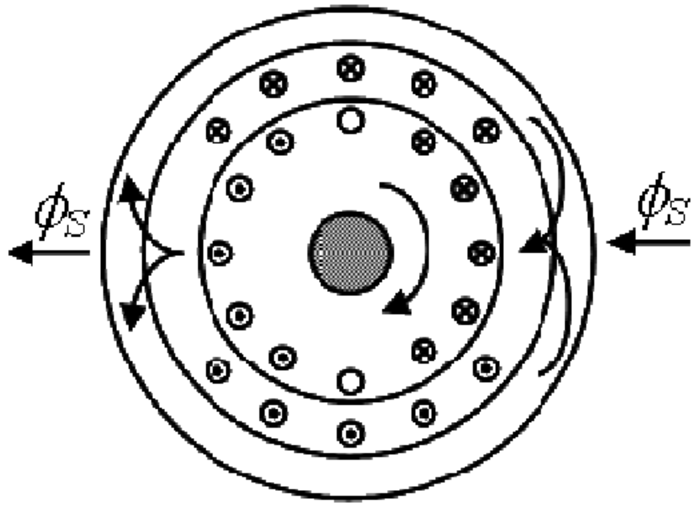


Fig: Stator field Φ_s sets up flux along horizontal axis; rotor rotating in clockwise direction

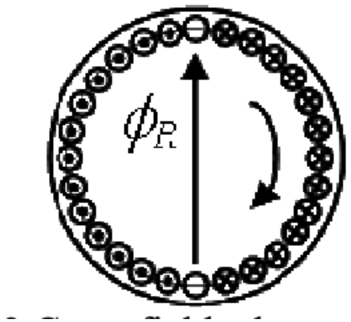


Fig: Cross field when stator field is zero.

Making Single-Phase Induction Motor Self-Starting

- To make a single-phase induction motor self-starting, phase splitting is done by temporarily converting a two-phase motor during the starting period.
- The stator is provided with an extra ***starting (auxiliary)*** winding, in addition to the ***main*** (***running***) winding.
- The two windings are spaced ***90° electrically apart*** and are connected in parallel across the single-phase supply.
- When the motor attains sufficient speed, the starting (auxiliary) winding may be removed depending upon the type of the motor.
- There are many methods by which the necessary phase-difference between the two currents can be created.
  (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.

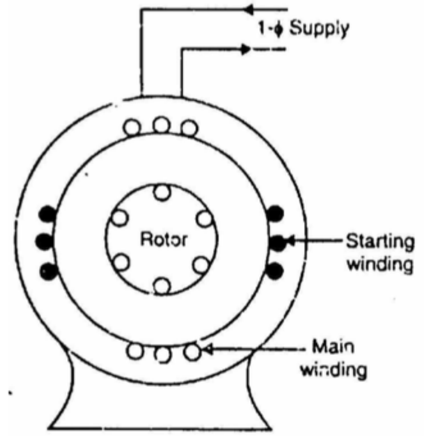
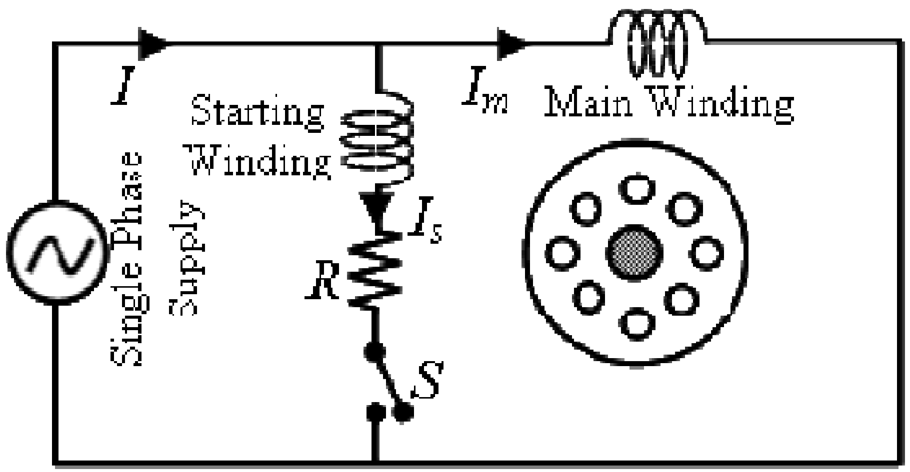


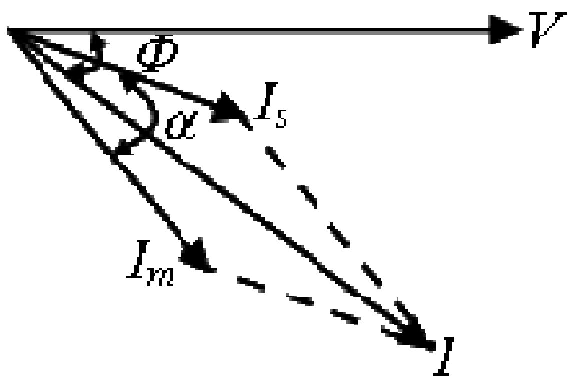
Fig: Auxiliary winding in stator to make 1-Φ motor self starting

Split-Phase Induction Motors

The single-phase induction motor is equipped with an auxiliary winding in addition to the main winding. The starting winding is connected in parallel with the main running winding.



(a)

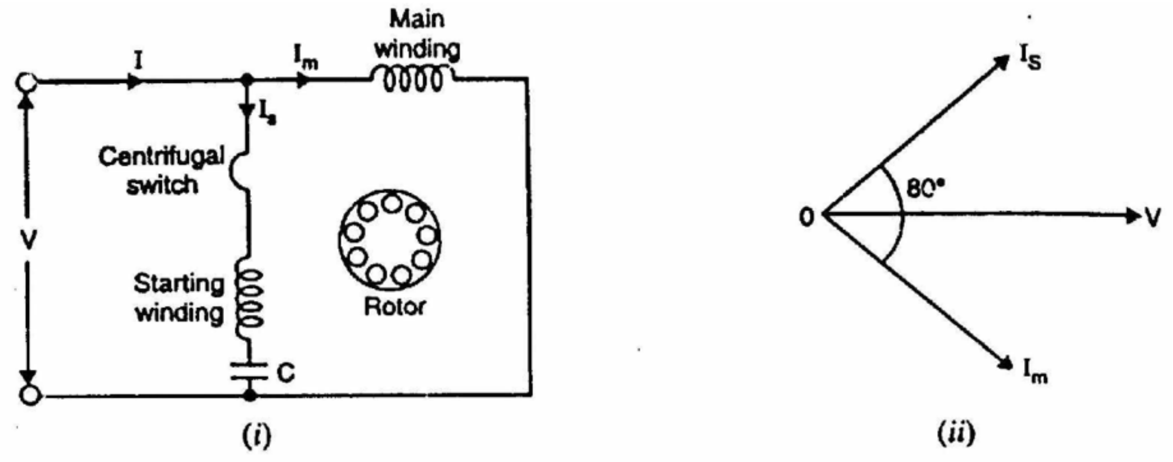


(b)

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

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.



- 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.
- The phase angle between the two currents is about 80° compared to about 25° in a split-phase motor.
- 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.
- 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**.

Difference between capacitor start and capacitor run motor

- Capacitor-run motor is identical to a capacitor-start motor except that starting (auxiliary) winding is not opened after starting so that both the windings remain connected to the supply when running as well as at starting.
- In Capacitor-run motor, a single capacitor C is used for both starting and running. This design eliminates the need of a centrifugal switch and at the same time improves the power factor and efficiency of the motor.
- In the other motor, two capacitors C_1 and C_2 are used in the starting winding. 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_2 is disconnected when the motor approaches about 75% of synchronous speed. The motor then runs as a single-phase induction motor.
- Because of the capacitor-run motor produces a constant torque, it is vibration free and can be used in: (a) hospitals (b) studios and (c) other places where silence is important.

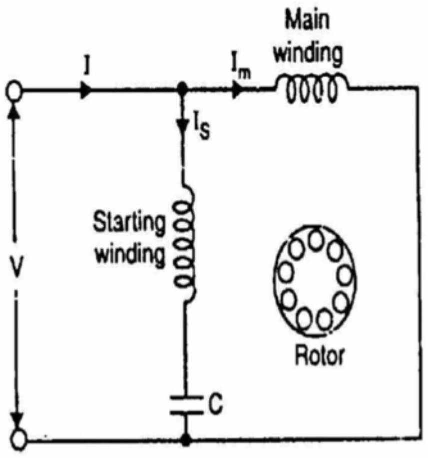


Fig: Capacitor Run Motor

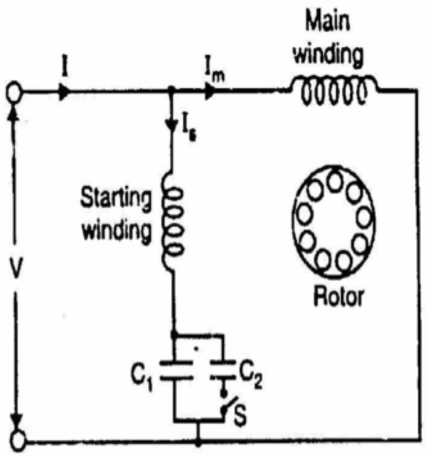
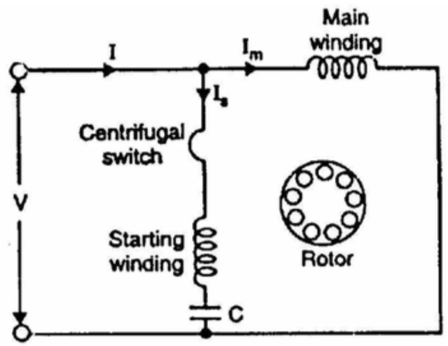


Fig: Capacitor Start Motor

Example Problems

Problem [6.1]: The impedance of the main and auxiliary windings of a 50 Hz single-phase induction motor are $Z_m = (3+j3)\ \Omega$ and $Z_a = (6+j3)\ \Omega$ respectively. What will be the value of the capacitor to be connected in series with auxiliary winding to achieve a phase difference of 90^o between the currents of the two windings?

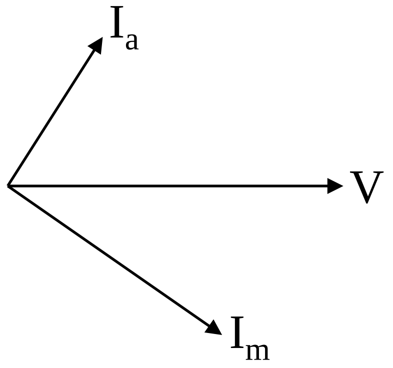
$$I_m = \frac{V\angle 0}{3+j3} = \frac{V\angle 0}{4.24\angle 45°} = \frac{V\angle -45°}{4.24} \qquad I_a = \frac{V\angle 0}{6+j3} = \frac{V\angle 0}{6.7\angle 26.5°} = \frac{V\angle -26.5°}{6.7}$$



The current flowing through the auxiliary winding after connecting a capacitor C in series should make an angle 90^o with I_m or make an angle 90^o-45^o = 45^o with the applied voltage V.
Since the new current of auxiliary winding should be leading the voltage V by an angle of 45^o, the capacitive reactance of the auxiliary circuit is greater than the inductive reactance. Thus

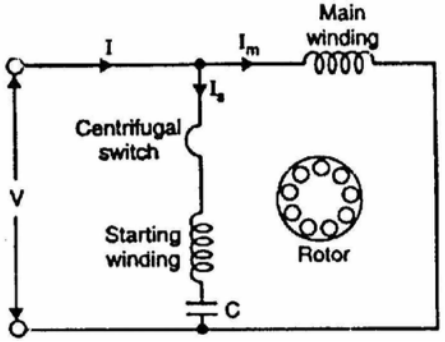
$$\tan 45° = \frac{X_C - X_L}{R} \qquad 1 = \frac{(1/\omega C) - 3}{6} \qquad (1/\omega C) - 3 = 6 \qquad (1/\omega C) = 9$$

$$\omega C = 1/9; \qquad C = 1/9\omega \qquad C = 353.6\ \mu F$$



Example Problems

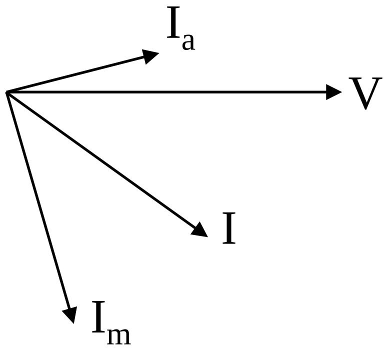
Problem [6.2]: A 50 Hz Capacitor-Start induction motor has a resistance 5 Ω and an inductive reactance 20 Ω in both main and auxiliary winding. Determine the value of resistance and capacitance to be added in series with auxiliary winding to send the same current in each winding with a phase difference of 90°.



$$Z = 5 + j20 = 20.6\angle 76^\circ$$

$$I_m = I_a = \frac{V\angle 0}{5 + j20} = \frac{V\angle 0}{20.6\angle 76^\circ} = \frac{V\angle -76^\circ}{20.6}$$

The current flowing through the auxiliary winding after connecting resistor R and a capacitor C in series should make an angle 90° with I_m or make an angle 90°-76° =14° with the applied voltage V. Since the new current of auxiliary winding should be leading the voltage V by an angle of 14°, the capacitive reactance of the auxiliary circuit is greater than the inductive reactance. Thus



$$\cos 14^\circ = \frac{5 + R}{Z}; \qquad 5 + R = Z\cos 14^\circ; \qquad R = 20.6\cos 14^\circ - 5 = 19.99 - 5 = 14.99 \ \ \Omega$$

$$\text{Again } \sin 14^\circ = \frac{X_C - X_L}{Z}; \qquad X_C - X_L = Z\sin 14^\circ; \qquad X_C = 20.6\sin 14^\circ + X_L$$

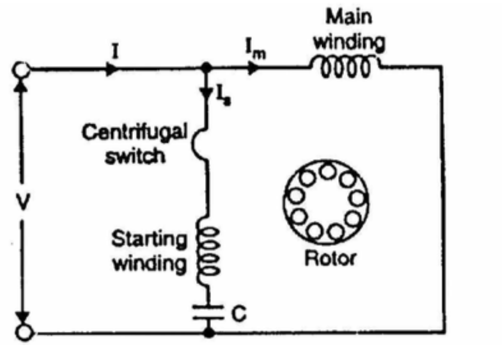
$$X_C = 20.6\sin 14^\circ + 20 = 24.98 \ \ \Omega$$

$$(1/\omega C) = 24.98 \qquad C = 127 \ \ \mu F$$

Example Problems

Example 36.3. A 250 W, 230 V, 50 Hz capacitor-start motor has the following constants for the main and auxiliary winding: Main winding, Z_m=(4.5+j3.7) ohm, Auxiliary winding, Z_a=(9.5+j3.5) ohm. Determine the value of the starting capacitor that will place the main and auxiliary winding currents in quadrature at starting.

Solution: Let X_C be the reactance of the capacitor connected in the auxiliary winding.



Then $\quad Z_a=9.5+j(3.5-X_C)=(9.5-jX)$ ohm

where, X is the net reactance

Now, $\quad Z_m=(4.5+j3.7)=5.82\angle 39.4^o$ ohm

Obviously, I_m lags behind V by 39.4°.

Since time phase angle between I_m and I_a has to be 90°,

I_a must lead V by (39.4°- 90°)=-50.6°.

For auxiliary winding,

$\tan\phi_a=(3.5-X_C)/R$

or $\tan(-50.6^o)=(3.5-X_C)/9.5=-1.217$

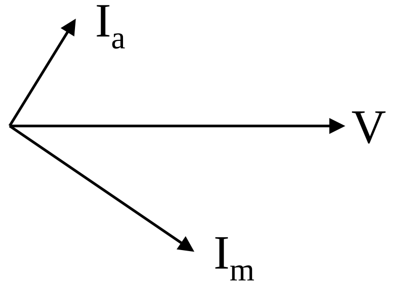
Or $(3.5-X_C)=-9.5\times1.217=-11.56$ ohm

$\therefore X_C=11.56+3.5=15.06$ ohm

Or $1/(2\times\pi\times50\times C)=15.06$

or $C=1/(2\times\pi\times50\times15.06)=211\times10^{-06}$ F

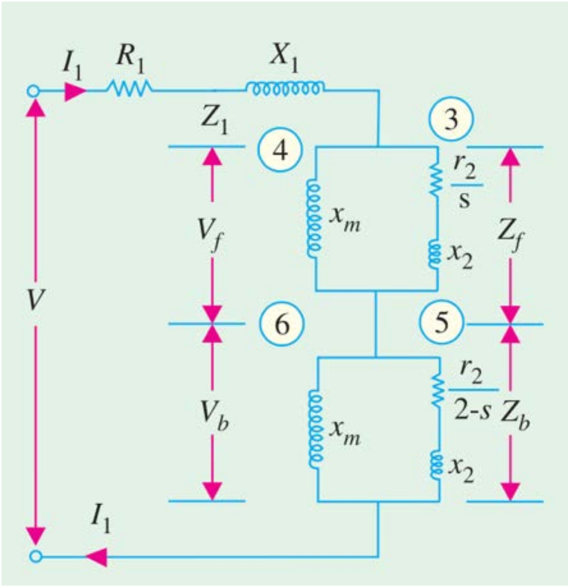
$\therefore C=211$ μF.



Example Problems

Example 36.1. Find the mechanical power output at a slip of 0.05 of the 185-W, 4-pole, 110-V, 60-Hz single-phase induction motor, whose constants are given below:

Resistance of the stator main winding	R_1 = 1.86 ohm
Reactance of the stator main winding	X_1 = 2.56 ohm
Magnetizing reactance of the stator main winding	X_m = 53.5 ohm
Rotor resistance at standstill	R_2 = 3.56 ohm
Rotor reactance at standstill	X_2 = 2.56 ohm



Solution. Here, $X_m = 53.5\ \Omega$, hence $x_m = 53.5/2 = 26.7\ \Omega$

Similarly, $r_2 = R_2/2 = 3.56/2 = 1.78\ \Omega$ and $x_2 = X_2/2 = 2.56/2 = 1.28\ \Omega$

$$\therefore \quad Z_f = \frac{j x_m \left(\frac{r_2}{s} + j x_2\right)}{\frac{r_2}{s} + j(x_2 + x_m)} = x_m \frac{\frac{r_2}{s} \cdot x_m + j\left[(r_2/s)^2 + x_2 x_0\right]}{(r_2/s)^2 + x_0^2} \quad \text{where } x_0 = (x_m + x_2)$$

$$\therefore \quad Z_f = 26.7 \frac{(1.78/0.05) \times 26.7 + j\,[(1.78/0.05)^2 + 1.28 \times 27.98]}{(1.78/0.05)^2 + (27.98)^2}$$

$$= 12.4 + j\,17.15 = 21.15 \angle 54.2^\circ$$

Similarly,
$$Z_b = \frac{j x_m \left(\frac{r_2}{2-s} + j x_2\right)}{\frac{r_2}{2-s} + j(x_2 + x_m)} = x_m \frac{\left(\frac{r_2}{2-s}\right) x_m + j\left[\left(\frac{r_2}{2-s}\right)^2 + x_0 x_2\right]}{\left(\frac{r_2}{2-s}\right)^2 + x_0^2}$$

$$= 26.7 \frac{(1.78/1.95) \times 26.7 + j\,[(1.78/1.95)^2 + 1.28 \times 27.98]}{(1.78/1.95)^2 + (27.98)^2}$$

$$= 0.84 + j\,1.26 = 1.51 \angle 56.3^\circ$$

$$\mathbf{Z_1} = R_1 + j X_1 = 1.86 + j\,2.56 = 3.16 \angle 54^\circ$$

Total circuit impedance is

$$\mathbf{Z_{01}} = \mathbf{Z_1} + \mathbf{Z_f} + \mathbf{Z_b} = (1.86 + j\,2.56) + (12.4 + j\,17.15) + (0.84 + j\,1.26)$$
$$= 15.1 + j\,20.97 = 25.85 \angle 54.3^\circ$$

Motor current $I_1 = 110/25.85 = 4.27$ A

$V_f = I_1 Z_f = 4.27 \times 21.15 = 90.4$ V; $V_b = I_1 Z_b = 4.27 \times 1.51 = 6.44$ V

$$Z_3 = \sqrt{\left(\frac{r_2}{s}\right)^2 + x_2^2} = 35.7\ \Omega,\ Z_5 = \sqrt{\left(\frac{r_2}{2-s}\right)^2 + x_2^2} = 1.57\ \Omega$$

$I_3 = V_f/Z_3 = 90.4/35.7 = 2.53$ A, $I_5 = V_b/Z_5 = 6.44/1.57 = 4.1$ A

$T_f = I_3^2 R_2/s = 228$ synch. watts, $T_5 = I_5^2 r_2/(2-s) = 15.3$ synch. watts.

$T = T_f - T_b = 228 - 15.3 = 212.7$ synch. watts

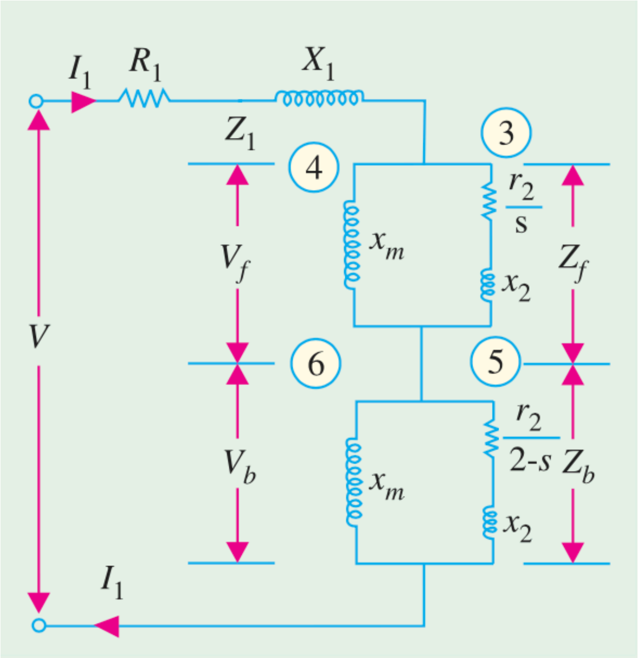
Output = synch. watt × $(1 - s) = 212.7 \times 0.95 =$ **202 W**

Since friction and windage losses are not given, this also represents the net output.

Example Problems

Example 36.2. Find the mechanical power output of the 185-W, 4-pole, 110-V, 60-Hz single-phase induction motor, whose constants are given below at a slip of 0.05.

R_1 = 1.86 ohm, X_1 = 2.56 ohm, X_m = 53.5 ohm, R_2 = 3.56 ohm, X_2 = 2.56 ohm
Core loss = 3.5 W, Friction and windage loss = 13.5 W.



Solution. It would be seen that major part of this problem has already been solved in Example 36.1. Let us, now, assume that V_f = 82.5% of 110 V = 90.7 V. Then the core-loss current I_c = 35/90.7 = 0.386 A ; r_c = 90.7/0.386 = 235 Ω.

Motor I

$$\text{conductance of core-loss branch} = 1/r_c = 1/235 = 0.00426 \text{ S}$$
$$\text{susceptance of magnetising branch} = -j/x_m = -j/26.7 = -j\,0.0374 \text{ S}$$
$$\text{admittance of branch 3} = \frac{(r_2/s) - j\,x_2}{(r_2/s)^2 + x_2^2} = 0.028 - j\,0.00101 \text{ S}$$
$$\text{admittance of 'motor' } I \text{ is } \mathbf{Y_f} = 0.00426 - j\,0.0374 + 0.028 - j\,0.00101$$
$$= 0.03226 - j\,0.03841 \text{ S}$$
$$\text{impedance } \mathbf{Z_f} = \mathbf{1/Y_f} = 12.96 + j\,15.2 \text{ or } 19.9\ \Omega$$

Motor II

$$\text{admittance of branch 5} = \frac{\frac{r_2}{2-s} - j\,x_2}{\left(\frac{r_2}{2-s}\right)^2 + x_2^2} = \frac{0.91 - j\,1.28}{2.469} = 0.369 - j\,0.517$$
$$\text{admittance of 'motor' II, } \mathbf{Y_b} = 0.00426 - j\,0.0374 + 0.369 - j\,0.517$$
$$= 0.3733 - j\,0.555 \text{ S}$$
$$\text{Impedance of 'motor' II, } \mathbf{Z_b} = 1/\mathbf{Y_b} = 0.836 + j\,1.242 \text{ or } 1.5\ \Omega$$
$$\text{Impedance of entire motor (Fig. 36.16) } Z_{01} = \mathbf{Z_1} + \mathbf{Z_f} + \mathbf{Z_b} = 15.66 + j\,19 \quad \text{or} \quad 24.7\ \Omega$$
$$I_1 = V/Z_{01} = 110/24.7 = 4.46 \text{ A}$$
$$V_f = I_1 Z_f = 4.46 \times 19.9 = 88.8 \text{ V}$$
$$V_b = 4.46 \times 1.5 = 6.69 \text{ V}$$

$$I_3 = 88.8/35.62 = 2.5 \text{ A}$$
$$I_5 = 6.69/1.57 = 4.25 \text{ A}$$
$$T_f = I_3^2(r_2/s) = 222 \text{ synch. watt}$$
$$T_b = I_5^2\left(\frac{r_2}{2-s}\right) = 16.5 \text{ synch. watt}$$
$$T = T_f - T_b = 205.5 \text{ synch. watt}$$
$$\text{Watts converted} = \text{synch. watt } (1 - s)$$
$$= 205.5 \times 0.95 = 195 \text{ W}$$
$$\text{Net output} = 195 - 13.5 = \mathbf{181.5\ W.}$$

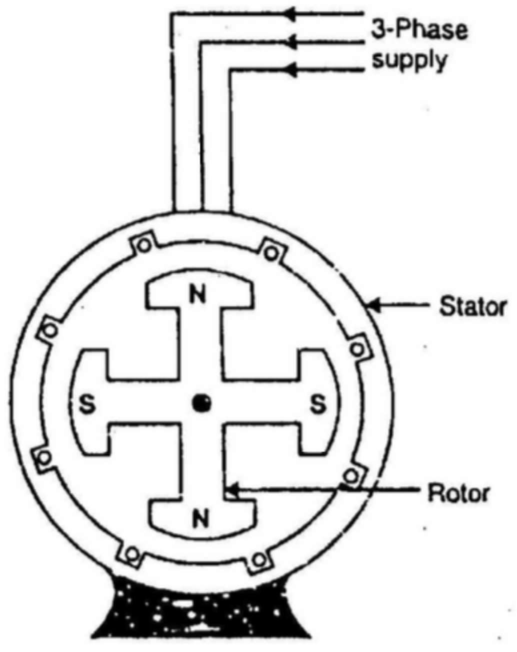
Synchronous Motor

- A synchronous motor is electrically identical with an alternator or a.c. generator.
- An alternator when driven as a motor by connecting its armature winding to a 3-phase supply, it is then called a synchronous motor.
- A synchronous motor runs at synchronous speed ($N_s = 120f/P$). The only way to change its speed is to vary the supply frequency.
- This type of motor is not inherently self-starting.
- It is capable of being operated under a wide range of power factors, both lagging and leading. Hence, it can be used for power correction purposes, in addition to supplying torque to drive loads.

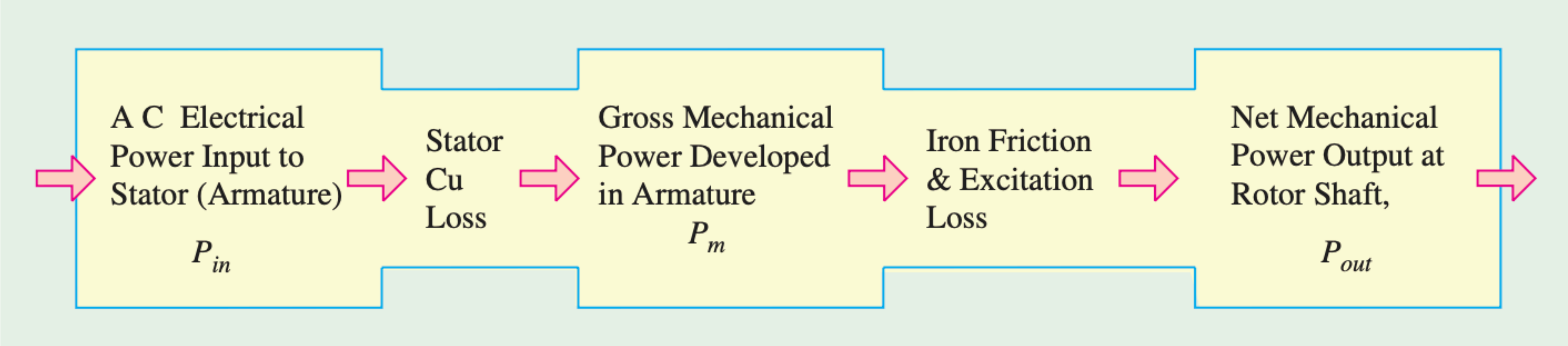
Construction:

Like an alternator, a synchronous motor has the following two parts:

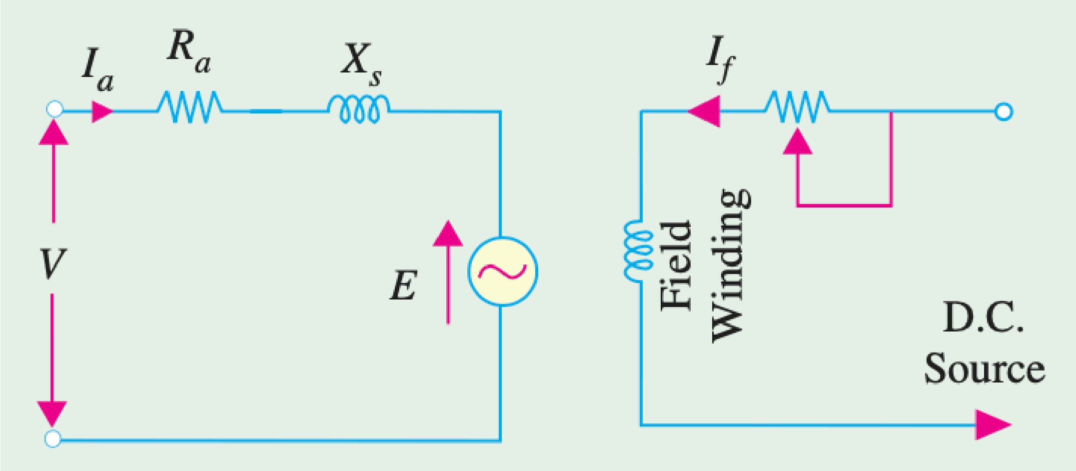
- **a stator** which houses 3-phase armature winding in the slots of the stator core and receives power from a 3-phase supply
- **a rotor** that has a set of salient poles excited by direct current to form alternate **N** and **S** poles. The exciting coils are connected in series to two slip rings and direct current is fed into the winding from an external exciter mounted on the rotor shaft.

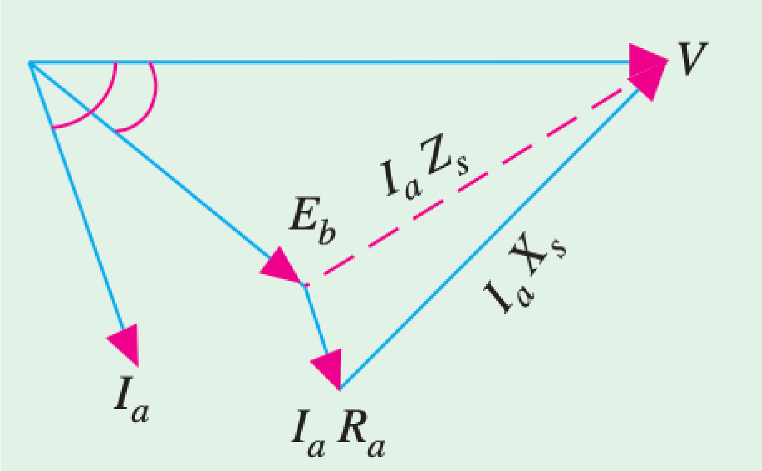


Power Flow Diagram



Equivalent Circuit of a Synchronous Motor





Power Developed by a Synchronous Motor

Except for very small machines, the armature resistance of a synchronous motor is negligible as compared to its synchronous reactance. Hence, the equivalent circuit for the motor becomes as shown in Fig. 38.10 (*a*). From the phasor diagram of Fig. 38.10 (*b*), it is seen that

$$AB = E_b \sin \alpha = I_a X_S \cos \phi$$

or $$VI_a \cos \phi = \frac{E_b V}{X_S} \sin \alpha$$

Now, $VI_a \cos \phi =$ motor power input/phase

$$\therefore \quad P_{in} = \frac{E_b V}{X_S} \sin \alpha \qquad \text{...per phase*}$$

$$= 3\frac{E_b V}{X_S} \sin \alpha \qquad \text{... for three phases}$$

Since stator Cu losses have been neglected, P_{in} also represents the gross mechanical power $\{P_m\}$ developed by the motor.

$$\therefore \quad P_m = \frac{3E_b V}{X_S} \sin \alpha$$

The gross torque developed by the motor is $T_g = 9.55\ P_m / N_s$ N–m ...Ns in rpm.

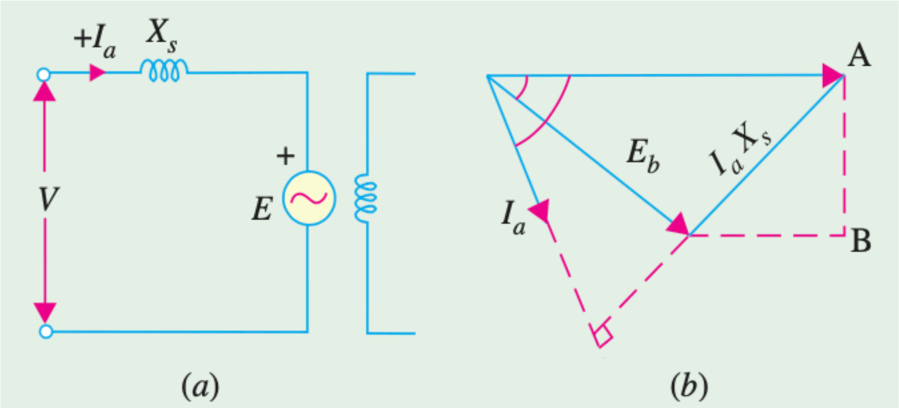


Fig. 38.10

Example Problems

Example 38.1. A 75-kW, 3-φ, Y-connected, 50-Hz, 440-V cylindrical rotor synchronous motor operates at rated condition with 0.8 p.f. leading. The motor efficiency excluding field and stator losses, is 95% and $X_s = 2.5\ \Omega$. Calculate (i) mechanical power developed (ii) armature current (iii) back e.m.f. (iv) power angle and (v) maximum or pull-out torque of the motor.

Solution. $N_S = 120 \times 50/4 = 1500$ rpm = 25 rps

(*i*) $P_m = P_{in} = P_{out}/\eta = 75 \times 10^3/0.95 =$ **78,950 W**

(*ii*) Since power input is known

$\therefore \quad \sqrt{3} \times 440 \times I_a \times 0.8 = 78{,}950; \quad I_a =$ **129 A**

(*iii*) Applied voltage/phase $= 440/\sqrt{3} = 254$ V. Let $V = 254\ \angle 0°$ as shown in Fig. 38.11.

Now, $V = E_b + j\,IX_S$ or $E_b = V - j\,I_a X_S = 254\ \angle 0° - 129\ \angle 36.9° \times 2.5\ \angle 90° = 250\ \angle 0° - 322\ \angle 126.9° = 254 - 322\ (\cos 126.9° + j \sin 126.9°) = 254 - 322\ (-0.6 + j\,0.8) =$ **516 ∠–30°**

(*iv*) $\therefore \quad \alpha = $ **–30°**

(*v*) pull-out torque occurs when $\alpha = 90°$

$$\text{maximum } P_m = 3\frac{E_b V}{X_S} \sin\delta = 3\,\frac{256 \times 516}{2.5} = \sin 90° = 157{,}275 \text{ W}$$

$\therefore$ pull-out torque $= 9.55 \times 157{,}275/1500 =$ **1,000 N-m**

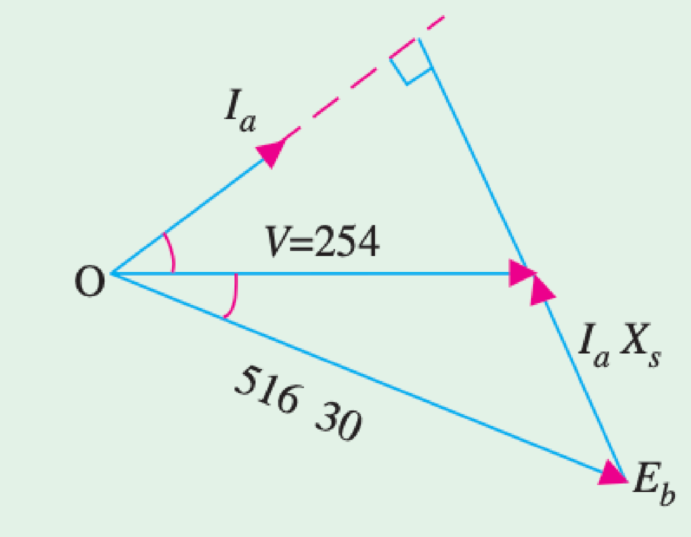


Fig. 38.11

Synchronous Motor with Different Excitations

A synchronous motor is said to have normal excitation when its $E_b = V$. If field excitation is such that $E_b < V$, the motor is said to be ***under-excited***. In both these conditions, it has a lagging power factor as shown in Fig. 38.12.

On the other hand, if d.c. field excitation is such that $E_b > V$, then motor is said to be ***over-excited*** and draws a leading current, as shown in Fig. 38.13 (*a*). There will be some value of excitation for which armature current will be in phase with V, so that power factor will become unity, as shown in Fig. 38.13 (*b*).

The value of α and back e.m.f. E_b can be found with the help of vector diagrams for various power factors, shown in Fig. 38.14.

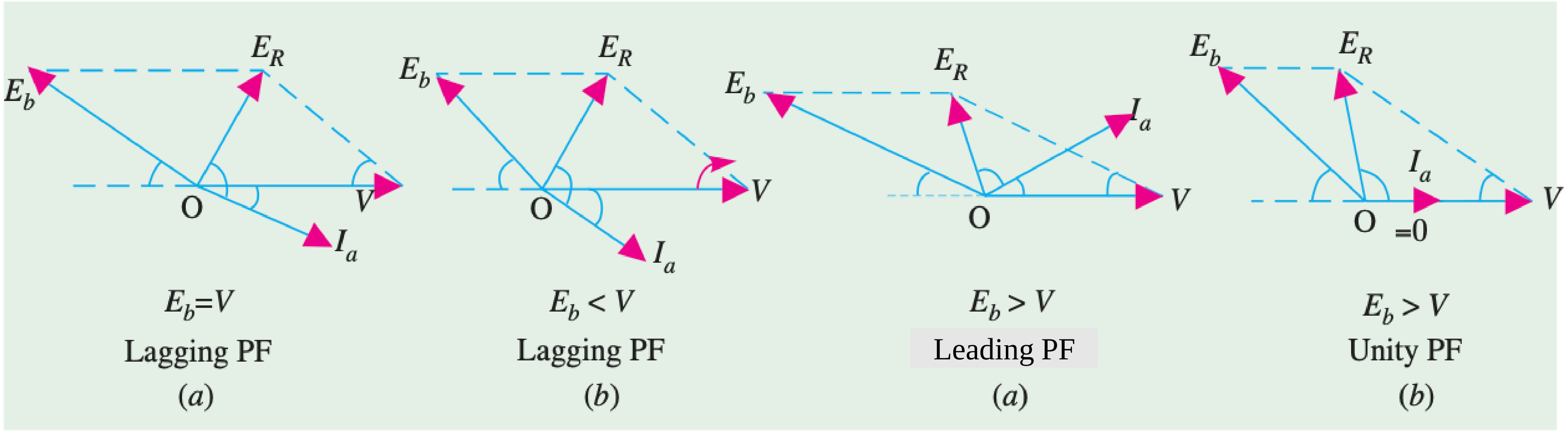


Fig. 38.12 **Fig. 38.13**

Example Problems

Example 38.31. A 3-φ, 3300-V, Y-connected synchronous motor has an effective resistance and synchronous reactance of 2.0 Ω and 18.0 Ω per phase respectively. If the open-circuit generated e.m.f. is 3800 V between lines, calculate (i) the maximum total mechanical power that the motor can develop and (ii) the current and p.f. at the maximum mechanical power.

Solution. $\theta = \tan^{-1}(18/2) = 83.7°$; $V_{ph} = 3300/\sqrt{3} = 1905$ V; $E_b = 3800/\sqrt{3} = 2195$ V

Remembering that $\alpha = \theta$ for maximum power development (Ar. 38-10)

$$E_R = (1905^2 + 2195^2 - 2 \times 1905 \times 2195 \times \cos 83.7°)^{1/2} = 2744 \text{ volt per phase}$$

$$\therefore \quad I_a Z_S = 2{,}744 \text{ ; Now, } Z_S = \sqrt{2^2 + 18^2} = 18.11\ \Omega$$

$$\therefore \quad I_a = 2744/18.11 = 152 \text{ A/phase ; line current} = 152 \text{ A}$$

$$(P_m)_{max} \text{ per phase} = \frac{E_b V}{Z_S} - \frac{E_b^2 R_a}{Z_{S^2}} = \frac{2195 \times 1905}{18.11} - \frac{2195^2 \times 2}{18.11^2}$$

$$= 230{,}900 - 29{,}380 = 201520 \text{ W per phase}$$

Maximum power for three phases that the motor can develop *in its armature*

$$= 201,520 \times 3 = 604{,}560 \text{ W}$$

$$\text{Total Cu losses} = 3 \times 152^2 \times 2 = 138{,}700 \text{ W}$$

$$\text{Motor input} = 604{,}560 + 138{,}700 = 743{,}260 \text{ W}$$

$$\therefore \quad \sqrt{3} \times 3300 \times 152 \times \cos\phi = 743{,}260 \qquad \therefore \quad \cos\phi = 0.855 \text{ (lead).}$$

Stepper Motor

- Stepper motors are also called stepping motors or step motors.
- This motor rotates through a **fixed angular step** in response to each input current pulse received by its controller.
- Stepper motors are ideally suited for situations where either **precise positioning** or **precise speed control** or both are required in automation systems.

Step Angle:

The angle through which the motor shaft rotates for each command pulse is called the **step angle β**.

- Smaller the step angle, greater the number of steps per revolution and higher the resolution or accuracy of positioning obtained.

- Step angles range from 0.72^o to 90^o.
- Most common step sizes are 1.8^o, 2.5^o, 7.5^o and 15^o.

- The value of step angle can be expressed either in terms of the rotor and stator poles (teeth) N_r and N_s respectively or in terms of the number of stator phases (m) and the number of rotor teeth.

$$\beta = \frac{(N_s - N_r)}{N_s . N_r} \times 360° = \frac{360°}{m\, N_r}$$

Example Problems

Example 39.1. A hybrid VR stepping motor has 8 main poles which have been castleated to have 5 teeth each. If rotor has 50 teeth, calculate the stepping angle.

Solution. $N_s = 8 \times 5 = 40; \quad N_r = 50$

$\therefore \quad \beta = (50 - 40) \times 360 / 50 \times 40 = 1.8°.$

Example 39.2. A stepper motor has a step angle of 2.5°. Determine (a) resolution (b) number of steps required for the shaft to make 25 revolutions and (c) shaft speed, if the stepping frequency is 3600 pps.

Solution. (*a*) Resolution = 360° / β = 360° / 2.5° = 144 steps / revolution.

(*b*) Now, steps / revolution = 144. Hence, steps required for making 25 revolutions = 144 × 25 = 3600.

(*c*) $n = \beta \times f / 360° = 2.5 \times 3600 / 360° = 25$ rps

Stepper Motor

Applications:

- Stepper motors are used for in motion-controlled positioning system as it is easy to produce precise position control with the help of computer controlled stepper motors.
- They are widely used in biomedical equipment where precise and accurate position control is needed.
- Stepper motors are also present in disc drivers, computer printers and scanners, intelligent lighting, camera lenses.
- Stepper motors are preferred in robotics because of their precision characteristic.
- Because of its high reliability and precision, 3D cameras, X Y Plotters, CNC and some other camera platforms also impart stepper motors.

Difference between conventional motor and stepper motor:

- Industrial motors are used to convert electric energy into mechanical energy but they cannot be used for precision control of speed without using closed-loop feedback.
- Stepping motors are ideally suited for situations where either precise positioning or precise speed control or both are required in automation systems.
- Stepper motor is well-suited for open-loop position control because no feedback need be taken from the output shaft.
- The only moving part in a stepping motor is its rotor which has no windings, commutator or brushes.

Advantages and Disadvantages of Stepper Motor

Advantages:

- Because of the precise increment of rotor movement, it is very easy to control the rotation speed precisely.
- Simplicity of construction and low maintenance cost are other advantages.
- Since the torque at low speed is comparatively higher in stepper motors, they are preferred in applications where high torque is needed at low speed.
- The lack of brushes is an advantage as it increases the overall life of the motor.

Disadvantages:

- It requires more amount of current than a normal dc motor.
- Though the torque is comparatively higher in lower speeds, it is very low in higher speeds and it is not really easy to operate at higher speeds.
- This kind of motors are relatively inefficient.
- Lack of feedback mechanism is another drawback as the feedback system is required to ensure safety.

Types of Stepper Motor

Stepper motors can be divided into the following three basic categories:

i. Variable Reluctance Stepper Motor
ii. Permanent Magnet Stepper Motor
iii. Hybrid Stepper Motor

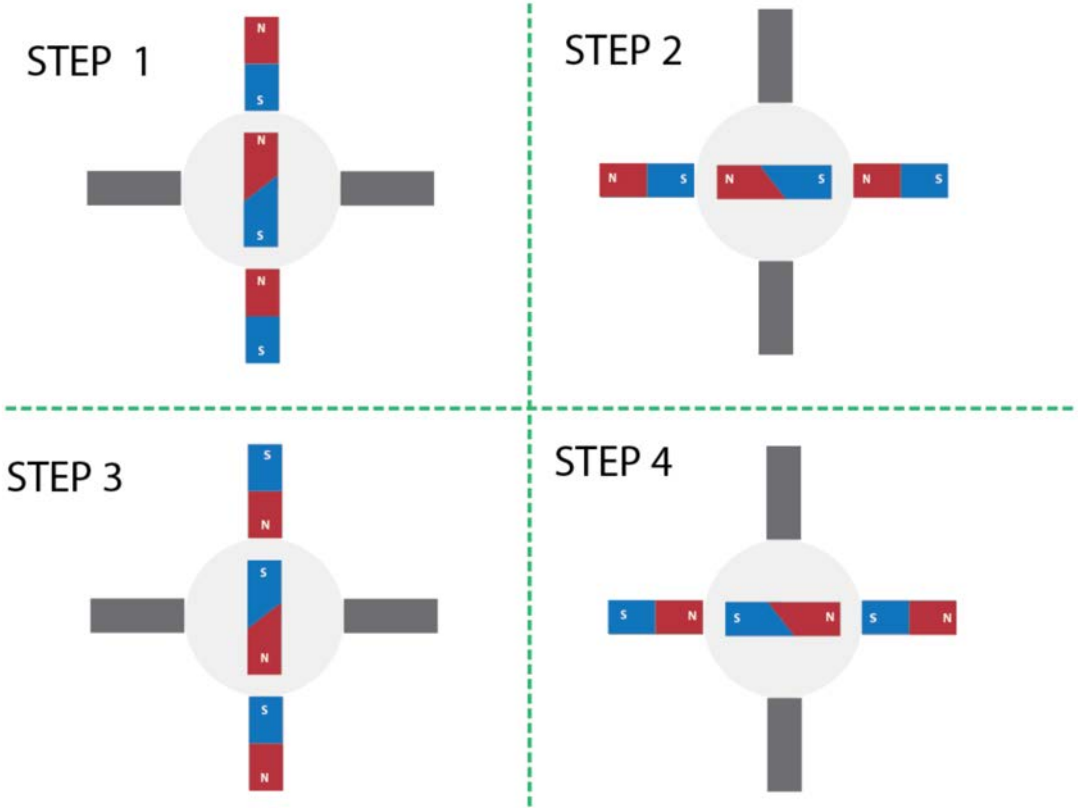

Variable reluctance motor


Permanent magnet stepper motor

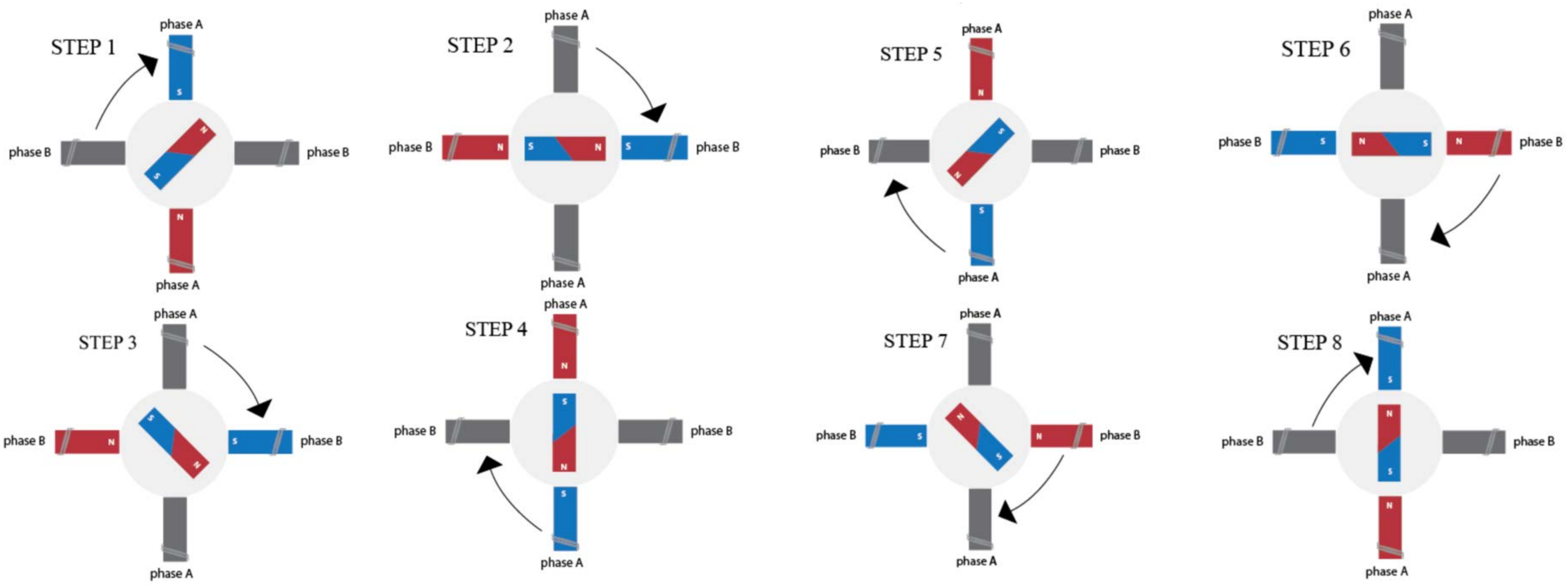

Hybrid stepper motor

Full step operation

- In this mode the rotor moves through the basic angle of 1.8 degrees in a single step and thereby taking 200 steps to finish off a rotation.
- We can make this happen by energizing either only one phase of stator windings or two phases.
- Single phase on operation requires minimum amount of power from the driver circuit.
- In dual phase on operation, two phases are energized at the same time which results in increased torque and speed.



Half step operation



- The rotor moves through half the base angle in a single step which results in improved torque than single phase full step operation.
- Also it doubles smoothness of rotation and resolution.