Review Last Class

DC Generator

- Armature Winding
- Working Principal
- EMF Equation
- Losses and Efficiency
- Power Stage
- Applications

DC Motor

- Working Principal
- Back EMF Equation
- Electromagnetic Torque Equation
- Significance of Back EMF
- Applications

Universal Motor

- Definition
- Construction
- Working Principal
- Characteristics Curve
- Purpose of Governor Universal Motors
- Advantages and Disadvantages
- Applications

Induction Machines

- Construction
- Working Principal

Induction Motor
Chapter 34

B. L. Theraja, A. K. Theraja, "A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines," S. Chand & Company Ltd.

Synchronous Speed (N_s): The speed of rotating flux which is produced due to the supply of three-phase voltage in the stator of an induction motor is called synchronous speed.

$$N_s = \frac{120f}{P} \text{ [rpm]}$$

Slip Speed (N_{sl}) : The difference between synchronous speed (N_s) and the actual rotor speed (N) is called slip speed.

$$N_{sl} = N_s - N \text{ [rpm]}$$

Slip (s): The per-unit value of slip speed with respect to synchronous speed is called slip.

$$s = \frac{N_{sl}}{N_s} = \frac{N_s - N}{N_s} \qquad N = (1-s)N_s \qquad N_{sl} = sN_s$$

Under Running Condition

Frequency of Rotor Current (f_r): $f_r = sf$

Rotor Induced Voltage (E_r): $E_r = sE_2$

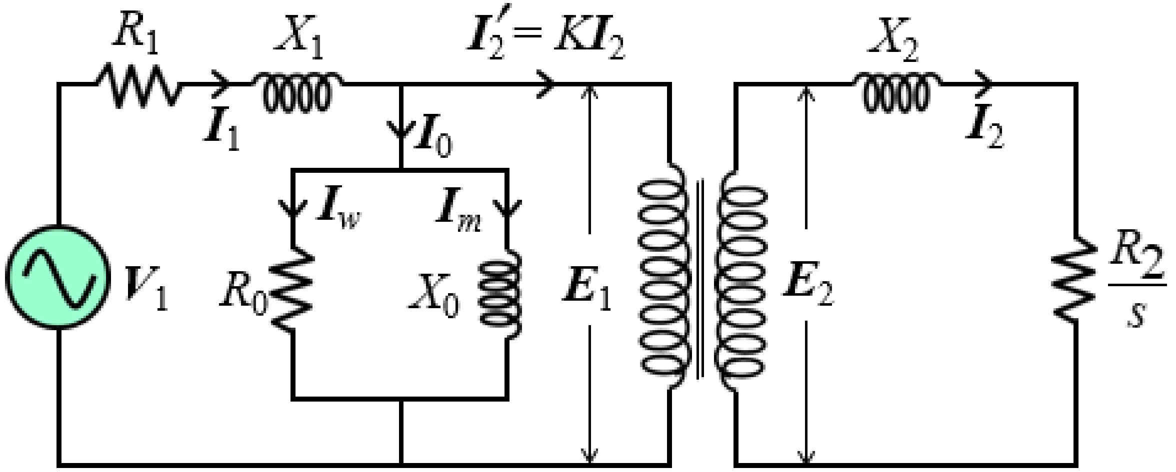
Rotor Reactance (X_r): $X_r = sX_2$

At standstill ($N = 0$) condition the value of slip, $s = 1$.

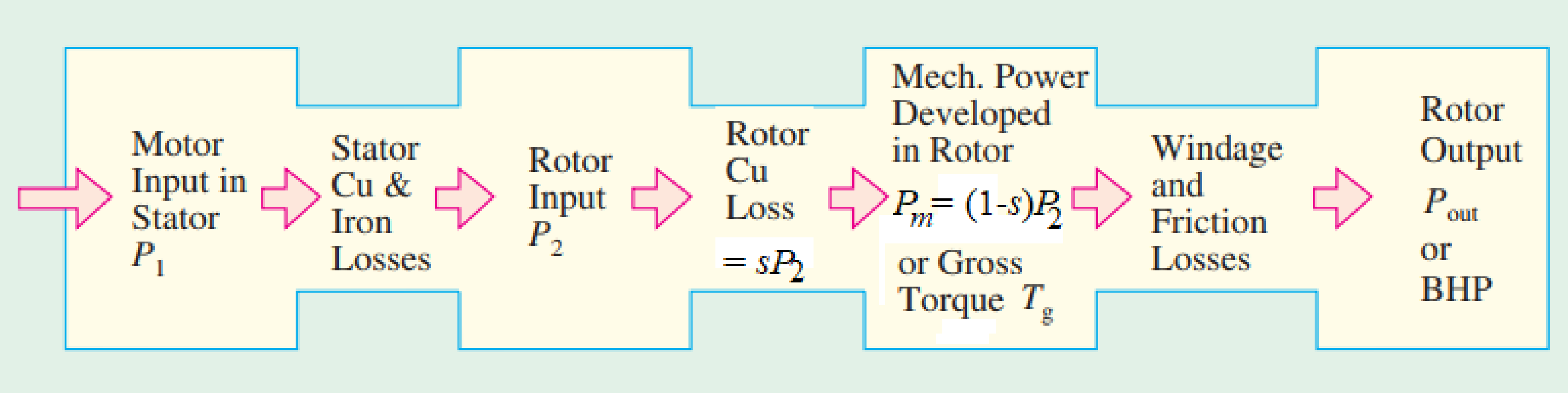
$$f_r = f \qquad E_r = E_2 \qquad X_r = X_2$$

If in an induction motor the rotor speed equal to the synchronous speed, no voltage will be induced in the rotor. No current and flux will be produced by the rotor circuit as well as the rotor will be rotated. So, the rotor speed of an induction motor is always less than the synchronous speed. That's why induction motor is also called ***asynchronous motor***.

Equivalent Circuit of an Induction Motor



Power Stage and Torque Develop by an Induction Motor



$$T_{sh} = \frac{P_{out}}{\omega} = \frac{P_{out}}{2\pi \times N(\text{rps})} = \frac{P_{out}}{2\pi \times [N(\text{rpm})/60]}$$

$$T_g = \frac{\text{Rotor Input}}{\omega_s} = \frac{P_2}{\omega_s} = \frac{P_2}{2\pi \times N_s(\text{rps})} = \frac{P_2}{2\pi \times [N_s(\text{rpm})/60]}$$

$$T_g = \frac{\text{Rotor Output}}{\omega} = \frac{P_m}{\omega} = \frac{P_m}{2\pi \times N(\text{rps})} = \frac{P_m}{2\pi \times [N(\text{rpm})/60]}$$

Synchronous watt (which is rotor input) is the torque that develops the power of 1 watt when the machine is running as synchronous speed. Thus, Synchronous wattage of an induction motor equals the power transferred across the air0gap to the rotor.

$$T_{sw} = \text{Rotor Input} = \frac{\text{Gross output Power}}{1-s} = \frac{P_m}{1-s}$$

$$\text{Gross output Power, } (P_m) = T_{sw} \times (1-s)$$

Example 34.3. *A 4-pole, 3-phase induction motor operates from a supply whose frequency is 50 Hz. Calculate :*

(i) *the speed at which the magnetic field of the stator is rotating.*

(ii) *the speed of the rotor when the slip is 0.04.*

(iii) *the frequency of the rotor currents when the slip is 0.03.*

(iv) *the frequency of the rotor currents at standstill.*

Solution. **(i)** Stator field revolves at synchronous speed, given by

$$N_s = 120\,f/P = 120 \times 50/4 = \mathbf{1500\ r.p.m.}$$

(ii) rotor (or motor) speed, $N = N_s(1-s) = 1500(1-0.04) = \mathbf{1440\ r.p.m.}$

(iii) frequency of rotor current, $f' = sf = 0.03 \times 50 = 1.5\ \text{r.p.s} = \mathbf{90\ r.p.m}$

(iv) Since at standstill, $s = 1$, $f' = sf = 1 \times f = f = \mathbf{50Hz}$

Example 34.4. *A 3-ϕ induction motor is wound for 4 poles and is supplied from 50-Hz system. Calculate* **(i)** *the synchronous speed* **(ii)** *the rotor speed, when slip is 4% and* **(iii)** *rotor frequency when rotor runs at 600 rpm.*

Solution. **(*i*)** $N_s = 120\,f/P = 120 \times 50/4 = 1500$ rpm

(*ii*) rotor speed, $N = N_s(1 - s) = 1500\,(1 - 0.04) = \mathbf{1440\ rpm}$

(*iii*) when rotor speed is 600 rpm, slip is

$$s = (Ns - N)/N_s = (1500 - 600)/1500 = 0.6$$

rotor current frequency, $f' = sf = 0.6 \times 50 = \mathbf{30\ Hz}$

Single Phase Induction Motor
Chapter 36

B. L. Theraja, A. K. Theraja, "A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines," S. Chand & Company Ltd.

A single-phase induction motor is, more or less, similar to a polyphase induction motor, except that: (*i*)

(***i***) its stator is provided with a single-phase winding and

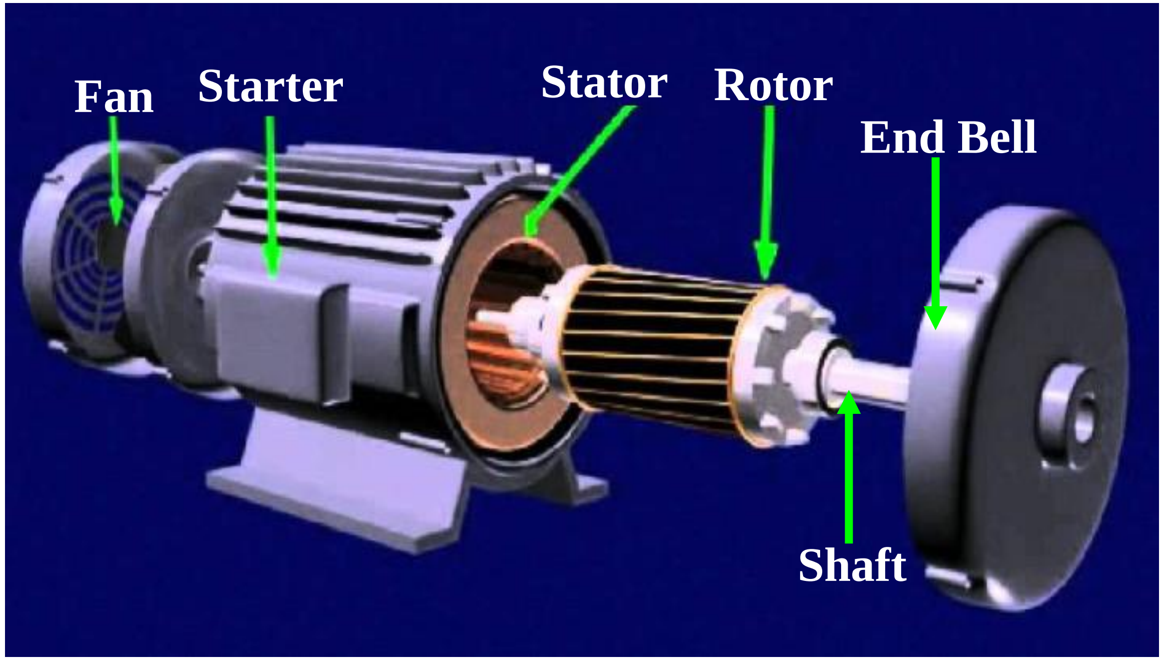
(***ii***) a centrifugal switch is used in order to cut out a winding, used only for starting purpose.

It has ***distributed stator winding*** and a ***squirrel-cage rotor***.

When fed from a single-phase supply, its stator winding produces an alternating flux which is ***not a synchronously rotating flux***.

An alternating or pulsating flux acting on a *stationary*, squirrel-cage rotor cannot produce rotation. That is why a single-phase motor is not ***self-starting***.

However, if the rotor of such a machine is given an initial start by hand (or small motor) or otherwise, *in either* direction, then immediately a torque arises and the motor accelerates to its final speed.



This peculiar behavior of the motor has been explained in two ways:

(***a***) **Two-field or double-field revolving theory**

(***b***) **Cross-field theory**

Double Field Revolving Theory

The flux can be represented by:

$$\Phi = \Phi_m \cos \omega t = \frac{\Phi_m}{2}(e^{j\omega t} + e^{-j\omega t})$$

The right-hand expression represents two oppositely-rotating vectors of half magnitude as shown in **Fig. 36.1**.

Each of the two component fluxes, while revolving round the stator, cuts the rotor, induces an emf and this produces its own torque.

The slip of rotor for two component of flux are given by:

$$s = s_f = \frac{N_s - N}{N_s} \qquad s_b = 2 - s$$

The produced two torques are called ***forward torque*** and ***backward torque***. These torques are oppositely-directed, so that the net or resultant torques is equal to their difference as shown in **Fig. 36.3**.

However, if the rotor is started somewhat, say, in the clockwise direction, the clockwise torque starts increasing and, at the same time, the anticlockwise torque starts decreasing. Hence, there is a certain amount of net torque in the clockwise direction which accelerates the motor to full speed.

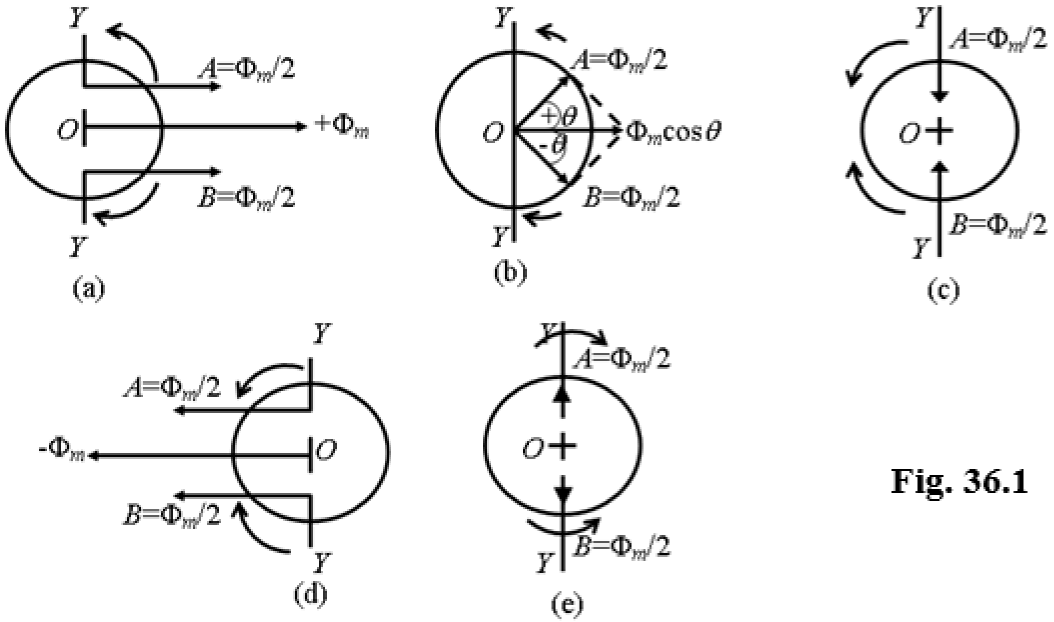


Fig. 36.1

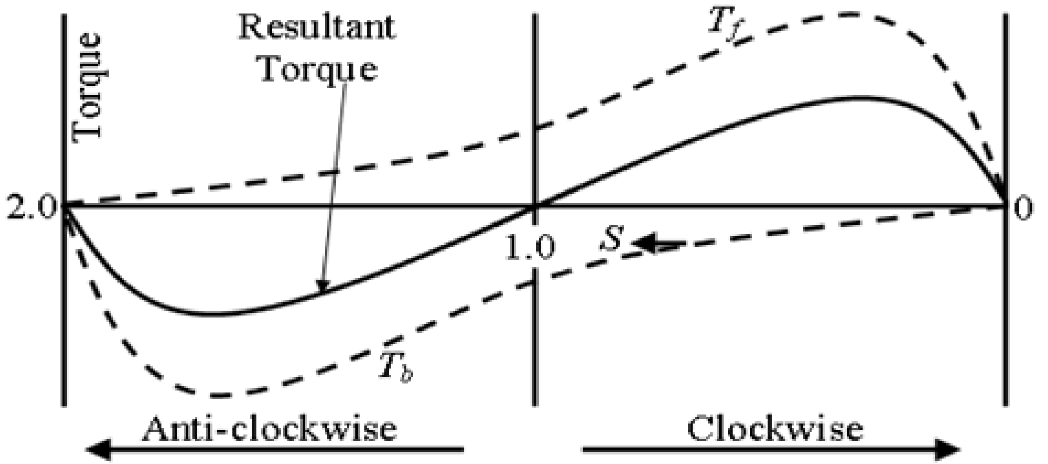


Fig. 36.3

Cross Field Theory

When ac voltage is applied to the stator winding, current is flowing to the squirrel-cage rotor windings by transformer action. The current produces magnetic flux which is opposing the stator flux as shown in **Fig. a**. No starting torque develops in rotor. At standstill, therefore, the single-phase induction motor behaves like a nonrotating transformer with a short-circuited secondary.

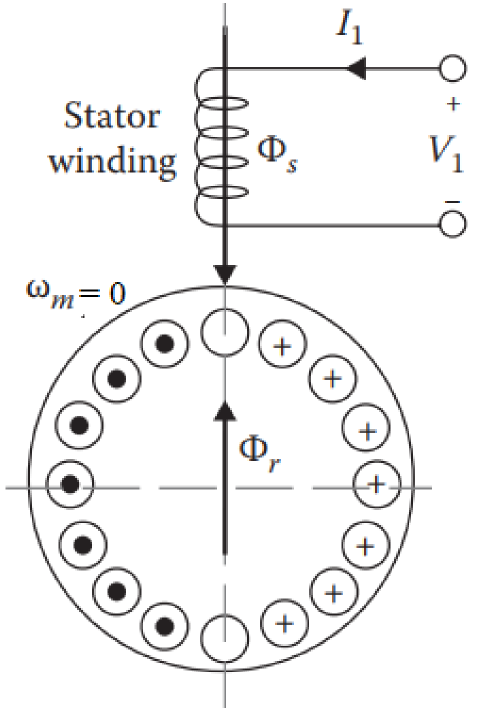


Fig. a: Rotor stationary

- Let the motor is running anyway as shown in **Fig. b**, an emf is induced in the rotor conductors, as they cut the stator flux Φ_s.
- Since the rotor is shorted, current is flowing in rotor and produces flux Φ_r which act at right angle to the stator flux Φ_s.
- Due to the high inductance value of rotor circuit, Φ_r lags behind Φ_s almost 90°.
- The combined action of Φ_s and Φ_r produces a revolving magnetic field.
- The revolving magnetic field rotates in the same direction of the initial push given to the rotor and it rotates at synchronous speed.

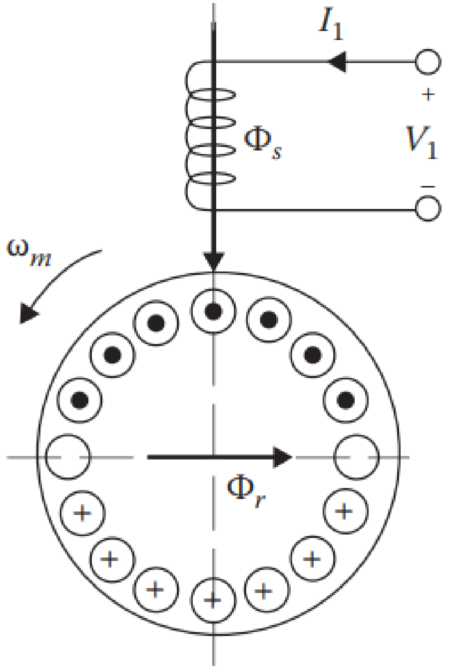


Fig. b: Rotor running

- Thus, rotor experiences a torque in the same direction as that of rotating magnetic field *i.e.* the direction of initial push.

36.4 Making Single-Phase Induction Motor Self-Starting

To make a single-phase induction motor self-starting, the stator is provided with an extra winding known as ***starting*** (or ***auxiliary***) winding, in addition t the ***main*** (or ***running***) winding.
Two winding are connected in parallel across the supply and they are spaced 90° electrically apart.

It is arranged that the phase difference between the currents in the two stator windings is very large (ideal value is 90°). Hence, the motor behaves like a two-phase motor. These two currents produce a revolving flux and hence make the motor self starting.

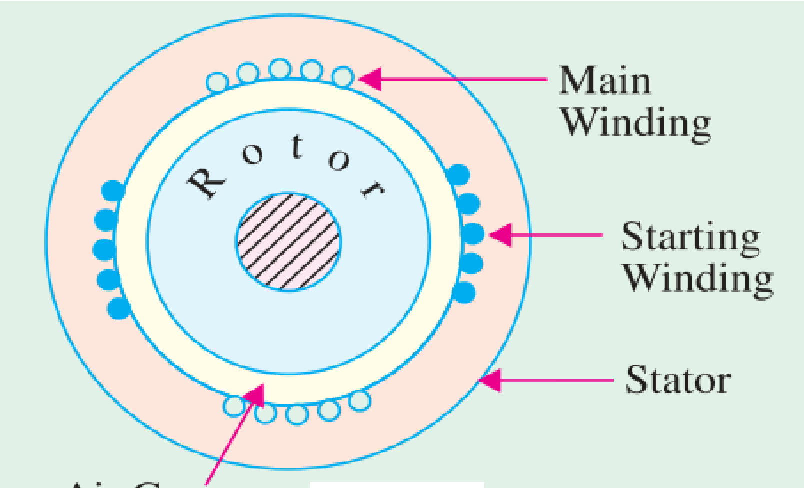


Fig. 36.4

Classification of Single-Phase Induction Motor

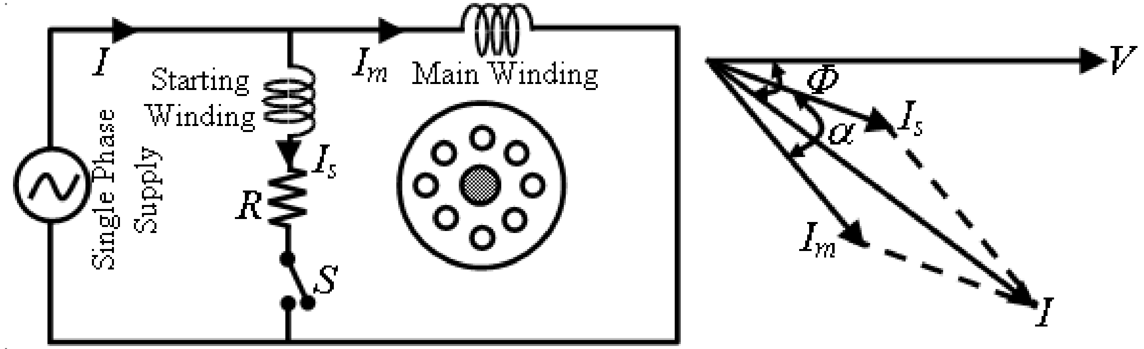
Single-phase induction motors are categorized based on the methods used to start them. Each starting method differs in cost and in the amount of starting torque it produces.

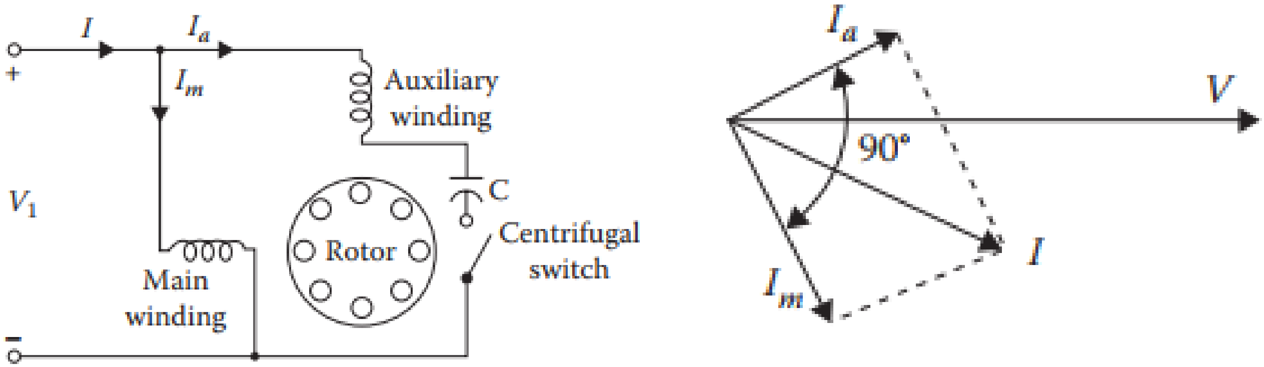
1. Split-Phase (or resistance-start) Motor
2. Capacitor-Start Motor
3. Capacitor-Run Motor
4. Capacitor-Start Capacitor-Run Motor
5. Shaded-Pole Motor

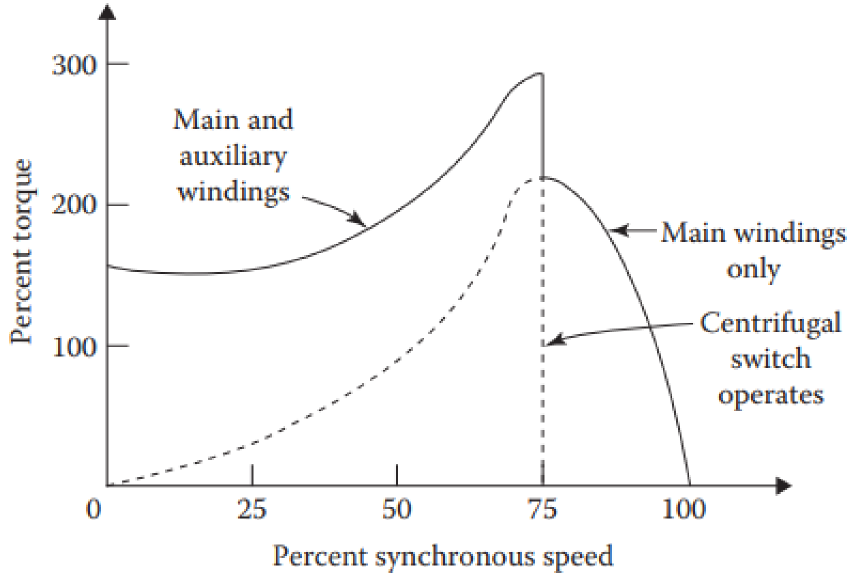
Split-Phase (or resistance-start) Motor

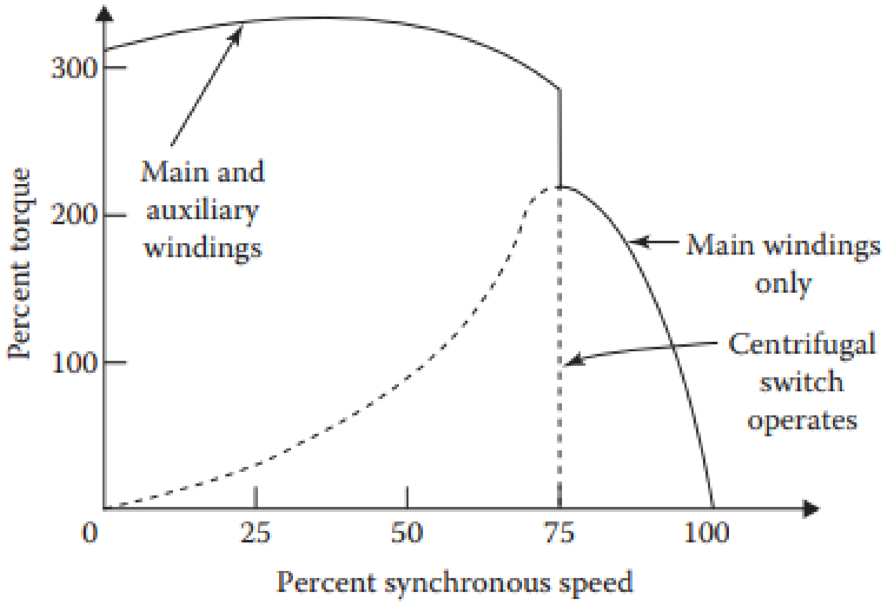
Capacitor Start Motor

The auxiliary winding may be disconnected automatically by the operation of a centrifugal switch at about 75% of synchronous speed. Once the motor is started, it continues to run in the same direction.

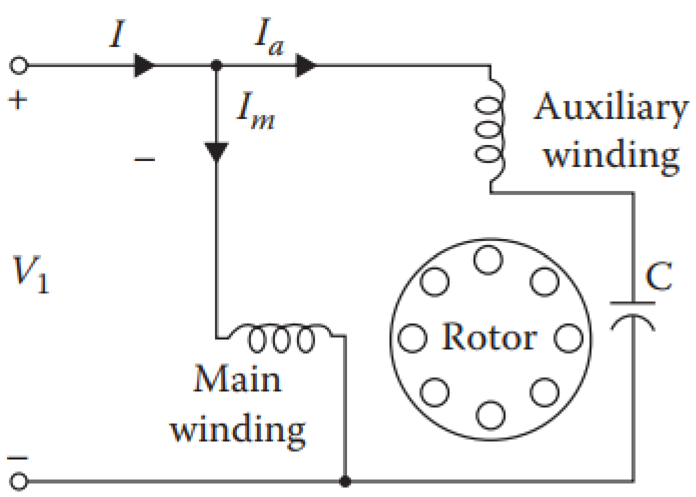


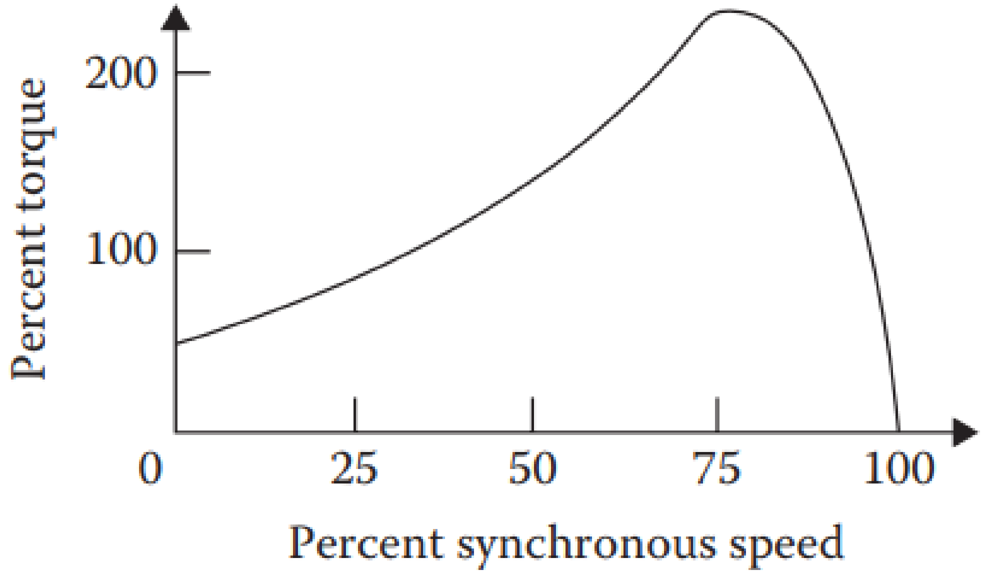




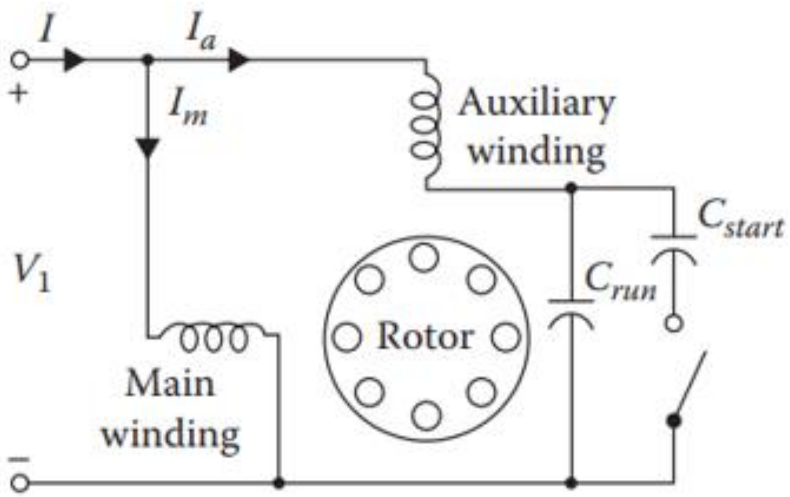


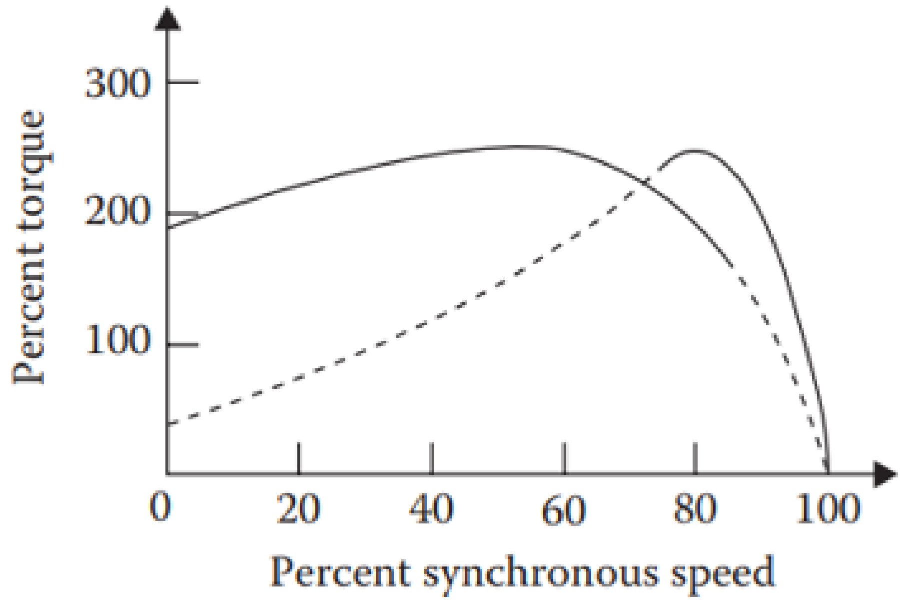
Capacitor Run Motor





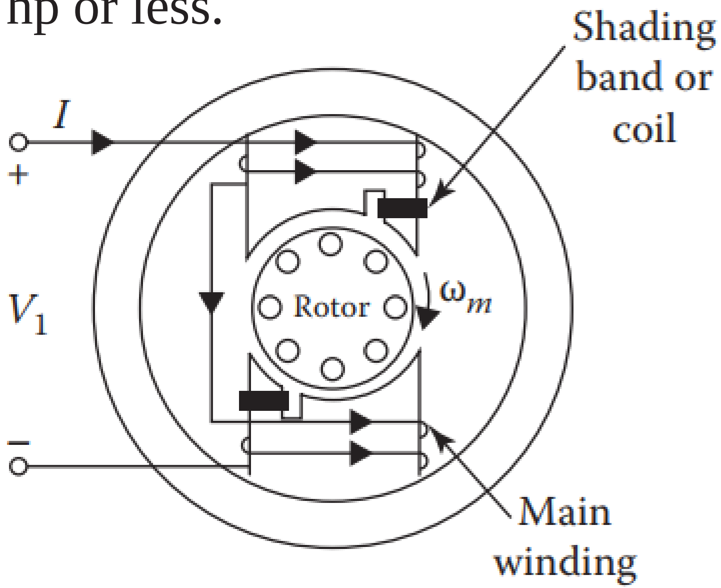
Capacitor Start Capacitor Run Motor





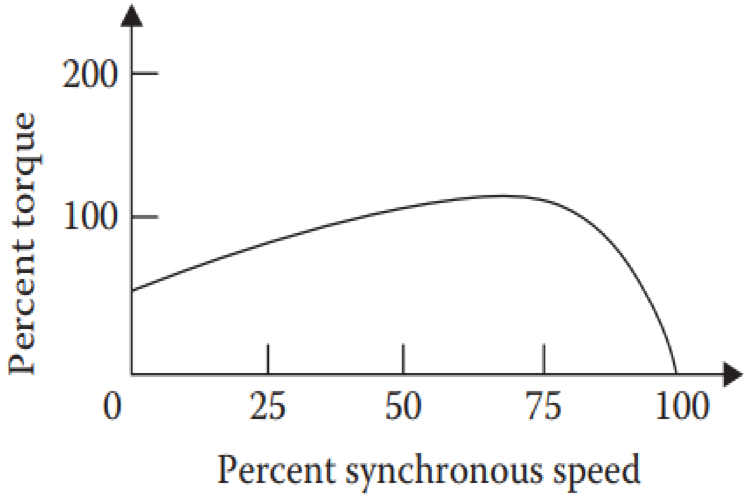
Shaded-Pole Motor

The shaded-pole induction motor is used widely in applications that require 1/20 hp or less.



As shown in the following figure, the motor has a salient-pole construction, with one-coil-per-pole main windings, and a squirrel-cage rotor.
One portion of each pole has a shading band or coil.
The shading band is simply a short-circuited copper strap (or single-turn solid copper ring) wound around the smaller segment of the pole piece.
The current induced in the shading band causes the flux in the shaded portion of the pole to lag the flux in the unshaded portion of the pole.

Therefore, the flux in the unshaded portion reaches its maximum before the flux in the shaded portion.
The result is like a rotating field moving from the unshaded to the shaded portion of the pole, and causing the motor to produce a slow starting torque.
The shaded-pole motor is rugged, cheap, small in size, and needs minimum maintenance.
It has very ***low starting torque, efficiency, and power factor***, and is used in ***turntables, motion-picture projectors, small fans, and vending machines***.



Equivalent Circuit of a Single Phase Induction Motor

Based on Double Field Revolving Theory

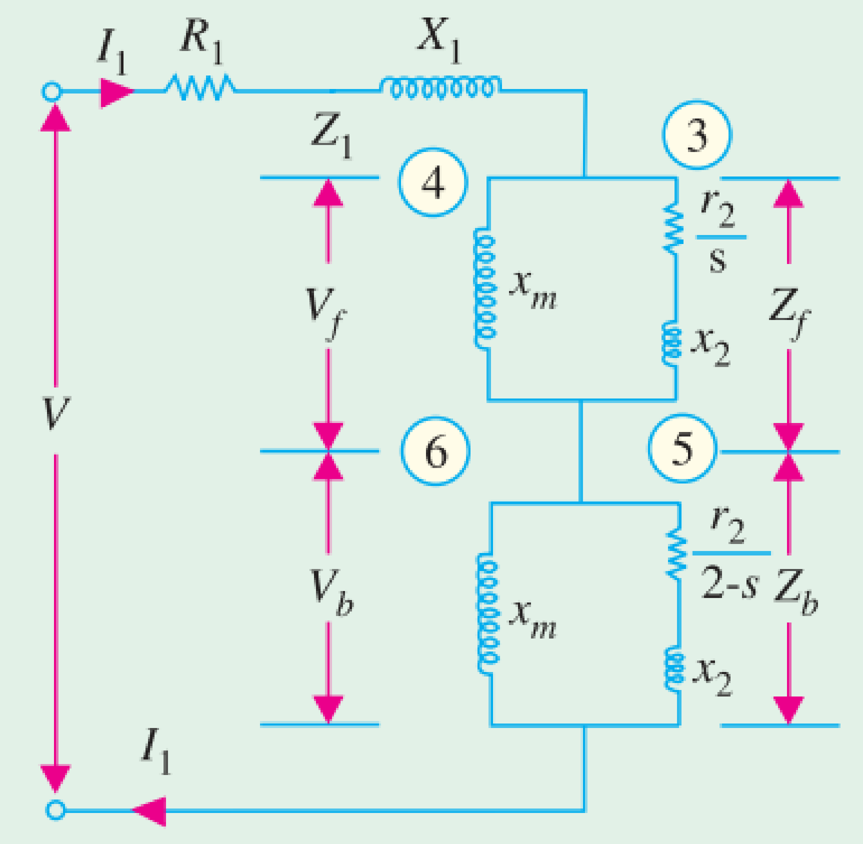


Figure 36.14

$$r_2 = \frac{R_2}{2} \qquad x_2 = \frac{X_2}{2} \qquad x_m = \frac{X_m}{2}$$

$$\boldsymbol{Z}_1 = R_1 + jX_1 \qquad \boldsymbol{Z}_3 = \frac{r_2}{s} + jx_2 \qquad \boldsymbol{Z}_5 = \frac{r_2}{2-s} + jx_2 \qquad \boldsymbol{Z}_m = jx_m$$

The impedance of forward and backward running motor are:

$$\boldsymbol{Z}_f = \frac{\boldsymbol{Z}_m \boldsymbol{Z}_3}{\boldsymbol{Z}_m + \boldsymbol{Z}_3} \qquad \boldsymbol{Z}_b = \frac{\boldsymbol{Z}_m \boldsymbol{Z}_5}{\boldsymbol{Z}_m + \boldsymbol{Z}_5}$$

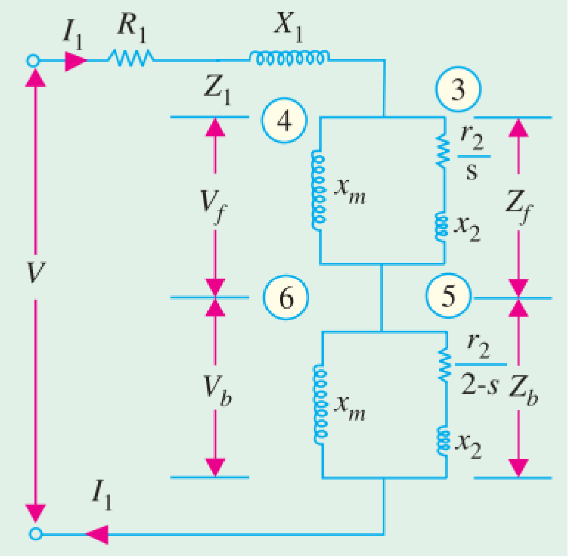
$$\boldsymbol{Z}_{01} = \boldsymbol{Z}_T = \boldsymbol{Z}_1 + \boldsymbol{Z}_f + \boldsymbol{Z}_b \qquad \boldsymbol{I}_1 = \frac{\boldsymbol{V}_1}{\boldsymbol{Z}_T} \qquad \boldsymbol{V}_f = \boldsymbol{I}_3 \boldsymbol{Z}_f \qquad \boldsymbol{V}_b = \boldsymbol{I}_5 \boldsymbol{Z}_b$$

The forward, backward and total torque are:

$$T_f = I_3^2 \frac{r_2}{s} \qquad T_b = I_5^2 \frac{r_2}{2-s} \qquad T = T_f - T_b$$

Example 36.1. *Discuss the revolving field theory of single-phase induction motors. 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 $x_2 = X_2/2 = 2.56/2 = 1.28\ \Omega$

$$Z_1 = R_1 + jX_1 = 1.86 + j2.56\ \Omega \qquad Z_3 = \frac{r_2}{s} + jx_2 = \frac{3.56}{0.05} + j1.28 \qquad Z_5 = \frac{r_2}{2-s} + jx_2 = \frac{3.56}{2-0.05} + j1.28$$

$$Z_m = jx_m = j26.7\ \Omega \qquad Z_f = \frac{Z_m Z_3}{Z_m + Z_3} = 12.4 + j17.15 = 21.15\angle 54.2^\circ$$

$$Z_b = \frac{Z_m Z_5}{Z_m + Z_5} = 0.84 + j1.26 = 1.51\angle 56.3^\circ \qquad Z_{01} = Z_1 + Z_f + Z_b = 5.1 + j20.97 = 25.85\angle 54.3^\circ$$

$$I_1 = 110/25.85 = 4.27 \text{ A}$$

$$V_f = I_1 Z_f = 4.27 \times 21.15 = 90.4 \text{ V};$$

$$V_b = I_1 Z_b = 4.27 \times 1.51 = 6.44 \text{ V}$$

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

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

$$I_3 = V_f / Z_3 = 90.4/35.7 = 2.53 \text{ A}$$

$$I_5 = V_b / Z_5 = 6.44/1.57 = 4.1 \text{ A}$$

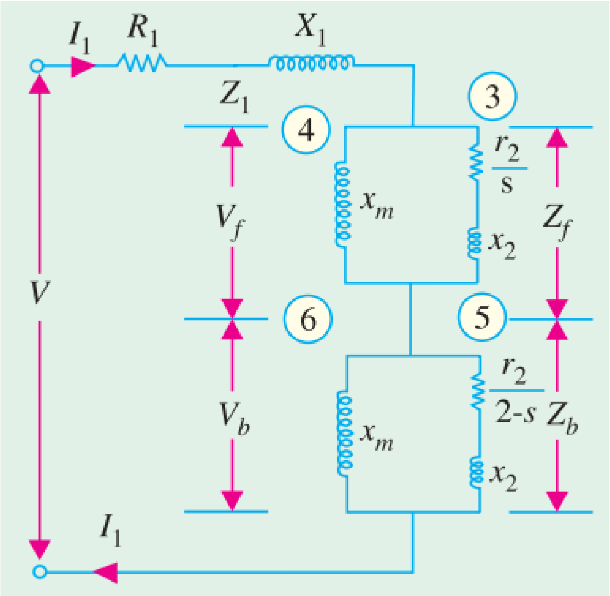
$$T_f = I_3^2 R_2 / s = 228 \text{ synch. watts}$$

$$T_5 = I_5^2 r_2/(2-s) = 15.3 \text{ synch. watts.}$$

$$T = T_f - T_b = 228 - 15.3 = 212.7 \text{ synch. watts}$$

$$\text{Output} = \text{synch. watt} \times (1-s) = 212.7 \times 0.95 = \textbf{202 W}$$

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



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

where, X is the net reactance

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

Obviously, I_m lags behind V by 39.4^o.

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

I_a must lead V by $(39.4^o - 90^o) = -50.6^o$.

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, $(3.5 - X_C) = -9.5\times 1.217 = -11.56$ ohm

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

Or, $1/(2\times\pi\times 50\times C) = 15.06$

Or, $C = 1/(2\times\pi\times 50\times 15.06) = 211\times 10^{-06}$ F

$\therefore C = 211\ \mu$F.

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

Solution: $I_m = \dfrac{V\angle 0}{3+j3} = \dfrac{V\angle 0}{4.24\angle 45^\circ} = \dfrac{V\angle -45^\circ}{4.24}$ $\qquad I_a = \dfrac{V\angle 0}{6+j3} = \dfrac{V\angle 0}{6.7\angle 26.5^\circ} = \dfrac{V\angle -26.5^\circ}{6.7}$

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

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

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

Synchronous Generator [Alternator]

Chapter 37

B. L. Theraja, A. K. Theraja, "A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines," S. Chand & Company Ltd.

Synchronous Generator Or Alternator

Almost whole of the world, all ***three-phase power*** is generated by synchronous machines operated as generators. Synchronous generators are also called **alternators** and are large machines producing electrical power at hydro, nuclear, or thermal power plants.

Synchronous generators rated in excess of **1000 MVA** are quite commonly used in generating stations.

The term ***synchronous*** refers to the fact that these machines ***operate at constant speeds and frequencies***.

A given synchronous machine can operate as a ***generator*** or as a ***motor***.

Such machines are used as motors in constant-speed drives in ***industrial applications*** and also for ***pumped-storage stations***.

In small sizes with only fractional horsepower, they are used in ***electric clocks***, ***timers***, ***record players***, and in other applications which ***require constant speed***.

Construction of a Synchronous Generator Or an Alternator

In a synchronous machine, the **armature winding** is on the **stator** and the **field winding** is on the rotor.

Stator: The stator consist of a cast-iron frame, which supports the armature core, having ***slots on its inner periphery*** for housing the armature conductors.

Rotor: Rotor consists of electromagnet which have the same number of poles as the stator winding. The rotor winding is supplied from ***an external dc source*** (or converted induced emf in alternator dc voltage using rectifier) through slip rings and brushes. There are two types rotor constructions as follows:

(*i*) **Salient (or projecting) Pole Type** , and (*ii*) **Smooth Cylindrical or Non-salient pole Type**

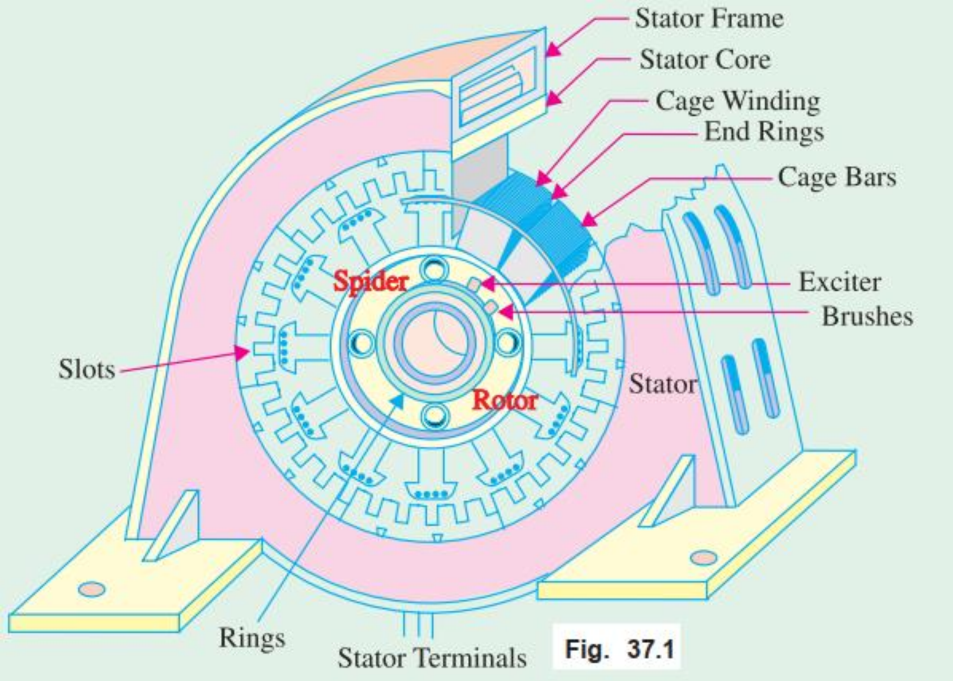
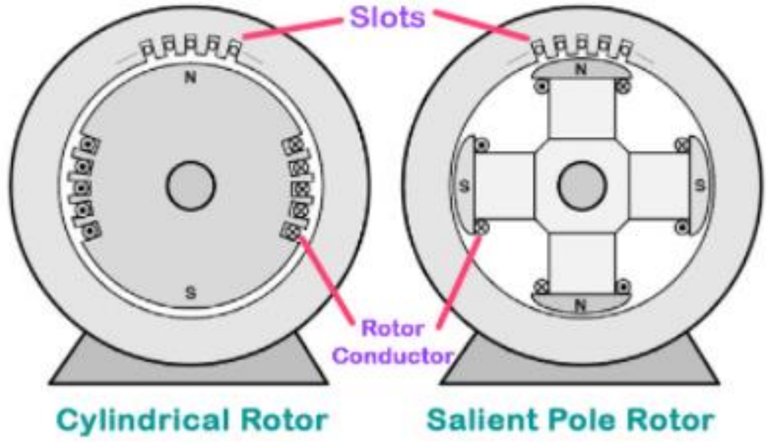


Fig. 37.1



Working Principal of a Synchronous Generator Or an Alternator

When the rotor rotates by applying the mechanical energy, the stator conductors (being stationary) are cut by the magnetic flux, hence they have induced emf produced in individual winding.

Because the magnetic poles are alternately *N* and *S*, they induce an emf and hence current in armature conductors, which first flows in one direction and then in the other.
Hence, an alternating emf is produced in the stator conductors:

(*i*) whose frequency depends on the number of *N* and *S* poles moving past a conductor in a one second, and
(*ii*) whose direction is given by Fleming's Right-hand rule

37.6 Speed and Frequency of an Alternator

The frequency of an alternator can relate with the speed as follows:

$$\text{Frequency}: \quad f = \frac{P}{2} \times \frac{N(\text{rpm})}{60} = \frac{PN(\text{rpm})}{120} \ \text{Hz} \quad \text{or} \quad f = \frac{P}{2} N(\text{rps}) \ \text{Hz}$$

where, P = total number of magnetic poles

N = rotating speed of the rotor

f = frequency of generated emf in Hz

It is clear from the above that for slower engine driven alternators, their number of poles is much greater as compared to that of the turbo-generators, which run at very high speeds.

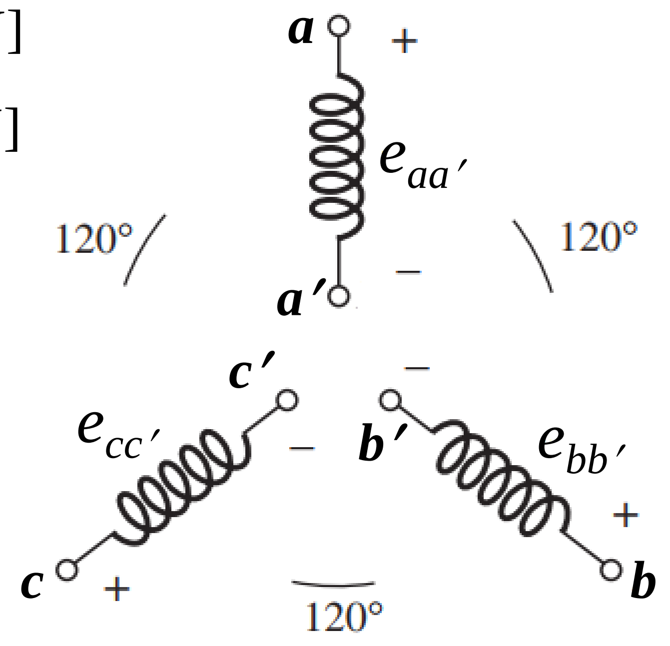
Equation of Induced EMF

The three-phase induced emf in an alternator can be given by:

$$e_{aa'} = E_{\max} \sin \omega t = \sqrt{2} E_{ph} \sin \omega t \quad [\text{V}]$$

$$e_{bb'} = E_{\max} \sin(\omega t - 120°) = \sqrt{2} E_{ph} \sin(\omega t - 120°) \quad [\text{V}]$$

$$e_{cc'} = E_{\max} \sin(\omega t + 120°) = \sqrt{2} E_{ph} \sin(\omega t + 120°) \quad [\text{V}]$$



where, $E_{ph} = 4.44 k_c k_d f \Phi T = 4.44 k_w f \Phi T$

$$E_{\max} = \sqrt{2} E_{ph}$$

E_{ph} = RMS value of per phase voltage
Φ = Flux/pole [Wb]
T = Number of coils or turns/phase
$f = (PN_s/120)$ Frequency in Hz
N_s = Rotor speed in rpm
$k_w = k_c k_d$ = winding factor
k_c or k_p = Pitch or chord factor [see 37.11]
k_d = Distribution factor [see 37.12]

Example: A 3-phase, 16 poles alternator has star-connected winding with 240 turns coil in each phase. The flux per pole is 0.03 Wb and the speed is 375 rpm. Its stator winding factor is 0.96. Find (*i*) the frequency, (ii) the rms value of phase voltage and line voltage of this generator, and (*iii*) the three phase voltages as a function of time.

Solution: Given, P = 16, T = 240, Φ = 0.03 Wb. N_s = 375 rpm and k_w = 0.96.

$$(i)\quad f = \frac{PN}{120} = \frac{16\times 375}{120} = 50 \text{ Hz}$$

$$(ii)\quad E_{ph} = 4.44 k_w f \Phi T = 4.44\times 0.96\times 50\times 0.03\times 240 = 1534.46 \text{ V}$$

$$E_L = \sqrt{3} E_{ph} = \sqrt{3}\times 1534 = 2657.76 \text{ V}$$

$$(iii)\quad E_{\max} = \sqrt{2} E_{ph} = \sqrt{2}\times E_{ph} = \sqrt{2}\times 1534.46 = 2170 \text{ V} \qquad \omega = 2\pi f = 2\times 3.14\times 50 = 314 \text{ rad/s}$$

$$e_{aa'} = 2170 \sin 314t \ \text{ V}$$

$$e_{bb'} = 2170 \sin(\omega t - 120°) \ \text{ V}$$

$$e_{cc'} = 2170 \sin(\omega t + 120°) \ \text{ V}$$

Practice Problem: A 3-phase, 16 poles alternator has star-connected winding with 96 turns coil in each phase. The flux per pole is 5×10^{-2} Wb and the speed is 450 rpm. Its stator pitch factor is 0.966 and distribution factor is 0.96. Find (*i*) the frequency, (ii) the rms value of phase voltage and line voltage of this generator, and (*iii*) the three phase voltages as a function of time.

Synchronous Motor

B. L. Theraja, A. K. Theraja, “A Textbook of ELECTRICAL TECHNOLOGY in SI Units **Volume II**, AC & DC Machines,” S. Chand & Company Ltd.

38.1 Synchronous Motor - General

A synchronous motor is electrically identical with an alternator or AC generator.

A given alternator (or synchronous machine) can be used as a motor, when driven electrically.

Some characteristic features of a synchronous motor are as follows:

1. **It runs either at synchronous speed or not at all** *i.e.* while running it maintains a constant speed. The only way to change its speed is to vary the supply frequency (because $N_S=120f/P$).

2. **It is not inherently self-starting.** It has to be run up to synchronous (or near synchronous) speed by some means, before it can be synchronized to the supply.

3. **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.

38.2 Working Principal of Synchronous Motor

When a 3-phase winding is fed by a 3-phase supply, then a magnetic flux of constant magnitude but *rotating* at synchronous speed, is produced.

Consider a two-pole stator of **Fig. 38.2**, in which are shown two stator poles (marked N_S and S_S) rotating at synchronous speed say, in clockwise direction.

Since the two similar poles, N (of rotor) and N_S (of stator) as well as S and S_S will repel each other, the rotor tends to rotate in the anti-clockwise direction.

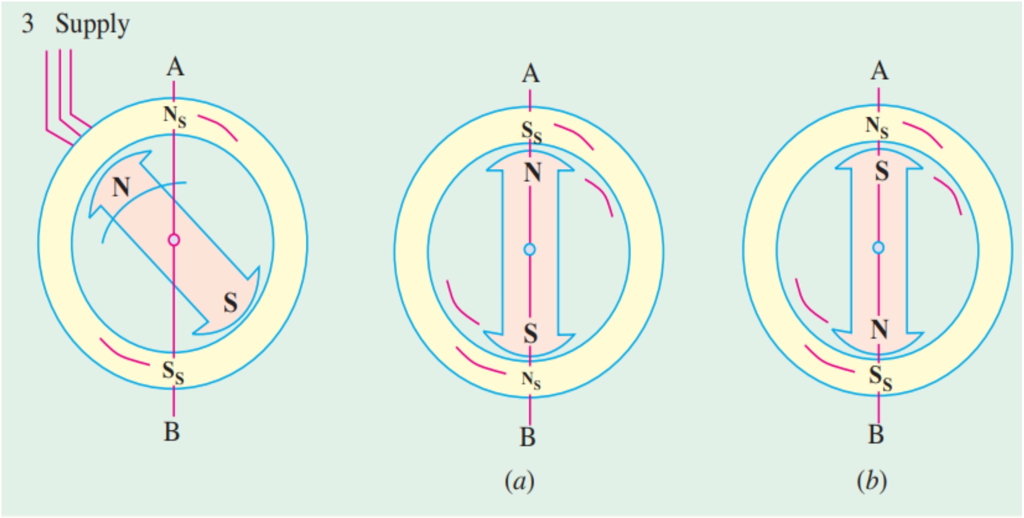


Fig. 38.2 Fig. 38.3 Fig. 38.3

But half a period latter, stator poles, having rotated around, interchange their position *i.e.* N_S is at position B and S_S at point A. under these conditions, N_S attracts S and S_S attracts N and rotor tends to rotate clockwise.

Hence, we find that due to continuous and rapid rotation of stator poles, the rotor is subjected to torque which tends to move it first in one direction and then in the opposite direction.

Owing to its large inertia, the rotor cannot instantaneously respond to such quickly reversing torque, with the result that it remains stationary.

Now, consider the condition shown in **Fig. 38.3**(a) where the stator and rotor poles are attracting each other.

Suppose that the rotor is not stationary, but it is rotating clockwise, with such a speed that turns through one pole-pitch by the time the stator poles interchange their positions, as shown in Fig. 38.3(b).

Here, again the stator and rotor poles attract each other.

It means that if the rotor poles also shift their positions along with the stator poles, then they will continuously experience a unidirectional torque *i.e*. clockwise torque, as shown in Fig. 38.3.

38.3 Method of Staring of Synchronous Motor

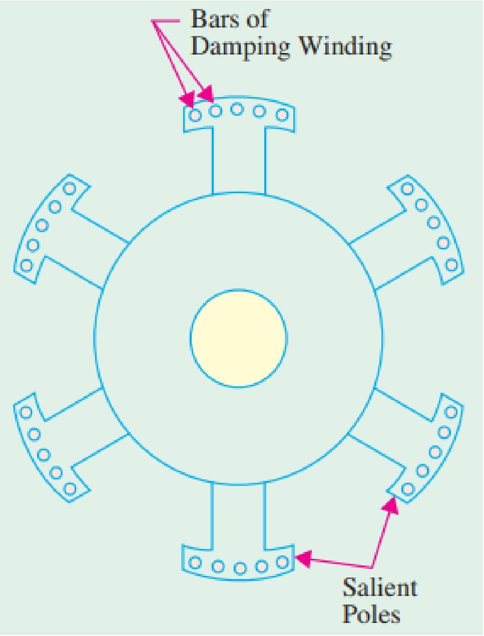
There are several methods to start the synchronous motor such as:

(*a*) Auxiliary drive

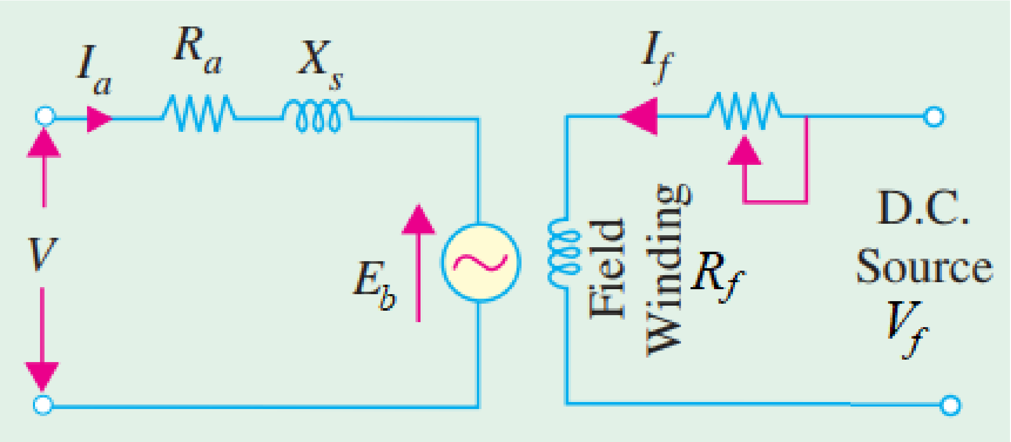
(induction motor or dc motor)

(*b*) Induction start

(using damper winding), etc



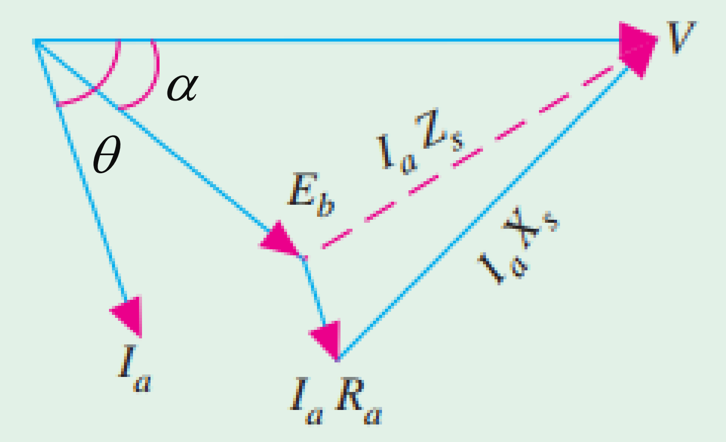
38.6 Equivalent Circuit of Synchronous Motor



$$E_R = V - E_b$$
$$= I_a Z_s$$

$$I_a = \frac{E_R}{Z_s} = \frac{V - E_b}{Z_s}$$

$\boldsymbol{V}$ = Supply voltage
$\boldsymbol{I_a}$ = Armature current
R_a = Armature resistance
$\boldsymbol{E_b}$ = Back emf
X_s = Synchronous reactance
$\boldsymbol{Z_s} = R_a + jX_s$
= Synchronous impedance



V_f = Field voltage
I_f = Field current
R_f = Field resistance

α = Load or Power Angle
θ = Power Factor Angle