UNIT – 3

INDUCTION MACHINES AND SYNCHRONOUS MACHINES

3.1 INTRODUCTION - THREE PHASE INDUCTION MOTORS

Three phase induction motors are extensively used for electric drives. The main **advantages** which make it so popular for industrial use are:

i) It is simple and extremely rugged construction.
ii) High reliability.
iii) Low cost.
iv) Its ability to start off from rest unlike synchronous motors which have to be started and run up by separate prime movers.
v) High efficiency.
vi) It requires little maintenance.

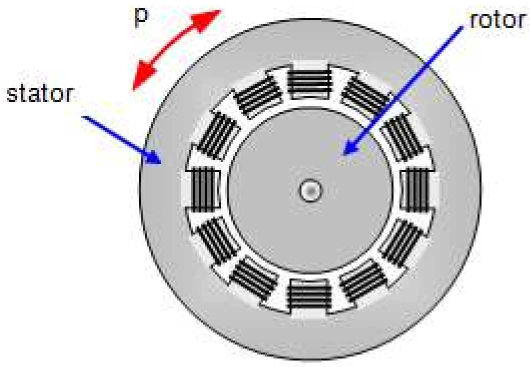
The **disadvantages** of induction motors are

i) The speed is not constant, when load is varied.
ii) Low starting torque compared to DC shunt motor.
iii) Reduction in efficiency when speed is varied.

3.2 CONSTRUCTION OF THREE PHASE INDUCTION MOTORS

The induction motor consists of two main parts

a) Stator
b) Rotor



Stator

The stator is made up of a number of stampings with alternate slot and tooth. Stampings are insulated from each other. Number of stampings are stamped together to build the stator core. The stator core is then fitted in a casted or fabricated steel frame. The slots house the three phase winding just like the three-phase alternator. The three-phase winding is called stator winding. It may be connected either in star or delta. The stator winding is made for a fixed number of poles.

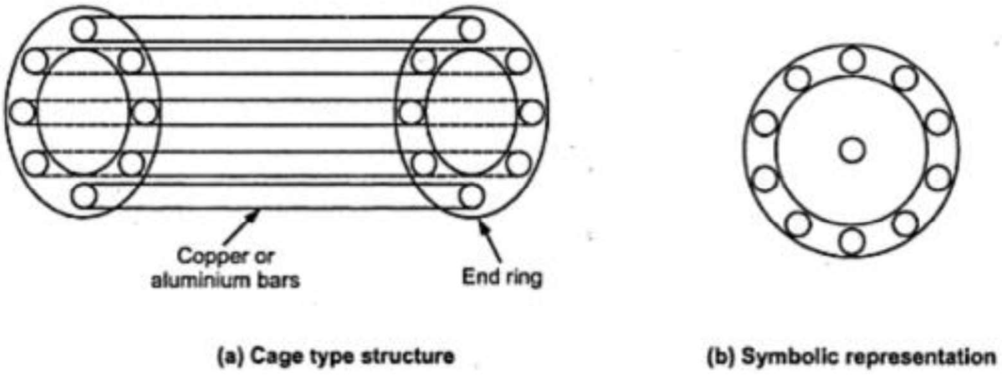
Rotor

These are two types of rotors used in induction motors. They are

1. Squirrel cage rotor
2. Slip ring or wound rotor

Squirrel cage rotor

This made up of a cylindrical laminated core with slots to carry the rotor conductors. The rotor conductors are heavy bars of copper or aluminium short circuited at both ends by end rings. Hence this rotor is also called a short circuited rotor. The entire rotor resistance is very small. External resistance cannot be connected in the rotor circuit. Motors using such rotor are called squirrel cage induction motors. The majority of induction motors are cage rotors.

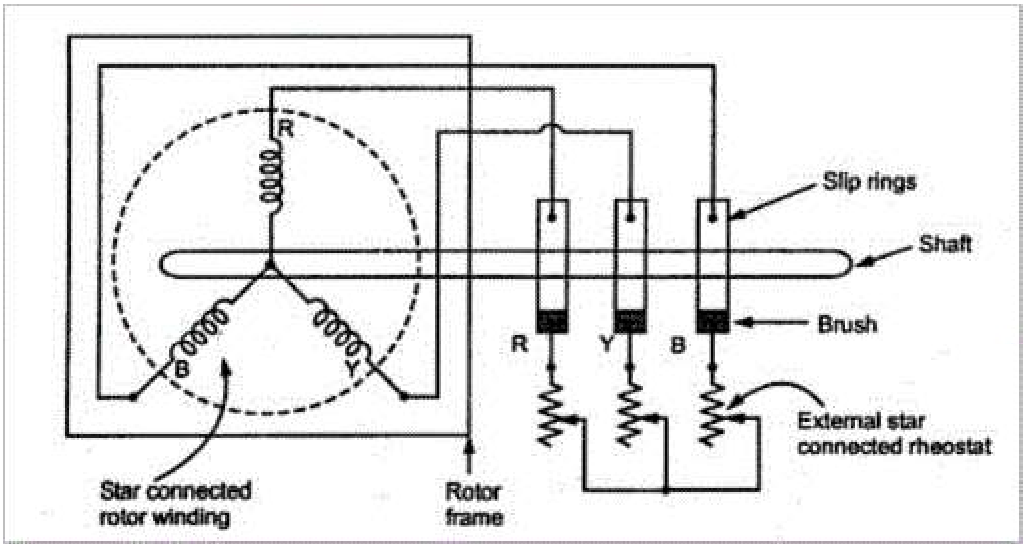


(a) Cage type structure

(b) Symbolic representation

Slip ring or wound rotor

In this type of rotor, rotor windings are similar to the stator winding. The rotor winding may be star or delta connected. The distributed winding, wound for as many number of poles as the stator is wound for. The three phase are brought out and connected to slip rings mounted on the rotor shaft. Variable external resistance in the rotor circuit, the motor speed and torque can be controlled. This motor is called slip ring induction motor or wound rotor induction motor.



3.3 TYPES OF 3 – PHASE INDUCTION MOTORS

These are two types of 3 – Phase Induction motors

1. Squirrel cage induction motor
2. Slip ring or wound induction motor

3.4 PRINCIPLE OF OPERATION OF THREE PHASE INDUCTION MOTOR

Three-phase supply is given to the stator winding. Due to this, current flows through the stator winding. This current is called stator current. It produces a rotating magnetic field in the space between stator and rotor. This magnetic field rotates at synchronous speed given by

$$\boxed{N_s = \frac{120f}{P}}$$

Where N_s = synchronous speed

f = Supply frequency

P = number of poles for which the stator is wound.

As a result of the rotating magnetic field cutting the rotor conductors, an emf is induced in the rotor. If the rotor winding is shorted (in cage rotor they are already shorted and in wound rotor, they to be shorted externally) then the induced emf produced current. This current produces a rotor field (rotor mmf).

The interaction of stator and rotor fields develops torque. Then the rotor rotates in the same direction as the rotating magnetic field.

As the rotor speed picks up, the frequency of rotor emf and the magnitude of rotor emf decrease.

The rotor tries to catch up with the rotating magnetic field. However, the rotor cannot really catch up and rotate at the synchronous speed because if it does so, the relative speed would become zero and then there is no rotor induced emf, no current and hence no torque. Therefore, the rotor runs at a speed slightly less than the synchronous speed. In an induction motor, the rotor speed is always less than the synchronous speed. Therefore this machine is called asynchronous machine.

The difference between synchronous speed and rotor speed is called the slip speed.

Slip speed = N_2-N

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

So $$N = N_s (1 - s)$$

$$\boxed{\%\ \text{Slip} = \frac{N_s - N}{N_s} \times 100}$$

At no-load, the difference between synchronous speed and rotor speed is only about 1%. At loaded condition, the rotor slows down. The emf induced in the rotor and hence the rotor current increase. Due to this, torque also increases. Under steady state conditions, the electromagnetic torque is equal to the load torque. At full load conditions, the difference between synchronous speed and rotor speed is about 3 to 5%.

The variation of speed from no-load to full-load is very small. Thus a three phase induction motor is also called a constant speed motor.

Advantages of squirrel cage induction motor

1. Cheaper
2. Light weight

3. Rugged construction
4. More efficient
5. Requires less maintains.
6. It can be operated in dirty & explosive environment.

Disadvantages of squirrel cage induction motor

1. Moderate starting torque
2. External resistance cannot be connected to rotor circuit. So starting torque cannot be controlled.

Applications of squirrel cage induction motor

Squirrel cage induction motors are used in lathes, drilling machines, fans, blowers, water pumps, grinders, printing machines etc.,

The advantages disadvantages and applications of slip ring induction motor are as follows.

Advantages of slip ring induction motor

1. The starting torque can be controlled by varying the rotor circuit resistance.
2. The speed of the motor can also be controlled by varying the rotor circuit resistance.

Disadvantages of slip ring induction motor

1. Wound – rotor machine is heavier.
2. High cost
3. High rotor inertia
4. High speed limitation.
5. Maintenance and reliability problems due to brushes and slip ring.

Applications of slip ring induction motor

The slip ring induction motors are employed only when speed control or high starting torque is required. Examples are lifts, hoists, cranes, elevators, compressors etc.,

3.5 FREQUENCY OF ROTOR CURRENT OR EMF

When the rotor is stationary, the relative speed between the rotor winding and the rotating magnetic field is N_s. Hence the frequency of emf induced and the resultant current is $\frac{PN_s}{120}$ which is the same as the supply frequency, f. As the rotor speeds up, the relative speed is $(N_s - N)$ and hence the rotor frequency is

$$f_r = \frac{\text{Relative speed in rpm}}{120/p} = \frac{N_s - N}{120/P}$$

Since, slip, $s = \frac{N_s - N}{N_s}$

$N_s - N = sN_s = s \times \frac{120f}{P}$

Substituting $N_s - N = sN_s = s \times \frac{120f}{P}$ in equation we have

Rotor frequency $fr = s \times \frac{120f}{P} \times \frac{P}{120}$

$$\boxed{f_r = sf}$$

Thus the frequency of rotor induced emf in an induction motor is equal to the product of slip and supply frequency. It is also called the slip frequency.

3.6 ROTOR EMF

Under standstill condition slip s = 1, i.e. relative speed is maximum and maximum emf is induced in the rotor.

E_2 = rotor induced emf per phase under standstill condition

As the motor speed increases, the relative speed between rotor and rotating magnetic field decreases. Due to this, induced emf in the rotor also decreases.

E_{2r} = rotor induced emf per phase under running condition

Therefore, $E_2 \propto N_s$; $E_{2r} \propto N_s - N$

Dividing these two equations

$$\frac{E_{2r}}{E_2} = \frac{N_s - N}{N_s} = s$$

$$\boxed{E_{2r} = s E_2}$$

Hence for slip ‘s’, the induced emf in the rotor is ‘s’ times the magnitude of the induced emf at standstill condition.

3.7 ROTOR CURRENT AND POWER FACTOR

R_2 = rotor resistance per phase under standstill

X_2 = rotor reactance per phase under standstill

$X_2 = 2\pi f L_2 \,\Omega/ph$

L_2 = inductance / phase of the rotor

$Z_2 = \sqrt{R_2^2 + X_2^2}$

Rotor current, $I_2 = \dfrac{E_2}{Z_2}$

Rotor power factor, $\cos\phi_2 = \dfrac{R_2}{Z_2}$

Now in running condition, $f_r = sf$

Rotor induced emf, $E_{2r} = sE_2$

Rotor reactance per phase under running condition

$X_{2r} = sX_2 = 2\pi f_r L_2$

Rotor impedance per phase under running condition

$Z_{2r} = \sqrt{R_2^2 + (sX_2)^2}$

Rotor current per phase under running condition, $I_{2r} = \dfrac{sE_2}{Z_{2r}}$

$$= \frac{sE_2}{\sqrt{R_2{}^2 + (sX_2)^2}}$$

Rotor power factor under running condition, $\cos \phi_{2r} = \frac{R_2}{Z_{2r}}$

$$= \frac{R_2}{\sqrt{R_2^{\ 2} + (sX_2)^2}}$$

3.8 EQUIVALENT CIRCUIT OF INDUCTION MOTOR

The three phase induction motor is generally treated as a rotating transformer. The transformer has two winding one is primary and another one, secondary winding, Similarly in an induction motor, stator acts as primary and rotor acts as rotating secondary (or short circuited). Hence, the transfer of energy from stator to rotor in an induction motor takes place entirely inductively linking the two.

3.9 SINGLE PHASE INDUCTION MOTORS

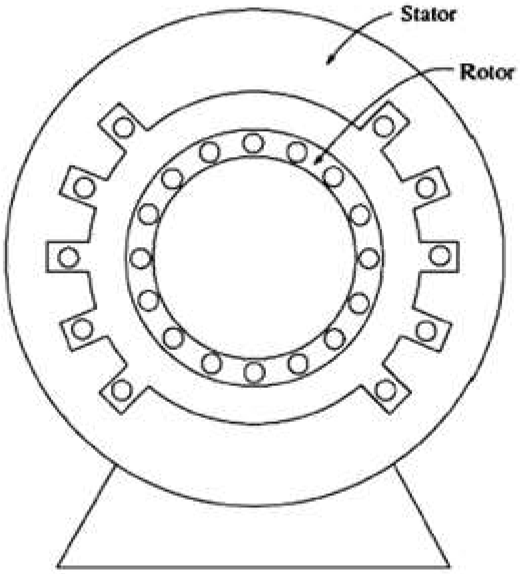
The majority of single phase motors are of induction type. The power rating is in terms of fractional horse power. They are classified according to the starting methods, employed.

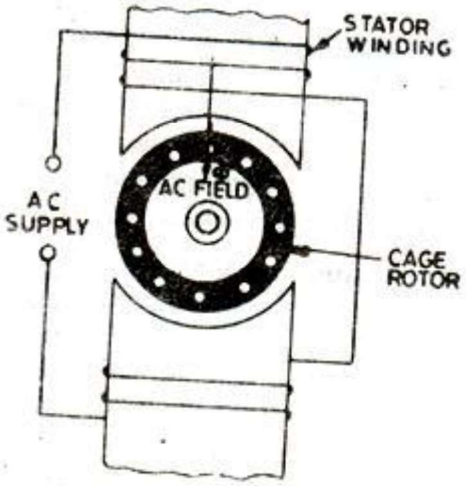
They are

1. Resistance – start (split- phase)
2. Capacitor – start induction motor
3. Capacitor – run induction motor
4. Capacitor start And run motor
5. Shaded pole induction motor

3.10 CONSTRUCTION OF SINGLE PHASE INDUCTION MOTORS

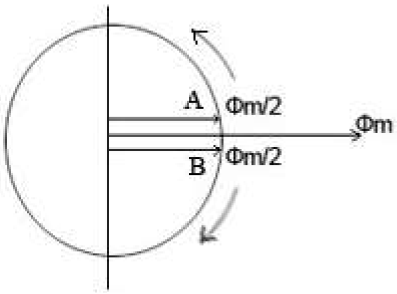
The construction of a Single phase induction motors is similar to three phase squired cage induction motor. The rotor is the same as that of a three-phase induction motor, but the stator has only a single phase distributed winding. It consists of two parts. One is stator and another one is rotor. The air gap between stator and rotor is uniform. There is no external connection between stator and rotor.


Stator
Rotor

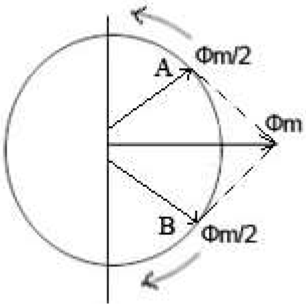

STATOR WINDING
1φ
AC FIELD
AC SUPPLY
CAGE ROTOR

3.11 DOUBLE REVOLVING FIELD THEORY

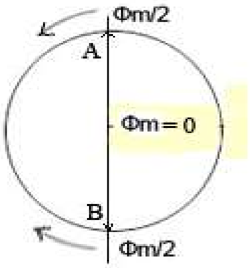
The alternating flux (ϕ_m) produced in the 1ϕ induction motor can be represented by two revolving fluxes, each equal to half the value of $\left(\frac{\phi_m}{2}\right)$ the alternating flux and each rotating synchronously $\left(N_s = \frac{120f}{p}\right)$ in opposite directions.



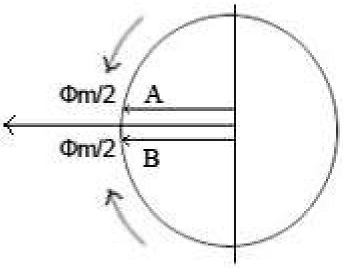
The vectors have been rotated by an angle $+\theta$ and $-\theta$.



The resultant flux would be $2 \times \frac{\phi_m}{2} \frac{\sin 2\theta}{2} = \emptyset_m \sin\theta$. After a quarter cycle of rotation, fluxes an b will be oppositely directed.

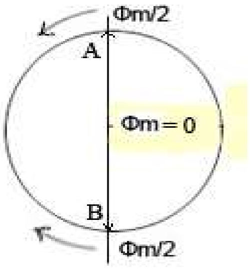


The resultant flux is now zero.

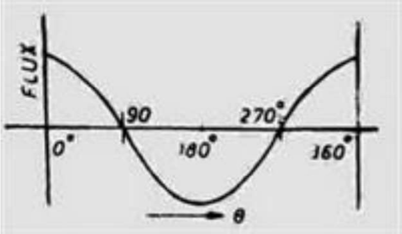


After half cycle, fluxes a and b will have resultant of $-2 \times \frac{\phi_m}{2} = \phi_m$

After three quarters of a cycle, again the resultant is zero



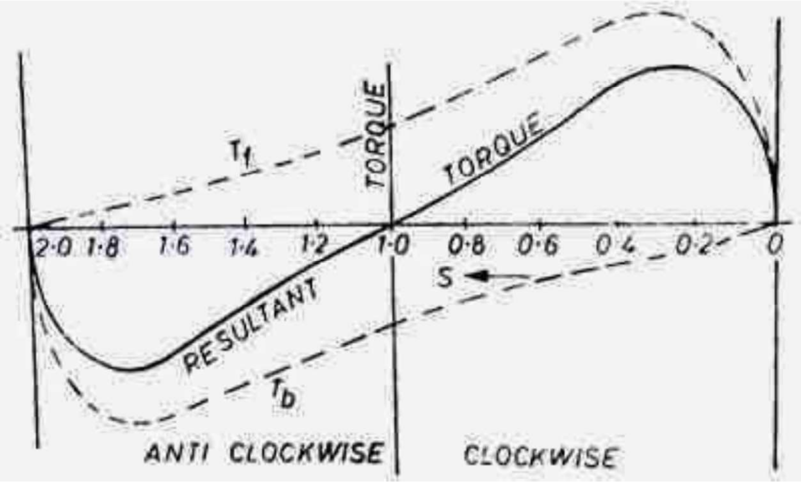
So the flux variation is ϕ_m , 0, -ϕ_m , 0.



The slip of the rotor is given by $S_f = \frac{Ns-N}{Ns}$

with respect to the forward rotating flux. The slip with respect to the backward rotating flux is,

$$S_b = \frac{N_s-(-N)}{N_s} = 1 + \frac{N}{N_s} = 1+1\text{-}s = 2\text{-}s$$



3.12 OPERATION OF SINGLE-PHASE INDUCTION MOTOR

The stator winding of a single phase induction motor is connected to single phase AC supply. Then a magnetic field is developed in the stator whose axis is always along the axis of stator windings. With alternating current in the fixed stator coil the mmf wave is stationary in space but pulsates in magnitude and varies sinusoidally with time.

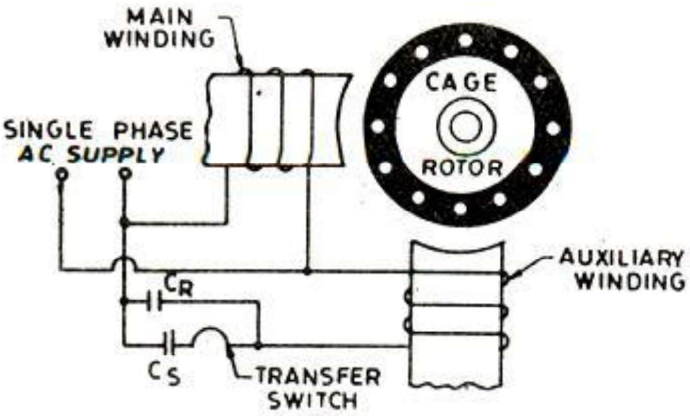
Due to the transformer action, currents are induced in the rotor conductors. The direction of the current is to oppose the stator mmf.

Thus the axis of rotor mmf wave coincides with the axis of stator mmf wave. Therefore the torque angle is zero and no starting torque is developed in the motor. However if rotor is initially given a starting torque by some means, the motor will pick up the speed and continue to rotate in the same direction. Thus the single phase induction motor is not a self-starting motor. The starting torque can be produced by some external arrangement.

3.13 STARTING OF SINGLE-PHASE INDUCTION MOTOR

The starting method of single phase induction motor is very simple. An auxiliary winding in the stator is provided in addition to the main winding. Then the induction motor starts as a two phase motor.

The main winding axis and auxiliary winding axis are displaced by 90 electrical degrees. The impedance of the windings differs and currents in the main and auxiliary winding are phase shifted from each other. As a result of this, a rotating stator field is produced and the rotor rotates.



When the motor speed is about 75% of synchronous speed, the auxiliary winding is disconnected from the circuit. This is done by connecting a centrifugal switch in the auxiliary winding which is used for starting purpose only. That is why it is called starting winding. Under running condition, a single phase induction motor can develop torque only with main winding. That is why it is called running winding.

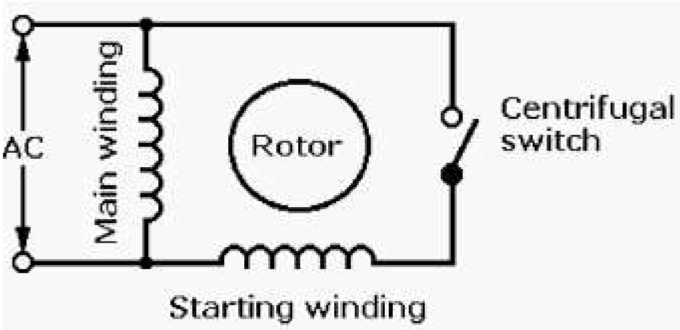
3.14 TYPES OF SINGLE-PHASE INDUCTION MOTOR

The single phase induction motors can be classified according to the phase difference produced between the current in the main and auxiliary windings. The classifications are

1. Split-phase motors
2. Capacitor – Start motors
3. Capacitor – run motors
4. Capacitor – Start and Run motors
5. Capacitor – Pole motors

Split-phase motors

It consists of two stator windings. One is the main winding or running winding and another is auxiliary winding or starting winding. These two winding axes are displaced by 90 electrical degrees. The auxiliary winding has high resistance and low reactance and main winding has low resistance and high reactance. I_r is the current flowing through the running winding and I_s is the current flowing through the starting winding. These two currents are out of phase.



The auxiliary winding is used only for starting period. When the motor is about 75% of synchronous speed, the auxiliary winding is disconnected from the circuit. This is done by connecting a centrifugal switch in the auxiliary circuit. After this, motor runs because of main winding only.

Upto 75% of speed, main and auxiliary windings are present in the circuit and after 75% of the speed is attained, only the main winding is present in the circuit. The starting torque of the motor can be increased by connecting a resistance in series with the auxiliary winding. Split-phase induction motor is also called resistance start induction motor.

It is mainly used for loads that require low or medium starting torque. The **applications** are

i) Fans
ii) Blowers
iii) Centrifugal pumps
iv) Washing machines

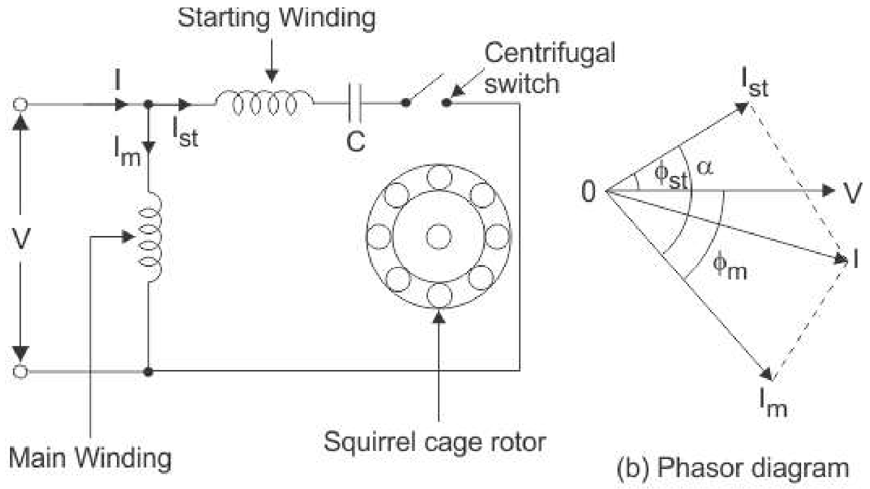
The **characteristics** of this motor are

1. The starting torque is 100% to 250% of the rated value
2. The breakdown torque is upto 300%
3. The power factor of the motor is 0.5 to 0.65.
4. The efficiency of the motor is 55% to 65%.

5. The power rating of this motor is in the range of ½ to 1 HP.

Capacitor start single phase induction motor

It is one type of single phase induction motor. Here, a capacitor is connected in series with the auxiliary winding. It is also used to get higher starting torque. Single- phase supply is applied to the windings. The starting current I_s leads the line voltage, Because of the capacitor present in the auxiliary winding. The running current I_r lags line voltage. The phase displacement between the two currents is approximately equal to 90° during starting.



(b) Phasor diagram

(a) Schematic representaion

Again the auxiliary winding is disconnected from the circuit by centrifugal switch at 75% of the synchronous speed. i.e., the capacitor is using during starting period only. The direction of rotation of the motor can be changed by changing the connections of one of the windings.

Its is mainly **used** for hard starting loads, such as

1. Compressors
2. Pumps
3. Conveyors
4. Refrigerators
5. Air conditioning equipments
6. Washing machines

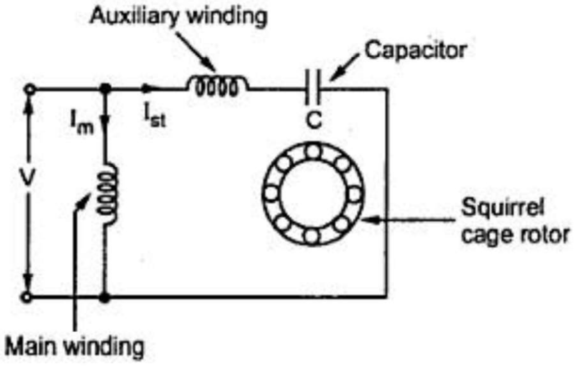
Characteristics of these motors are

1. The starting torque is 250% to 400% of the rated value.
2. The breakdown torque is upto 350%.

3. Power factor of the motor is 0.5 to 0.65.
4. The power rating of the motor is 1/8 to 1 HP.
5. The efficiency of the motor is 55% to 65%.

Capacitor – Run motor

In this motor, a capacitor is permanently connected in series with the auxiliary winding. Here, the centrifugal switch is not needed and therefore the cost of the motor is less.



Advantages

1. High power factor at full- load
2. High full-load efficiency
3. Increased pull-out torque
4. Low full-load line current

Applications

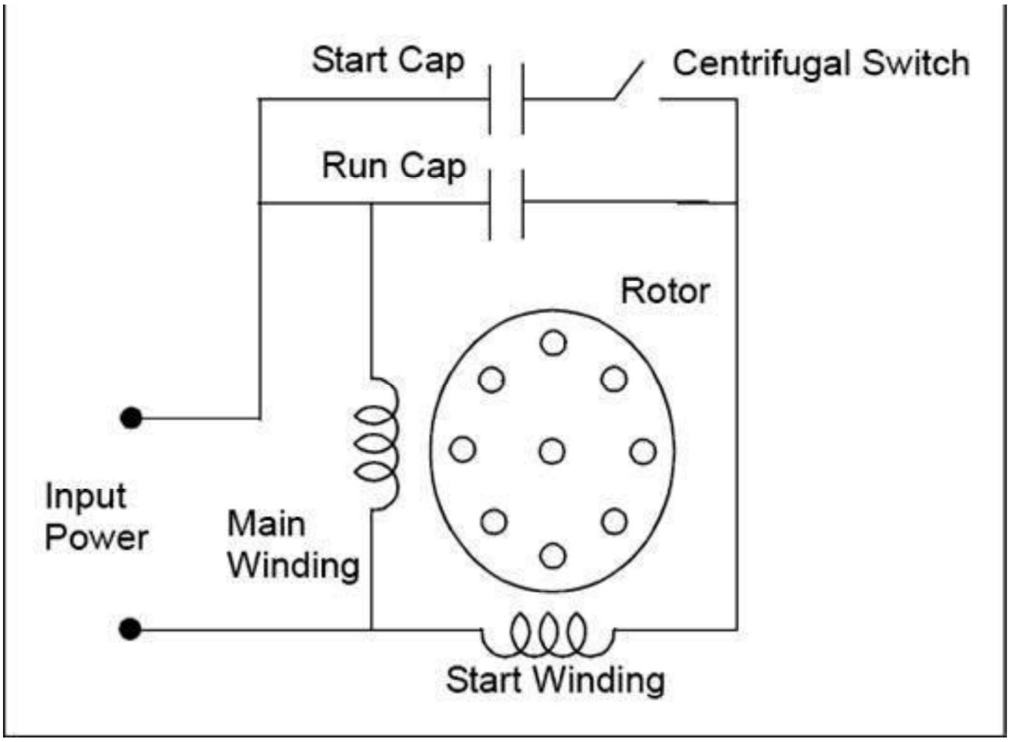
1. Fans
2. Blowers
3. Centrifugal pumps

Characteristics

1. The starting torque is 100% to 200% of the rated value.
2. The breakdown torque is upto 250%.
3. The power factor of the motor is in the range of 0.75 to 0.9.
4. The efficiency of the motor is 60% to 70%.
5. The power rating of the motor is $\frac{1}{8}$ to 1 HP.

Capacitor-start Capacitor-run motor

Here two capacitors are used. One capacitor C_s is used for starting purpose and another capacitor C_r is used for running purpose. In this motor, we can get high starting torque, because of two capacitors.



The value of a starting capacitor C_s is large and the value of running capacitor C_r is small. The running capacitor C_r is permanently connected in series with auxiliary winding. When the motor speed picks up to 75% of synchronous speed, the centrifugal switch is opened and the starting capacitor C_s is disconnected from the circuit.

The capacitor C_s is used for developing high starting torque and capacitor C_r is used to improve the power factor.

Advantages

1. High starting torque
2. High efficiency
3. High power factor

They are mainly **used** for low noise and high starting torque applications, such as

1. Compressors
2. Pumps
3. Conveyors
4. Refrigerators

Characteristics

1. The starting torque is 200% to 300% of the rated value.
2. The breakdown torque is upto 250%.
3. The power factor of the motor is in the range of 0.75 to 0.9.
4. The efficiency of the motor is 60% to 70%.
5. The power rating of the motor is $\frac{1}{8}$ to 1 HP.

Shaded Pole Motor

Construction

Shaded pole motor is a split phase type single phase induction motor. It has salient poles on the stator excited by single phase supply and a squirrel cage rotor. A portion of each pole is surrounded by a short circuited turn of copper strip called shading coil. It has no commutator, brushes, collector rings, contactors, capacitors or moving switch parts and so it is relatively cheaper, simpler and extremely rugged in construction and reliable.

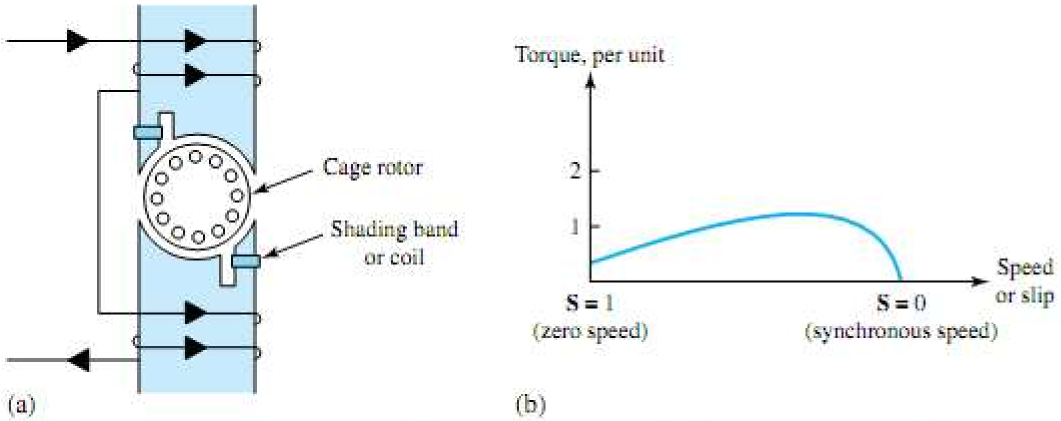


Figure Shaded-pole motor. (a) Schematic diagram. (b) Typical torque–speed characteristic.

Operation

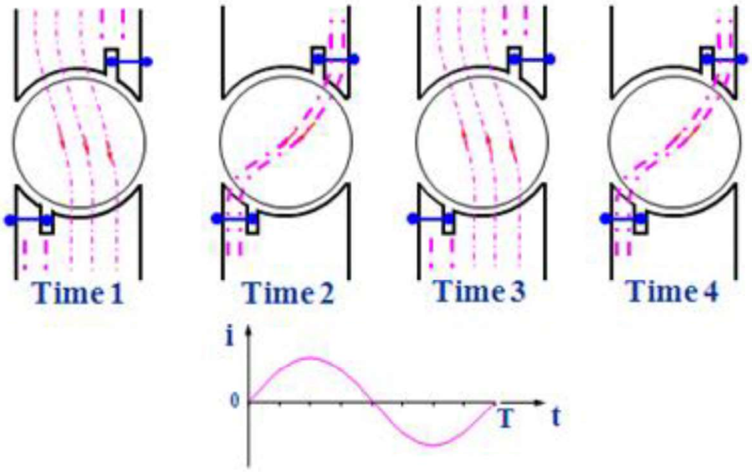
The operation of the motor can b understood by referring to which shows one pole of the motor with a shading coil.

a) During the position OA of the alternating current cycle the flux begins to increase and an emf is induced in the shading coil. The resulting current in the shading coil will be in such a direction as to oppose the change in flux. Thus the flux in the shaded portion of the pole is weakened while that in the un shaded portion in strengthened

b) During the position 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 since no current is flowing in the shading.

c) As the flux decreases i.e., 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 un shaded portion in weakened

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



The rotor is of 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. Torque speed characteristics of shaded pole motor.

The main **disadvantage** of these motors are

1. Low efficiency
2. Low power factor
3. Very low starting torque

The main **applications** of these motors are for loads requiring low starting torque such as

1. Fans
2. Blowers
3. Turn tables
4. Hair drivers
5. Motion picture projectors

The **characteristics** of these motors are

1. The starting torque is 40% to 60%.
2. The breakdown torque is upto 140%.
3. The power factor of the motor is in the range of 0.25 to 0.4.
4. The efficiency of the motor is 25% to 40%.
5. The power rating of the motor range upto 40W.

3.15 SYNCHRONOUS MACHINES – INTRODUCTION

The machine which produces three phase power from mechanical power is called an alternator or synchronous generator or AC generator.

An alternator works on the principle of electromagnetic induction.

Like a DC generator, an alternator also has an armature winding and a field winding. But there is one important difference between the two. In a DC generator, the armature winding is placed on the rotor in order to provide a way of converting alternating voltage generated in the winding to a direct voltage at the terminals through the use of a rotating commutator. The field poles are placed on the stationary part of the machine. In alternator, the armature winding is placed on the stationary part called stator and field windings are placed on the rotating part called rotor.

3.16 ADVANTAGES OF STATIONARY ARMATURE

1. Better insulation

2. Ease of current collection

3. Increased armature tooth strength

4. More rigid construction

5. Reduced armature leakage reactance
6. Lesser number of slip rings
7. Lesser rotor weight and inertia
8. Improved ventilation and heat dissipation

3.17 CONSTRUCTION OF ALTERNATOR

An alternator has 3 phase winding on the stator and a D.C field winding on the rotor.

Stator

It is the stationary part of the machine and is built up of sheet- steel laminations having slots on its inner periphery. A 3phase winding is placed in these slots serves as the armature winding of the alternator. The alternator winding is always connected in star and the neutral is connected to ground.

Rotor

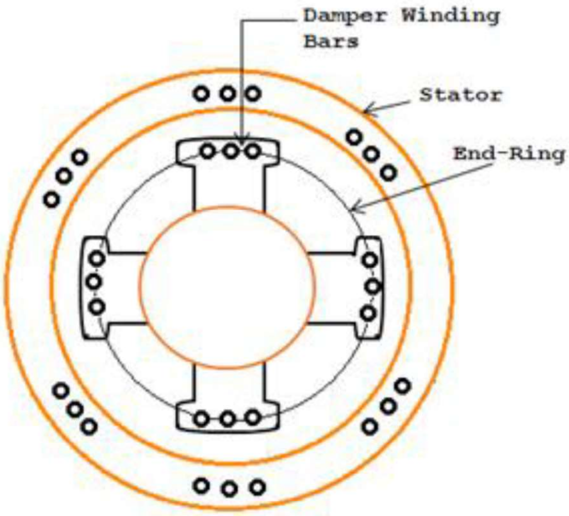
The rotor carries a field winding which is supplied with direct current through two slip rings by a separate d.c. source. Rotor construction is two types, namely,

1. Salient (or) projecting pole type
2. Non- Salient pole (or) cylindrical type

Salient (or) projecting pole type

The rotor of this type is used almost entirely for slow and moderate speed alternators, since it is least expensive and provides ample space for the field ampere-turns. Salient poles cannot be employed in high speed generators on account of very high peripheral speed and the difficulty of obtaining sufficient mechanical strength.

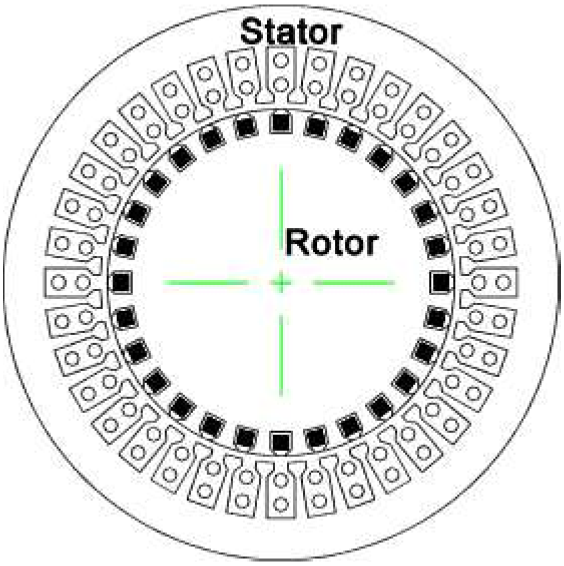
The salient poles are made of thick steel lamination riveted together and are fixed to rotor by a dove-tail joint. The pole faces are usually provided with slots for damper windings. These dampers are useful in preventing hunting. The pole faces are so shaped that the radial air gap length increases from the pole centre to the pole tips so that the flu distribution over the armature is sinusoidal. The field coils are placed on the pole-pieces and connected in series. The ends of the field windings are connected to a d.c. source through slip-rings carrying brushes and mounted on the shaft of the field structure.



Smooth cylindrical or non salient pole type

The rotors of this type are used in very high speed alternators driven by steam turbines. To reduce the peripheral velocity, the diameter of the rotor is reduced and axial length is increased. Such rotors have two or four poles.

It consists of a cylindrical steel forging which is suitably fabricated mechanically and treated thermally. The forging has radial slots in which the field copper, usually in strip from is placed. The coils are held in place by steel or bronze wedges and the coil ends are fastened by metal rings. The slots over certain portions of the core are omitted to form pole faces.



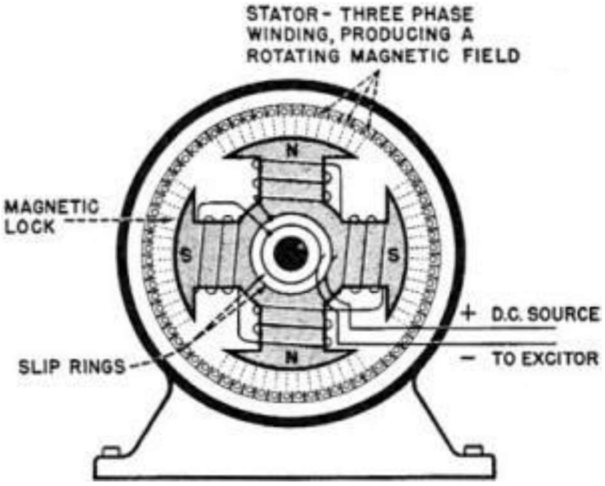
3.18 WORKING OF ALTERNATOR

The field magnets are magnetized by applying 125Volts or 250Volts through slip rings. The field windings are connected such that, alternate N and S poles are produced. The rotor and hence the field magnets are driven by the prime mover. As the rotor rotates, the armature conductor are cut by the magnetic poles are alternately N and S pole, this emf acts in one direction and then in the other direction. Hence an alternating emf is induced in the stator conductors. The frequency of induced emf depend on the number of N and S poles moving pas an armature conductor in one second. The direction of induced emf can be found by Fleming's right hand rule and frequency is given by

$$f = \frac{PN}{120}$$

Where N = speed of rotor in r.p.m,

P = Number of rotor poles.



3.19 TYPES OF ALTERNATOR

Alternators are two types

i) Rotating armature type

ii) Rotating field and stationary armature type.

3.20 EMF EQUATION OF AN ALTERNATOR

Let Z = number of conductors or coil sides in series/phase

Z = 2T, where T is the number of coils or turns per phase

P = number of poles

F = frequency of induced emf in Hz

ϕ = flux/pole in webers

K_d = distribution factor = $\dfrac{\sin\frac{m\beta}{2}}{m\sin\frac{\beta}{2}}$

K_c or K_p = pitch factor (or) coil span factor = cos $\alpha/2$

K_f= form factor = 1.11 – if emf is assumed sinusoidal

N = rotor speed in r.p.m

For one revolution of the rotor each stator conductor is cut by a flux of ϕ P webers

d ϕ = ϕ P and dt = 60/N second.

Average emf induced per conductor = $\frac{d\phi}{dt} = \frac{\phi P}{60/N} = \frac{\phi PN}{60}$

We know that f = $\frac{PN}{120}$ (or) N = $\frac{120f}{P}$

Substituting this value of N, we get average emf per conductor

$$= \frac{\phi P}{60} \times \frac{120f}{P} = 2f\phi \text{ volt}$$

If there are Z conductors in series / phase, then

Average e.m.f/phase = 2f ϕ z volts = 4f ϕ T volts

The above equation is true only, if the winding is concentrated in one slot. But practically it is not true, as the winding for each phase under each pole is distributed and for such cases K_p and K_d must be considered.

Actually available voltage/phase = 4.44 $K_p K_d$ f ϕ T volts

If the alternator is tar connected, then the line voltage is $\sqrt{3}$ times the phase voltage.

3.21 VOLTAGE REGULATION

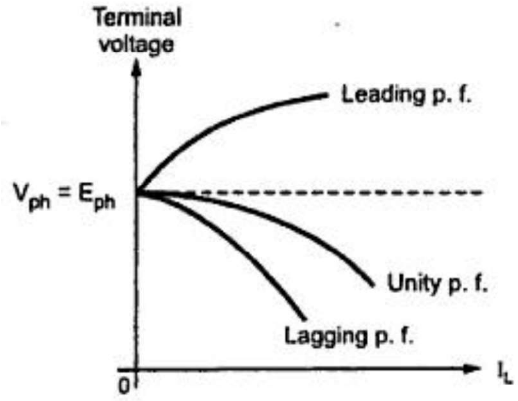
The voltage regulation of an alternator is defined as the increase in terminal voltage when full load is thrown off, assuming field current and speed remaining the same. The percentage regulation is defined as the ratio of change in terminal voltage from full load to no load rated terminal voltage.

Percentage regulation = $\frac{E_o - V}{V} \times 100$

Where, E_o = No load Terminal voltage

V = Full load rated terminal voltage

Voltage characteristics of an alternator are shown

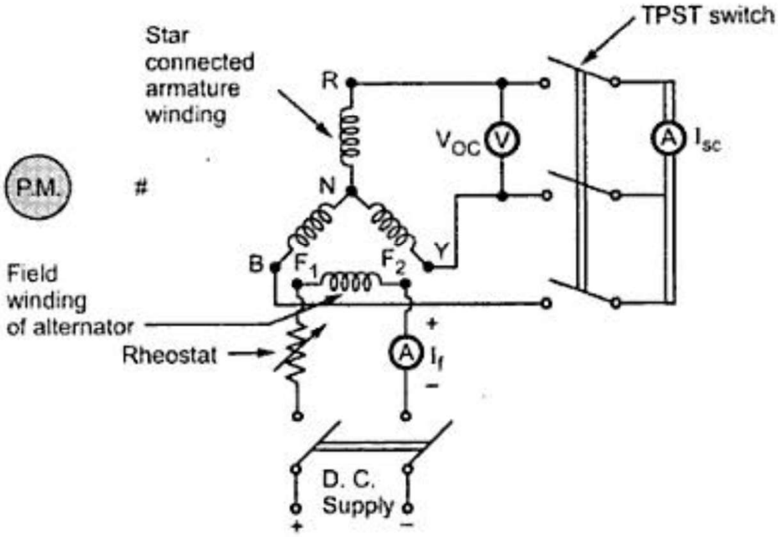


To determine the regulation of an alternator, open circuit and short circuit tests are performed, which give open circuit characteristic and short circuit characteristic.

1. Open circuit test
2. Short circuit test
3. Measurement of armature resistance per phase.

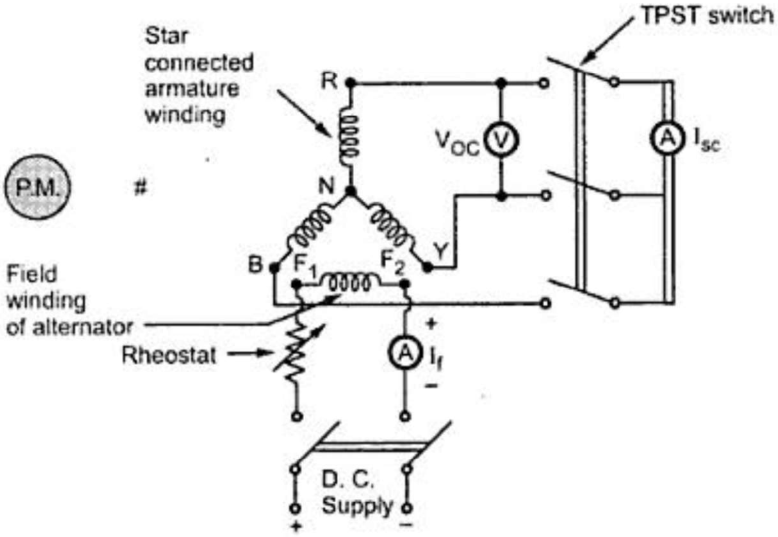
Open circuit test

The alternator is driven at its rated speed and this speed is kept constant throughout the test. The field excitation is gradually increased and for different values of the field current, corresponding values of the no-load induced emf are noted. Field excitation is increased until the alternator builds up the rated voltage. From the on data no-load test, a graph of the open circuit voltage per phase against the field current is plotted. This graph is known as open circuit characteristic (or OCC).



Short circuit test

The alternator is driven at its rated speed on no load. The field excitation is kept minimum.



The field current is adjusted such that the rated current flows through the short-circuited armature. The value of the field current which causes the rated current to flow through the short circuited armature windings is noted. From the data obtained the short circuit characteristic (or S.C.C) which is the graph of I_a V_s I_r is drawn.

Measurement of armature resistance per phase

The d.c resistance/phase of the armature winding is measured by Ammeter- Voltmeter method (or using Wheatstone Bridge).A small direct current is passed through one phase (or winding) of the armature and the voltage drop across it is noted.

$$\text{D.C resistance of armature/phase} = \frac{Voltmeter\ reading}{Ammeter\ reading}$$

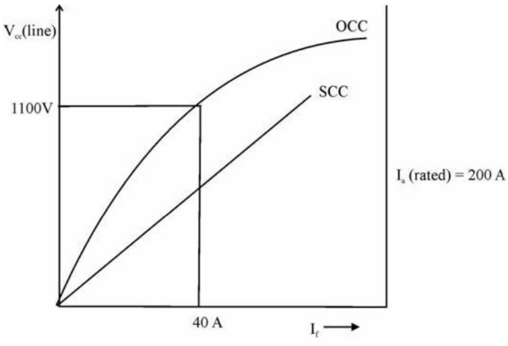


Fig. M4 Occ and Scc characteristics

$$Z_s = \frac{AC(in\ volts)}{AB(inamps)} \text{ at constant } I_f$$

$$\text{Synchronous reactance } X_s = \sqrt{Z_s^{\ 2} - R_a^{\ 2}}$$

3.22 DETERMINATION OF VOLTAGE REGULATION

In case of small machines, the regulation may be found by direct loading. In the case of large machines, the cost of finding the regulation by direct loading becomes prohibitive. Hence, indirect methods are used. Results of the open circuit and short circuit characteristics are required. Voltage regulation can be determined by the following indirect methods.

- EMF or synchronous impedance method
- MMF or Ampere turn method
- Zero power factor or Potier method

All the above methods have the following requirements.

1. Armature resistance (R_a)
2. Open-circuit characteristic (Zero power factor lagging characteristic is required for potier method).

SYNCHRONOUS Impedance Method or E.M.F Method

This method involves the following steps.

i) Plot the Open-circuit characteristic (O.C.C)

ii) Plot short-circuit characteristic (S.C.C)

Both these curves are drawn on a common field current base.

Consider a field current I_f. Corresponding to this field current the Open-circuit voltage is E_1. When the winding is short circuited, the terminal voltage is zero. Hence, it may be assumed that the whole of this voltage E_1 is being used to circulate the armature short-circuit current I_1 against the synchronous impedance Z_s.

$$E_1 = I_1 Z_s \text{ (or) } Z_s = \frac{E_1}{I_1}$$

iii) To find synchronous reactance X_s

iv) After finding R_a and X_s Vector diagrams for any load any power factor may be drawn. Three cases are considered a) unity power factor b) lagging power factor and c) leading power factor.

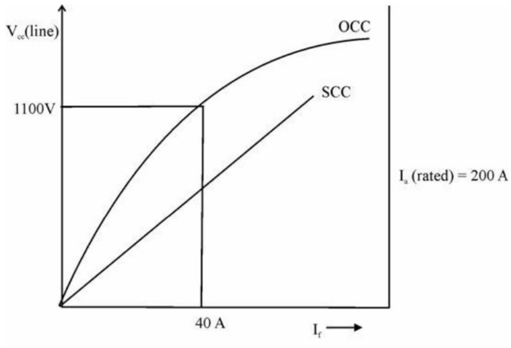
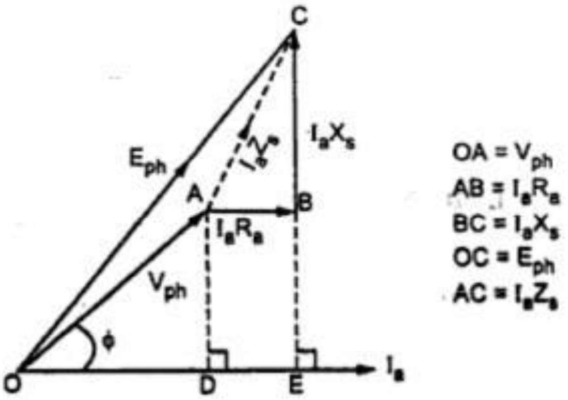


Fig. M4 Occ and Scc characteristics

$$OC^2 = (OA + AB)^2 + BC^2$$

i.e., $E_o^2 = (V + IR_a)^2 + (IX_s)^2$

(or) $$E_o = \sqrt{(V + IR_a)^2 + (IX_s)^2}$$



$$OC^2 = (OA + AB)^2 + (BD + DC)^2$$

$$E_o^2 = (V \cos\phi + IR_a)^2 + (V \sin\phi + IX_s)^2$$

(or) $$E_o = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_s)^2}$$

$$OC^2 = (OF + FD)^2 + (BD - BC)^2$$

$$E_o^2 = (V \cos\phi + IR_a)^2 + (V \sin\phi - IX_s)^2$$

(or) $$E_o = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi - IX_s)^2}$$

AMPERE- TURN OR M.M.F METHOD

This method is the converse of end method. In this method the effect of winding impedance and armature reaction are equivalent to ampere-turns and hence this method is called mmf method. The required data for calculation of regulation are obtained from the open and short circuit tests of the alternator.

From the OC and SC Characteristics, field current I_{f1} is determined to give rated voltage V on no load, neglecting armature resistance drop, and field current I_{f2} is determined to cause short circuit current, equal to full load current, on short circuit.

On short circuit, the field excitation I_{f1} balances the impedance drop in addition to armature reaction on full load. But since R_a is usually very small and X_L is also small for low voltage on short circuit, impedance drop can be neglected.

P.f. on short circuit is almost zero lagging and the field ampere-turns are used entirely to overcome armature reaction. Therefore I_{f2} gives demagnetizing ampere turns at full load.

Now let the alternator supply full load current at a p.f of $\cos\phi$. Draw OA representing I_{f1} to give full load rated voltage, V (or more exactly $V + IR_a\cos\phi$) then draw angle ($90° \pm \phi$) representing I_{f2} to give load rated current on short circuit; +ve sign for lagging power factor and –ve sign for leading power factor. Now find the field current I_f measuring OB, which will give on open circuit an e.m.f E_o, which can be determined from O.C.C.

The percentage regulation can be obtained from the following relation.

$$\%\text{Regulation} = \frac{E_o - V}{V} \times 100$$

This method is also known as optimistic method since it gives value lower than actual values.

3.23 SYNCHRONOUS MOTOR

The synchronous motor is one type of 3 phase A.C motors which operate at a constant speed from no load to full load.

3.24 PRINCIPLE OF OPERATION OF SYNCHRONOUS MOTOR

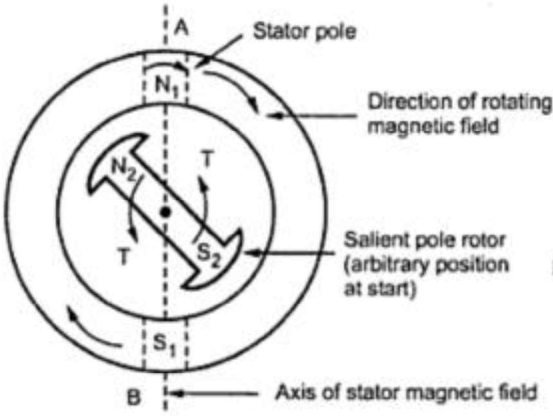
When a sinusoidal (single phase) voltage is applied to winding, the magnetic field produced by the resultant current flow will also be sinusoidally varying with respect to time. This means that the field is pulsating. Now when a three-phase voltage is applied to a three phase winding, the flux produced will be the resultant of all three pulsating fields.

It can be shown that the resultant field has a magnitude of $1.5\phi_m$ where ϕ_m is the maximum value of the flux due to single phase current. Further it can also be shown that the direction of the field changes continuously, i.e., the field is rotating in space at a speed given by.

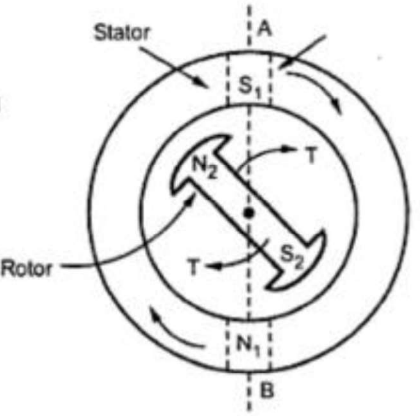
$$N_s = \frac{120 \times f}{P}$$

Where f is the frequency of supply and P is the number of poles. This speed is called the synchronous speed.

Hence it it to be remembered that when a three-phase supply is given to a three-phase winding a magnetic field of constant magnitude but rotating at a constant speed, N_s is produced.



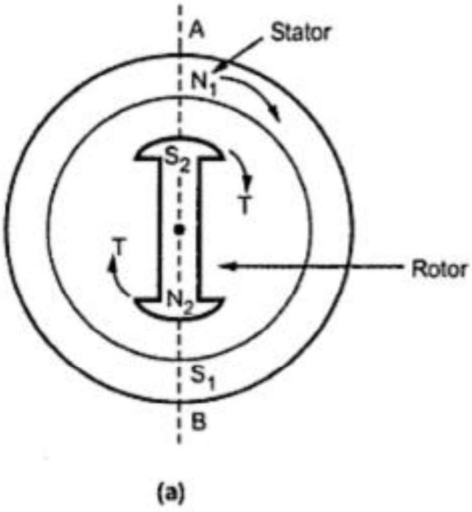
(a) Action of synchronous motor



(b) Action of synchronous motor

The two fictitious stator poles marked N_S and S_S assumed to rotate clockwise at a synchronous speed $N_{s.}$ The rotor poles (assumed to be only 2 in number), N_R and S_R are formed y the d.c excitation. When N_S and N_R are together (and similarly S_S and S_R) like poles repel each other; since N_S and S_S are moving in the clockwise direction, N_R and S_R tend to figure. Half a cycle later, the stator poles have moved, whereas the rotor poles have moved significantly. This situation is shown figure. N_S and S_R and similarly S_S and N_R get attracted and the rotor tries different to rotate in the clockwise direction. This implies that the rotor experiences torque in different directions every half cycle. As a result, the rotor is at standstill due to its large inertia. This explains why a synchronous motor has no starting torque and cannot start by itself.

However; if the rotor is now rotated separately by prime mover in the same direction as the synchronously rotating stator field, and at a speed near N_s then it is possible that at some instant of time, N_S and S_R and similarly S_S and N_R (i.e., The stator and rotor poles) get attracted and locked to one another.



Hence a synchronous motor, through not self starting, starts working as a motor if it is started up by some means. It needs two separate supplies – one a d.c source for excitation of the rotor and other, a three-phase supply for the stator. Because of the interlocking between the stator and rotor poles, the motor runs only at one speed, the synchronous speed.

3.25 TORQUE EQUATION OF SYNCHRONOUS MOTOR

$$AB = E_b \sin\alpha \text{ and } \cos\phi = \frac{AB}{I_a X_s}$$

So $$AB = I_a X_s \cos\phi$$

$$E_b \sin\alpha = I_a X_s \cos\phi \Rightarrow I_a \cos\phi = \frac{E_b \sin\alpha}{X_s}$$

$$P = V I_a \cos\phi$$

$$P = \frac{V E_b \sin\alpha}{X_s}$$

$$P_{in} = \frac{3 E_b V}{X_s} \sin\alpha \text{ For 3 phase}$$

Since stator copper loss has been neglected, P_{in} also represents the gross mechanical power (P_m) developed by the motor.

$$\boxed{P_m = \frac{3E_bV}{X_s}\sin\alpha}$$

Gross torque developed by the motor

$$T = \frac{P_m}{\omega_m}$$

$$\boxed{T = \frac{3E_bV}{\omega_m X_s}\sin\alpha} \qquad \left(\omega_m = \frac{2\pi N}{60}\right)$$

$$\boxed{T = \frac{9.55P_m}{N}\ Nm}$$

Starting Torque

- It indicates the ability of the motor to accelerate the load. It is also sometimes called "break away torque".
- It may be as low as 10% in case of centrifugal pumps, and as high as "200 or 250% of full load torque" as in case of loaded reciprocating two-cylinder compressors.
- The synchronous motor processes no self starting torque; yet in modern synchronous motors, by making proper changes in the design of damper windings, almost any reasonable torque can be developed.

Running Torque

- Running torque is the torque developed by the motor under running condition.
- It is determined by the output power and speed of the driven machine.
- Peak output power determines the maximum torque that would be required by the driven machine.
- The breakdown or maximum running torque of a motor must be greater than this value in order to avoid stalling of the machine.

Pull in Torque

- It pertains to the ability of the machine to pull in to synchronous when changing from induction to synchronous motor operation.

Pull out torque

- It is the maximum torque that the synchronous motor will develop without pulling out of synchronous. Its value ranges from 1.25 to 3.5 times the full load torque.

3.26 STARTING METHODS OF SYNCHRONOUS MOTOR

From Dc Source

- When dc supply and dc compound motor are available, the synchronous motor is coupled and started by means of a dc compound motor.
- The speed of dc motor is adjusted by the speed regulator.
- The synchronous motor is then excited and synchronized with AC supply mains.
- At the moment of synchronizing, the synchronous motor is switched on with the AC mains and either the dc motor is disconnected from the dc supply mains or the field of the dc machine is strengthened until it begins to function as a generator.
- Now the synchronous machine is operating as a motor, from ac supply mains and dc machine acts as load on it.
- The synchronous motor can also be started by the exciter mounted on an overhung synchronous motor bracket and shaft extension.
- Here again, an available dc source operates the exciter as a motor during the starting period then after the synchronous machine is brought up to speed and synchronized, the exciter assumes its normal function.

By Means of AC Motor

- A small direct coupled induction motor called the pony motor, may be used for starting the synchronous motor unless the motor is required to start against full load torque.
- The induction motor frequently has two poles less than the synchronous motor and so is capable of raising the speed of the latter to synchronous speed.
- Before switching on the AC supply to the synchronous motor, it must be synchronized with the bus bars.

- After normal operation is established, the pony motor is sometimes de-coupled from the synchronous motor.

- This method is not very satisfactory and not suited to industrial needs. Modern machine are usually of the self starting type and are arranged to start as induction motors.

By means of Damper Grids in the pole faces

- The synchronous motor is made self starting by providing a special winding on the rotor poles, known as damper winding or squirrel cage winding.

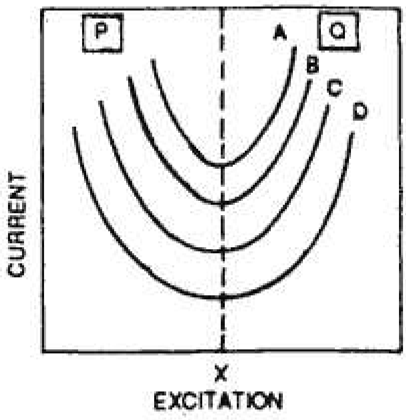
- The damper winding consists of short circuited copper bars embedded in the face of the field poles.

- AC supply given to the stator produces a rotating magnetic field which causes the rotor to rotate, therefore in the beginning synchronous motor provided with damper winding starts as a squirrel cage induction motor.

- The exciter moves along the rotor-when the motor attains about 95% of synchronous speed, the rotor winding is connected to exciter terminals and the rotor is magnetically locked by the rotating field of the stator and the motor runs as a synchronous motor.

3.27 V-CURVES

When the excitation of a three phase synchronous motor taking constant power ,P from constant voltage supply, the power factor of the motor changes. The power drawn by a 3 phase synchronous motor is given by, P = $\sqrt{3}$ V I cosΦ, where V is the line voltage, I is the armature current and cosΦ is the power factor. Since input power and supply voltage are constant, decrease in power factor causes increase in armature current and vice-versa.



Hence variation in excitation or in field current causes the variation in armature current and curves are drawn between armature current and field current for different power inputs are known as 'V' curves due to their shape similar to English letter V.

The two wattmeter method is used to measure the input power. Ammeter reading gives the line current whereas voltmeter reading gives the line voltage.

3.28 ADVANTAGES OF SYNCHRONOUS MOTOR

1. Constant speed
2. Operate at high frequencies
3. Power varies linearly with voltage
4. Better mechanically

3.29 DISADVANTAGES OF SYNCHRONOUS MOTOR

1. It cannot be started under load
2. It requires separate DC excitation
3. It has a tendency to hunt
4. Collector rings and brushes are required

3.30 APPLICATIONS OF SYNCHRONOUS MOTOR

Used in

1. Fans
2. Dc generators
3. Compressors
4. Centrifugal pumps

PROBLEMS

1. A 4 pole , 3 phase induction motor operates from a supply of frequency of 50Hz. Calculate the speed at which the magnetic field of the stator is rotating.

Given data

$P=4$

f=50Hz

To find

Ns = ?

Solution

$$Ns = \frac{120f}{P} = \frac{120\times 50}{4} = 1500\text{rpm}$$

Ns = 1500rpm

2. A 6pole , 3 phase, 50Hz induction motor has a slip of 3% at full load. Calculate the speed of full load.

Given data

P=6

f=50Hz

s=0.03

To find

N= ?

Solution

$$Ns = \frac{120f}{P} = \frac{120\times 50}{6} = 1000\text{rpm}$$

N=Ns(1-s)= 1000(1-0.03)=970rpm

N=970rpm

3. A 6 pole , 3 phase, 50Hz induction motor runs at 800rpm at full load. Calculate the value of slip at this load conditon.

Given data

P=6

f=50Hz

N=800rpm

To find

S = ?

Solution

$$Ns = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000\text{rpm}$$

$$S = \frac{Ns - N}{Ns} \times 100 = \frac{1000 - 800}{1000} \times 100$$

S = 0.2 = 20%

4. A 3 phase, 50Hz induction motor is operating at 400V supply. If the slip is 4% Calculate the frequency of its rotor induced emf.

Given data

V=400V

f=50Hz

s=0.04

To find

fr = ?

Solution

fr=sf=0.04×50=2Hz

fr=2Hz

5. A 6 pole induction motor is fed from 50Hz supply. If the frequency of rotor emfat full load is 2Hz, Calculate the slip and speed at full load.

Given data

P=6

f=50Hz

fr=2Hz

To find

S=?

N = ?

Solution

fr=sf

s=fr/f=2/50=0.04

s=0.04

$$Ns = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000 rpm$$

N=Ns(1-s)= 1000(1-0.04)=960rpm

N=960rpm

TWO MARKS

1.) What is the function of slip ring in 3 phase induction motor?

Slip rings are used to connect external stationary circuit to internal rotating circuit.

2.) Under what condition the slip in an induction motor is? a)negative b)greater than 1

a)When rotor is running at a speed above the synchronous speed slip is negative.

b) When motor is rotated in opposite direction to that of rotating field slip is greater than 1

3.) What are the 2 fundamental characteristics of a rotating magnetic field?

a) The resultant of three alternating fluxes separated from each other by 120 degree has constant amplitude of 1.5

b) The resultant always keeps on rotating with a certain speed in space.