Unit iii

AC Machines

AC machines have large advantages over DC machines.

→ Basic generation of electricity is in form of AC voltage, no converting device is necessary.

→ Cost of AC machine for same power & voltage rating is less than that of DC machines

→ As transformers are used in AC only, AC generation is must for commercial purpose operation.

AC Machines

- Generator (Alternator)
  - Salient Pole
  - Smooth Cylindrical
- Motor
  - Synchronous
  - Asynchronous
    - 3Ø Induction Motor
      - Squirrel Cage
        - Single Cage
        - Double Cage
      - Slip Ring
    - Commutator Motor
      - Series
      - Repulsion
      - Induction
        - 1Ø induction motor
          - Split Phase
          - Capacitor
          - Shaded Pole

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Three phase Induction Motor

3ϕ induction motors are most commonly & frequently encountered machines in industry.

- Simple design, low-price, easy maintenance, rugged.
- Speed depends on frequency of power source.
- Run essentially as constant speed from no-load to full load.

⇒ Construction

> Stator: 3ϕ winding in star or delta

> Rotor:

→ Squirrel Cage Rotor : Rotor windings are shorted internally.

→ Slip ring or phase wound Rotor : Rotor windings are short circuited externally through three slip rings.

> Rotor windings are short circuited.

> Slip (S): Difference b/w speed of rotor (N) & speed of rotating magnetic field (N_s).

It is expressed in % as

$$S = \left[\frac{(N_s - N)}{N_s}\right] \times 100$$

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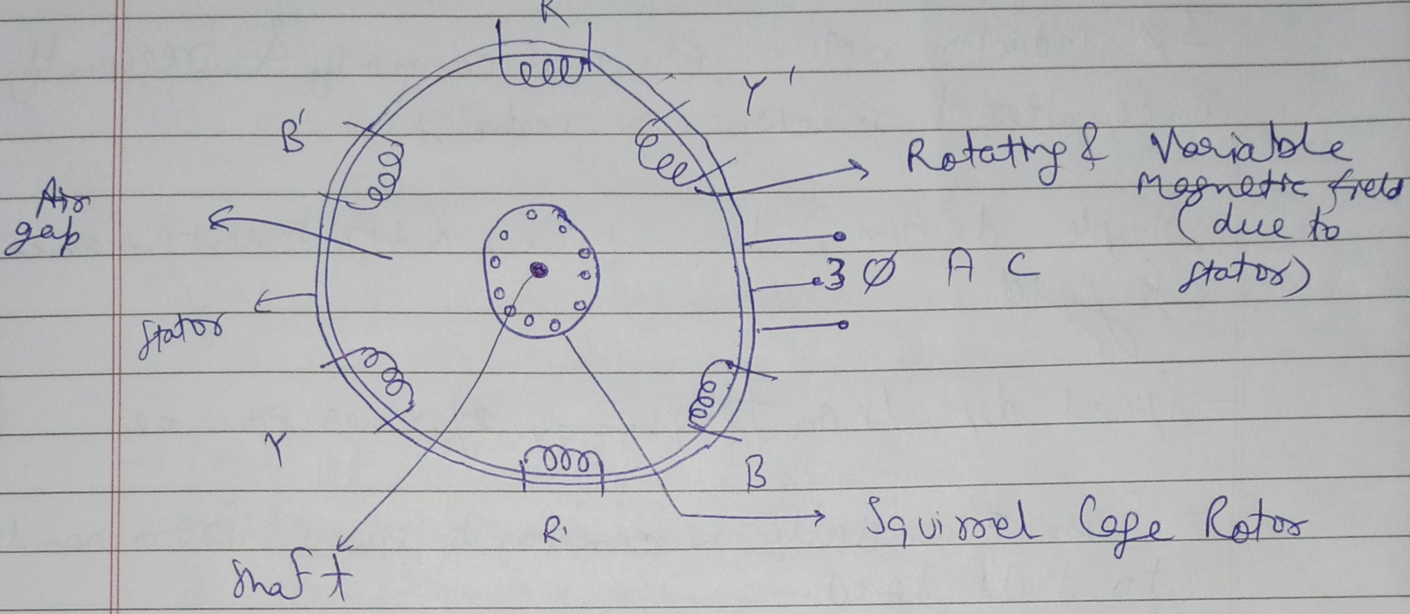
Diagram



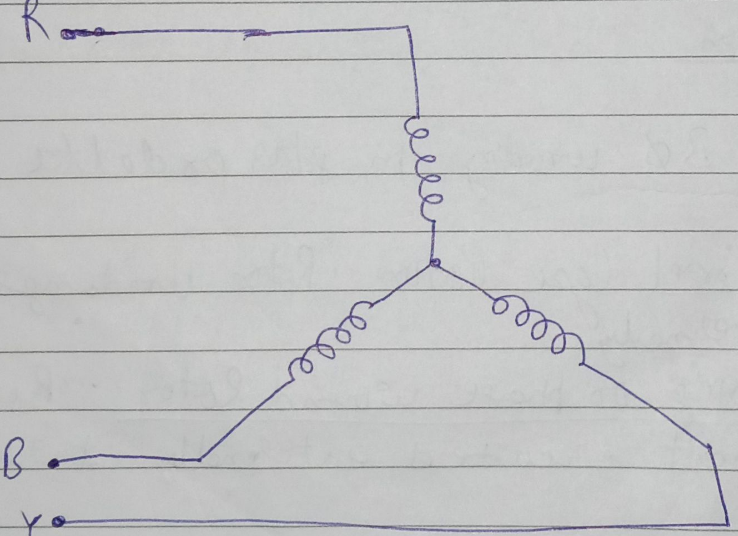


Fig - Stator Winding

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⇒ Principle

① Faraday: Electromagnetic Induction
② Lenz's Law

⇒ Operation

- 3Ø AC supply will be given to stator. So, current will flow through stator conductor & due to which stator flux rotating at constant speed speed & constant amplitude comes into picture.

- Initially rotor is at stand still condition, now stator flux will link with rotor conductors. Due to this an emf is induced in rotor circuit.

- As the rotor circuit is short circuited. So, current will flow through the rotor conductor. Corresponding to this, rotor mmf will come into the picture.
(mmf ↓ magnetomotive force)

- To follow Lenz's law, rotor mmf will try to catch stator mmf and due to this a electromagnetic torque will be produced.

- Due to this rotor will start rotating & relative speed ($N_s - N_r$) will be reduced.

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(Prerequisite) → Right Hand Thumb Rule

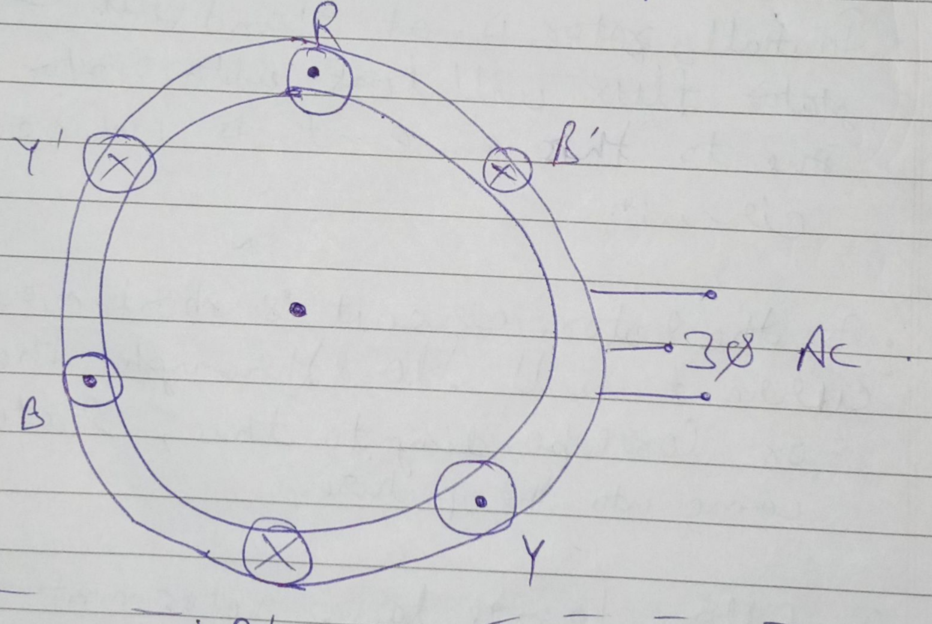
Rotating Magnetic Field

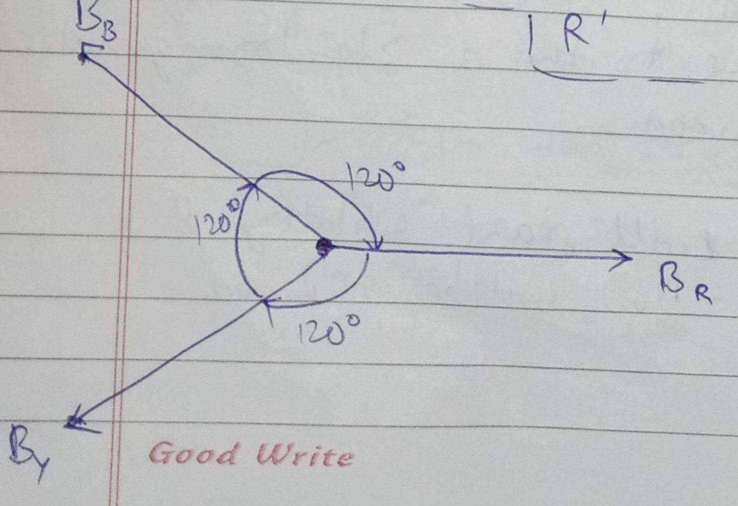
- Balanced three phase windings, i.e., mechanically displaced 120 degrees from each other, fed by balanced three phase source.

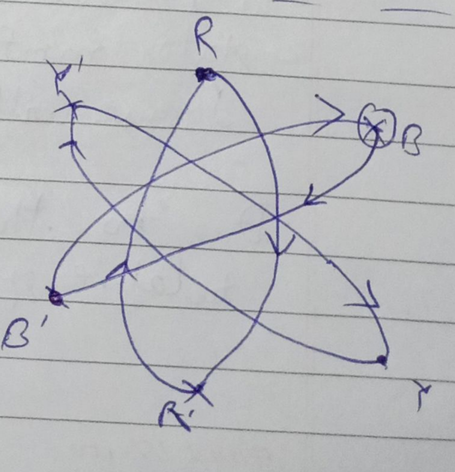
- A rotating magnetic field with constant magnitude is produced, rotating with a speed.

$$\boxed{N_{sync} = \frac{120 f_e}{P} \text{ rpm}}$$

where f_e is supply frequency &
P = no. of poles
N_{sync} = synchronous speed in rpm







Principle of operation

- This rotating magnetic field cuts rotor windings & produces an induced voltage in rotor windings.

- Due to fact that rotor windings are short circuited, for both squirrel cage and wound rotor and induced current flows in the rotor windings.

- The rotor current produces another magnetic field.

A torque is produced as a result of interaction of those two magnetic fields

$$\boxed{\tau_{ind} = K B_R B_S}$$

τ_{ind} → induced Torque

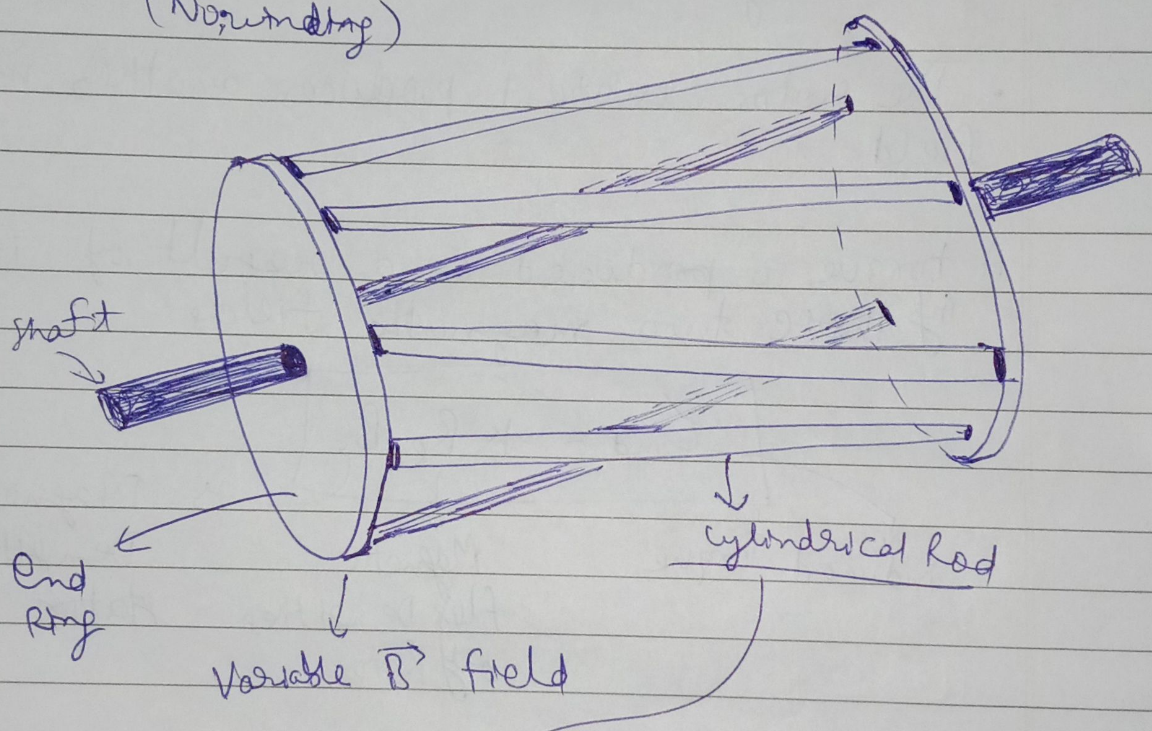
B_R → Magnetic flux Densities of Rotor

B_S → Magnetic flux Densities of stator

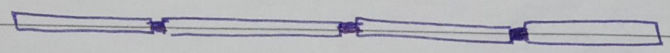
- Rotor
  - Squirrel Cage
  - Slip Wound

⇒ Squirrel Cage Rotor

(No winding)



{ Cylindrical laminated conducting bar (skewed)



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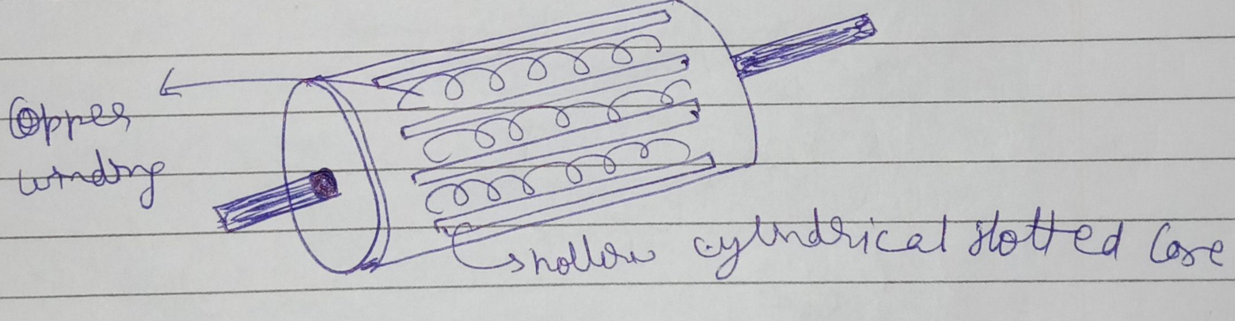
Advantages

→ Construction is simple
→ Weight is less
→ Cost is less
→ Maintenance is less
→ Efficiency is high
→ Heating effect is less

Disadvantages

→ Starting torque is less
→ Consumes more current during starting
→ Speed control is not possible.

⇒ Slip Ring Rotor



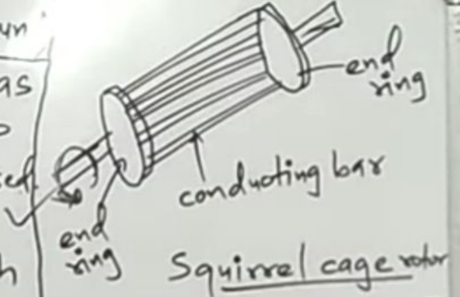
Advantages

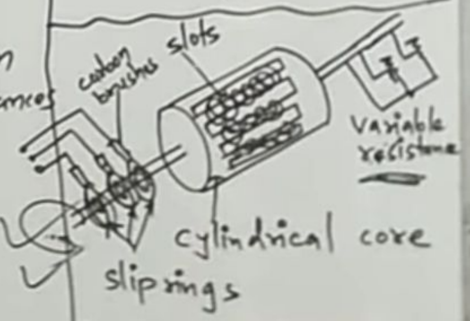
→ High starting torque
→ During starting less current is used
→ Speed control is possible.
→ ~~Ra~~ More Rotating Contacts.

Demerit

→ Construction is complicated
→ Maintenance is High
→ Cost is high.

#) Squirrel Cage induction Motor.	#) Slip ring Induction Motor (Woun
1. Construction is Simple	Construction is complicated as windings, carbon brushes, slip rings & variable resistances are used.
2. Cylindrical laminated conducting bars are used.	Cylindrical laminated core is used which is slotted on which copper winding is present.
3. Conducting bars are short circuited with end rings on both sides.	On one side slip rings & on another side variable resistances are connected.
4. No possibility to add external resistance.	Possible to add external resistance in windings.
5. Speed control is not possible	Speed control is possible.
6. Starting torque is less	Starting torque is more.
7. No moving contacts in rotor	Carbon brushes & slip rings are moving contact in rotor.
8. Starting current is high to start the motor.	Starting current is less to start the motor.
9. Higher efficiency.	Lower efficiency.
10. Cheaper in cost.	Cost is high.





5.27. SLIP(S)

The difference in the speed of stator magnetic flux and rotor (conductor) is called slip.

$$\therefore \quad \text{Slip} = N_s - N \qquad ...(5.72)$$

where, N_s = Synchronous speed or speed of stator magnetic flux

N = Speed of rotor

It is expressed as the percentage of the synchronous speed

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

$$\%\ s = \frac{N_s - N}{N_s} \times 100 \qquad ...(5.73)$$

$$\text{or } s = \frac{N_s - N}{N_s} \qquad ...(5.74)$$

$$\Rightarrow \quad s = 1 - \frac{N}{N_s}$$

$$\Rightarrow \quad N = N_s(1 - s) \qquad ...(5.75)$$

5.28. FREQUENCY OF ROTOR CURRENT (f^1)

When the rotor is stationary the frequency of the rotor current is the same as the supply frequency (f). But, when the rotor starts rotating, the frequency of rotor current depends upon the relative speed. Let the frequency of rotor current be 'f^1'

We have, relative speed = $N_s - N$

$$\text{where,} \quad N_s = \frac{120\,f}{P} \qquad ...(i)$$

According to definition of 'f^1'

$$N_s - N = \frac{120\,f^1}{P} \qquad ...(ii)$$

$$\frac{(ii)}{(i)} \text{ gives } \frac{N_s - N}{N_s} = \frac{f^1}{f}$$

$$\therefore \quad s = \frac{f^1}{f}$$

$$\Rightarrow \quad f^1 = s.f. \qquad ...(5.76)$$

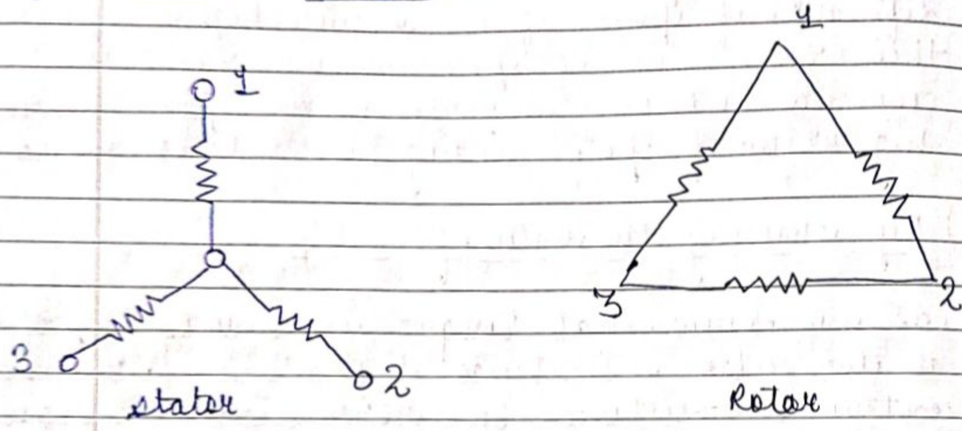
V. Imp.

Need of Starter

In the case of three phase induction motor when we provide three phase ac supply directly to the stator the value of starting current is 1.5 times greater than rated current this starting current may be damage the motor or create abnormal condition for controlling starting current or protection of motor we use starter.
There are following type of starter used in three phase induction motor :-

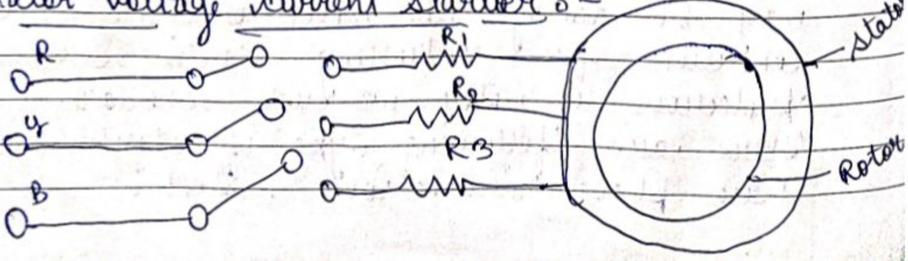
1) Star - delta starter.
2) Stator voltage control starter.
3) Autotransformer Starter.
4) Direct online Starter (D.O.L)

(*1) Star-Delta starter :-



In star-delta starter stator winding is connected as a star connection and rotor winding is connected in delta connection. Due to star connection on stator winding the value of ~~supply~~ phase voltage $V_P = \frac{V_L}{\sqrt{3}}$ is less. Therefore the value of supply voltage is low and starting current will be also low which is required condition for starting.

(* 2) Stator voltage current starter :-



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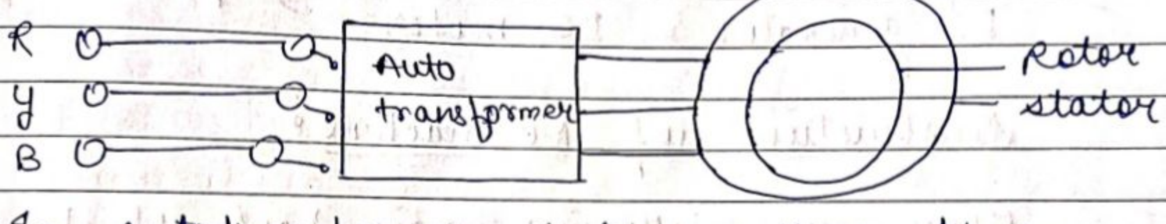
(increase) In stator voltage control method we can decrease the stator voltage by adding rheostat on stator side by varrying the value of resistance we can decrease the value of stator voltage which decrease the value of starting current and due to this motor will operate in normal condition.

(*3) Autotransformer Starter :-



In autotransformer starter a three phase autotransformer is connected to the stator of induction motor and supply is given to the autotransformer and with the help of autotransformer we can vary the value of stator voltage and in the case of starting ~~voltage~~ the value of stator voltage will be low due to this the value of starting current will also be low which operate the motor in normal condition.

(*4) Direct Online starter (D.O.L):-

D.O.L

In ~~that~~ starter a relay is used for connected ~~for n~~ of motor because if the value of current is high compared to the rated current relay send the signal to the fuse & fuse will be trip which is req condition for motor protection at the case of

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~~condition~~ for starting.

5.31. APPLICATIONS OF 3 PHASE INDUCTION MOTOR

Slipring induction motor: These motors are used in places where high starting torque is required (also starting currents should be low) such as pumps, fans, conveyors, hoists, compressors, lifts, etc.

Squirrel cage induction motor:

When the requirement is

(i) Low starting torque, with normal starting current e.g., fans and centrifugal pumps.

(ii) High torque with low starting current e.g., conveyors, compressors, crushes, agitators, reciprocating pumps.

(iii) High torque with medium and high slip e.g., sheers, punches, die stamping etc.

(iv) Normal torque with normal starting current e.g., fans, blowers, centrifugal pumps, line shafting etc.

Application
(Most used at household & <500 W works)

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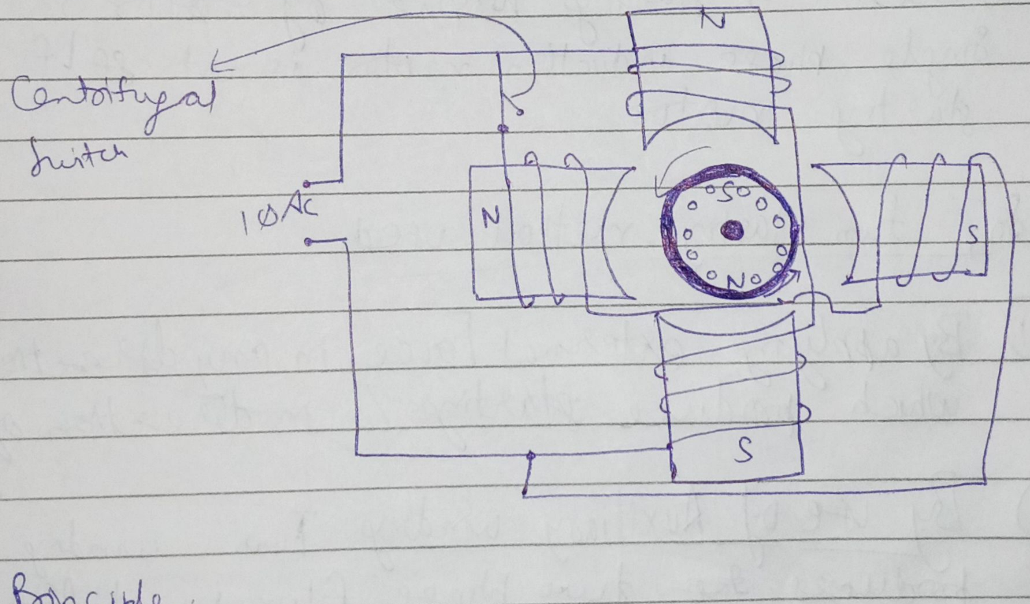
▪ Single Phase Induction Motors

Single phase induction motors operates on ~~single~~ single phase supply. They find wide variety of applications in industries, workshops, offices, space vehicles as well as for domestic purposes

Rotor → Squirrel cage type used.
Stator has two windings → i) main winding
ii) Auxiliary (starting) winding

Single ϕ induction motor is not self starting motor (unlike 3ϕ induction motor which is self starting).



Principle:

→ Faraday's Law
→ EMI (Electromagnetic Induction)
→ Lenz's Law

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(This can also be called Double field Revolving Theory)

Working / Operation

When pulsating flux linking with rotor conductor, then it produces torque due to faraday's law. When the portion of flux linked with rotor conductor, it produces forward torque in one direction, & -ve portion of flux produces torque in opposite direction as backward torque.

Continuous forward & backward torque acting in opposite direction in very small duration of time. Hence, due to moment of inertia, rotor will not rotate in any direction & starting torque of rotor is 0. Single phase induction motor is not self starting motor.

So, two starting method used:

1. By applying external Force in any direction, which produce starting T in direction of external F.

2. By use of Auxiliary winding: Two winding produces ~~too~~ two phase flux in difference phases. This produces rotating Magnetic Field, due to phase difference. When rotating Magnetic Field linked with rotor conductor, it produces starting torque in the direction of stator Magnetic field.

Double Field Revolving Theory

- When the rotor is stationary i.e. Standstill condition, the induced voltages are equal and opposite
- Consequently, the two torques are also equal and opposite
- Hence, at standstill the net torque is zero
- In other words, ***"a single phase induction motor with a single stator winding inherently has no starting torque"***
- However, if the rotor is given an initial rotation by auxiliary means in either directions, the torque due to the rotating field acting in the direction of the initial rotation will be more than the torque due to the other rotating field
- Hence the motor will develop a net positive torque in the same direction as the initial rotation
- The motor will, therefore, keep moving in the direction of the initial rotation

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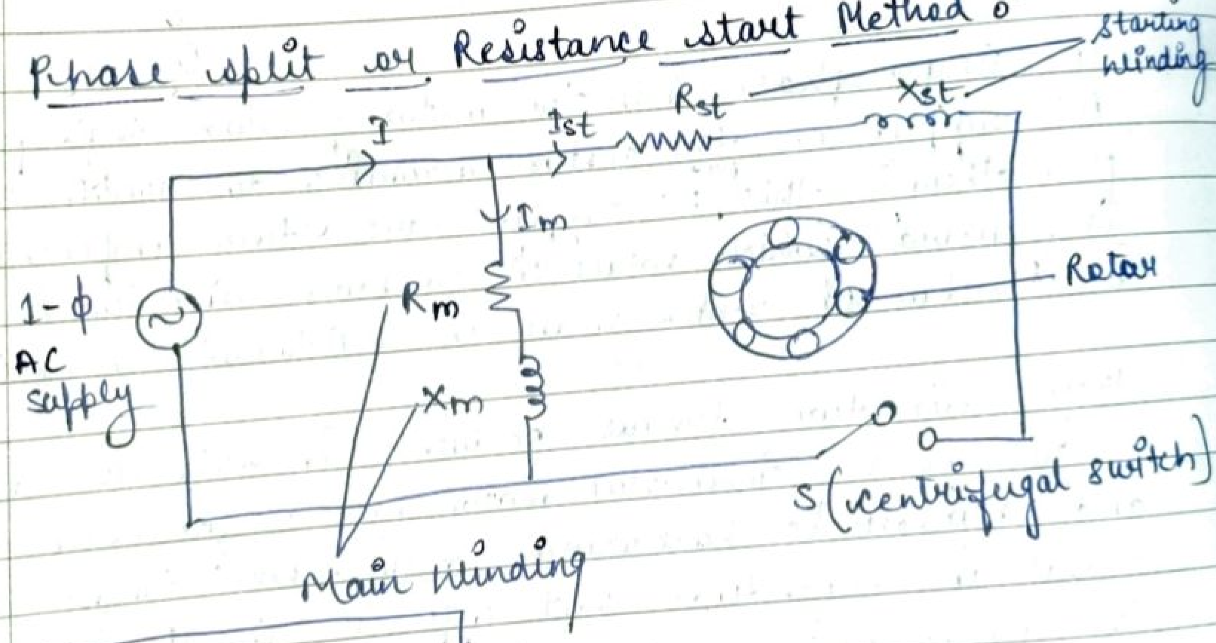
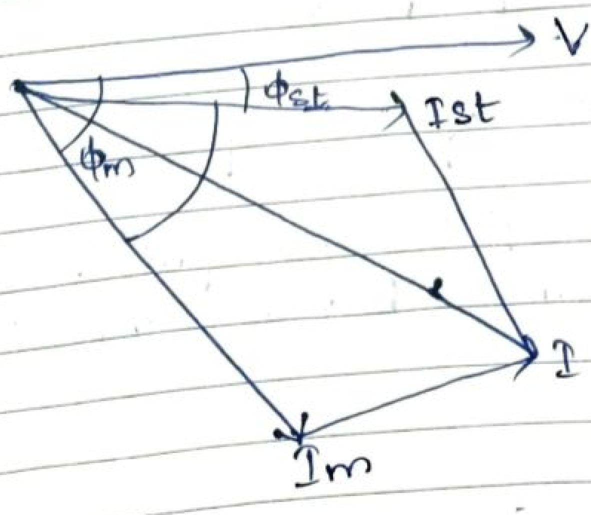
* There are following method of starting of {Types of motor} single phase induction motor —

1) Phase split or Resistance start Method.
2) Capacitor start Method.
3) Capacitor start Capacitor Run Method.
4) Permanent Capacitor Method.

*1) Phase split or Resistance start Method :—



$$\boxed{\frac{R_{st}}{X_{st}} > \frac{R_m}{X_m}}$$

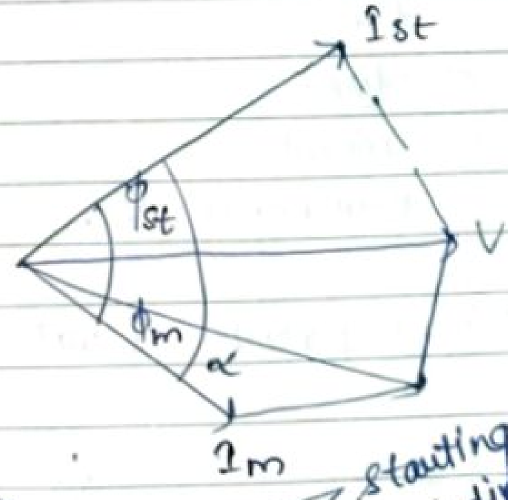


Phasor Diagram

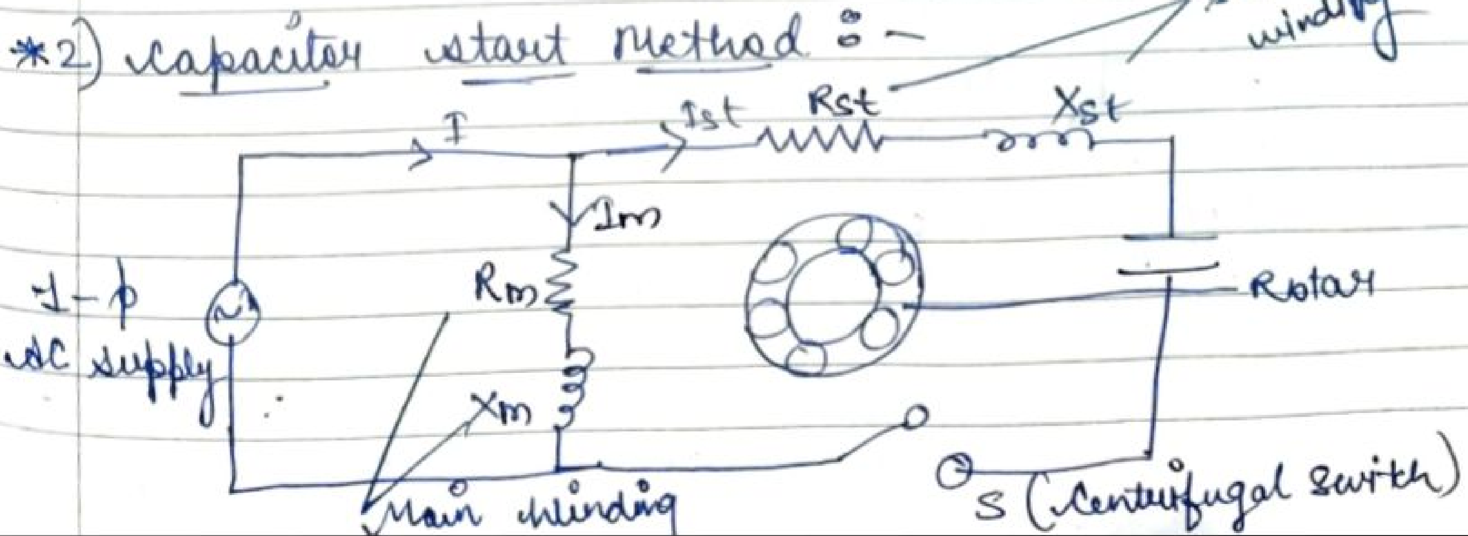
- In resistance start method single winding split in two part one is starting winding which have highly resistive and low inductive & another is main winding which have low resistive & highly inductive.
Due to highly resistive & low inductive the phase angle b/w voltage & current (I_{st}) is near about 25°-35° and due to low resistive & highly inductive the phase angle between voltage & current (I_m) 65°-75°. Due to interaction of starting winding current & main winding current a resultant current produce which develop a torque which rotate the rotor when motor speed will be reached at 70-80% of full speed centrifugal switch disconnected from the circuit & with the help of main winding motor will be rotate.

- Application :-

→ fans
→ Mixer
→ Grinder
→ Hair dryer etc.



*2) Capacitor start Method :-



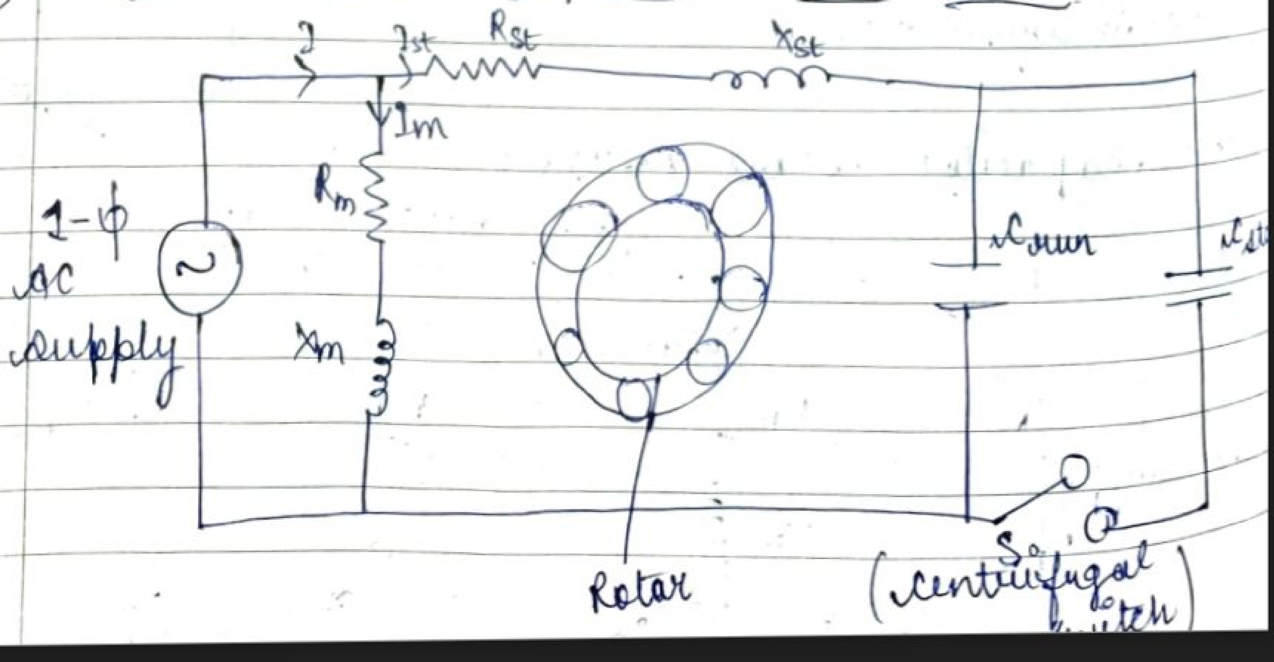
In the case of capacitor start method capacitor is connected with starting winding due to this capacitor, starting torque will be high but when motor speed Reach 70 – 80% of full speed centrifugal switch will be disconnected from the circuit & due to main winding motor will rotate.

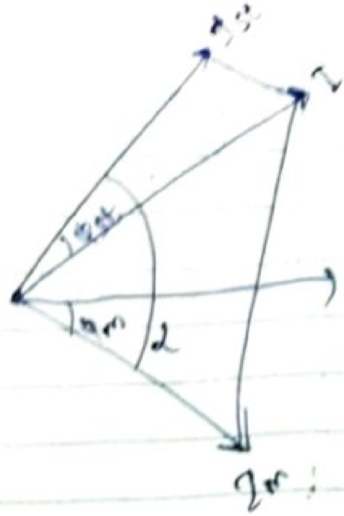
Due to non-availibility of capacitor ~~in running condition~~ the value of torque will be low therefore this method is not more suitable

Applications :-

- fans
- Mixer
- Grinder
- Hair dryer etc.

*3) capacitor start capacitor run method.





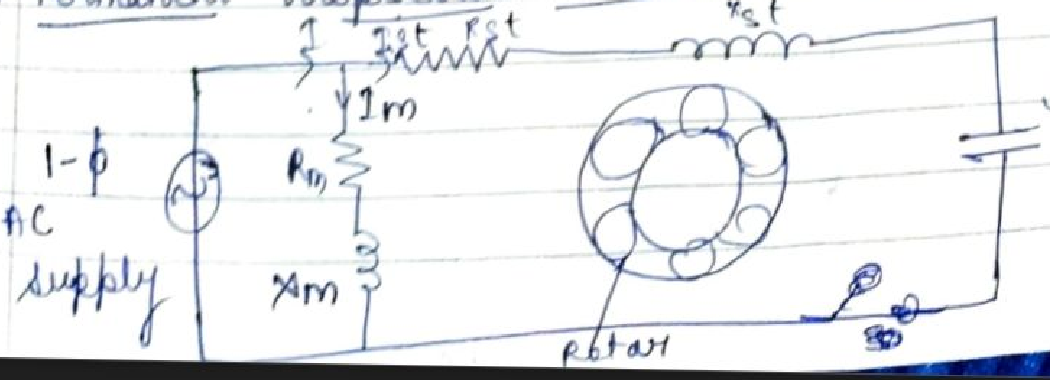
In capacitor start capacitor run method two capacitor are used, one is starting purpose known as C start & another is running purpose known as C run.

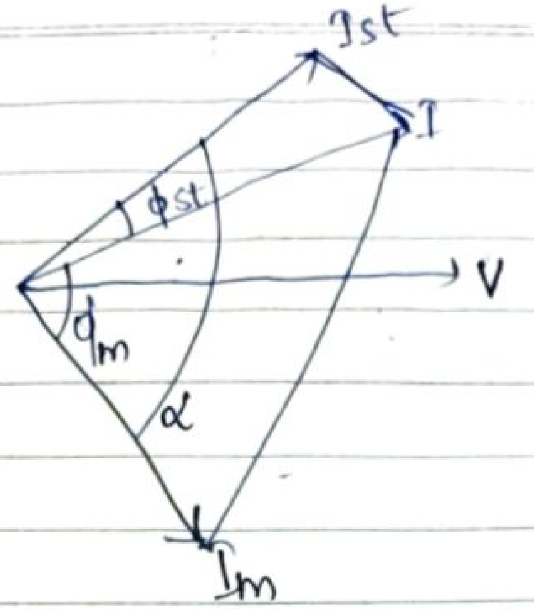
Due to two capacitor the value of torque will be high & better power factor, uniform speed will be obtain but due to two capacitor and centrifugal switch it is costly that is why this method is rarely used.

Applications :-

- fans
- Mixer
- Grinder
- Hair dryer
- AC
- Refrigerator etc.

*4) Permanent Capacitor Method





In Permanent Capacitor Method, a capacitor is connected for both starting as well as running & centrifugal switch is not used in this method. That's why this method is more economical than other. Therefore, Permanent capacitor method is mostly used for domestic application. In this method heavy torque, better power factor & uniform speed will be obtained

Applications :-

- Hair Dryer
- Fans
- AC
- Refrigerator etc.

36. Introduction to 3-Phase Synchronous Machines

An electromechanical energy conversion device (or electrical machine) which operates on synchronous speed (i.e. speed of rotating magnetic field) is termed as a **synchronous machine**. A synchronous machine an AC machine, i.e., it requires AC supply to work.

Based on the energy conversion, synchronous machines may be classified into two types:

- Synchronous Generator
- Synchronous Motor

The synchronous machines are the most extensively used electrical machines in power system applications like power generator, power factor correction, driving constant speed mechanical load, etc.

The synchronous machine which converts mechanical energy into alternating current electricity is called a **synchronous generator** or **alternator**. While the synchronous machine which converts alternating current electricity into mechanical energy is called a **synchronous motor**.

The synchronous machines, used in most practical applications, are three-phase AC machines. However, there are single-phase synchronous machines also exist but they are used in special applications.

A synchronous machine (generator or motor) always operate at a constant speed called **synchronous speed**. The synchronous speed is given by the following relation,

$$N_s = \frac{120f}{P} \quad ...(1)$$

Where,

- f is the supply frequency,
- P is the number of poles in the machine.

The synchronous speed is measured in revolution per minute (RPM).

For satisfactory operation, a synchronous machine always maintains the expression given in Equation-1. If the synchronous machine fails to maintain the above relationship of Equation-1. The machine will stop to operated, and this condition is known as **loss of synchronism** or **out of synchronism** of the machine. Hence, this proves that the synchronous machine is designed to operate at a constant speed.

Working Principle of Synchronous Machine

The working principle of a synchronous machine is based on the **law of electromagnetic interaction** and **law of magnetic interlocking**.

According to the law of electromagnetic interaction, when there is a relative motion between a conductor and a magnetic field, an EMF is induced in the conductor. On the other hand, when a current carrying conductor is placed in a magnetic field, a force acts on the conductor that tends to move it.

According to the law of magnetic interlocking, two different magnetic fields (field of stator and field of rotor) are locked together and rotate at the same speed. This phenomenon is called **magnetic interlocking**.

These two principles explain the working of a synchronous machine. The synchronous machine is first started by the electromagnetic interaction, and then the magnetic fields of rotor and stator are locked together to rotate at the synchronous speed.

Three-Phase Synchronous Generator

A synchronous machine that converts mechanical energy into 3-phase electrical energy through the process of electromagnetic induction is known as a **3-phase synchronous generator** or **alternator**.

A 3-phase alternator consists of an armature winding and a field winding, where the EMF is induced in the armature winding, while field winding produces the working magnetic field. In case of a 3-phase alternator, the armature winding is provided on the stator part of the machine while the field winding is provided on the rotor. The major advantage of stationary armature winding is that there is no need of commutator as required in the DC generators.

The 3-phase synchronous generators are most widely used for generation of electric power in power generating plants.

Three-Phase Synchronous Motor

A synchronous machine that converts three-phase electricity into mechanical energy is known as **three-phase synchronous motor**.

Like any other electric motor, a synchronous motor also consists of two major parts namely stator and rotor. The stator carries a three-phase armature winding, whereas the rotor carries a field winding which is excited from a dc supply to produce a certain number of fixed magnetic poles.

A unique feature of a synchronous motor is that it can run at a constant speed, called synchronous speed. Although, the major disadvantage of a three-phase synchronous motor is that it does not have self-starting torque. Therefore, in order to start a 3-phase synchronous motor, it is brought up almost to its synchronous speed by some auxiliary mean.

Being a constant speed motor, the load on the motor does not exceed the limiting value. If the load on the motor exceeds the limiting value, the motor will immediately stop. The three-phase synchronous motors are used for: driving mechanical loads at constant speed, improving power factor of a system, etc.

Features of Synchronous Machines

The following are the key features of synchronous machines (motor or generator):

- Synchronous motors do not self-starting torque.
- Synchronous machine is a doubly-excited machine because it requires two input supplies – one on the stator and the other on the rotor.
- Synchronous machines operate at constant speed, called synchronous speed.
- Synchronous generators can produce a voltage of constant magnitude and frequency.
- A synchronous machine can be operated at lagging, leading or unity power factor just by changing the excitation.
- Synchronous motors have relatively high starting torque as compared to induction motors.
- Synchronous motors are suitable for driving constant and slow speed (usually less than 300 RPM) loads.
- Synchronous machines are expensive.

5.41. CONSTRUCTIONAL DETAILS (of revolving field type alternator)

The two major parts of an alternator are (i) Stator and (ii) Rotor.

Stator

The stationary part of the alternator is called 'stator'. In the revolving-field type alternator, the armature is the stationary element hence it is called 'stator'. The stator assembly consists of a cast-iron frame supporting the laminated armature core as shown in Fig. 5.71. The armature core has slots on its inner periphery to accommodate the three-phase armature winding. The laminations of the armature core are annealed and are insulated from each other by a thin coating of oxide and an enamel. The 'open slots' are used which permit easy installation of armature coils. Ventilating holes are provided for cooling the machine.

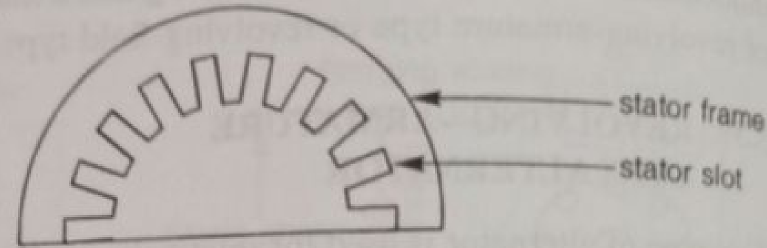


Fig. 5.71

Rotor

The revolving field structure is called 'rotor'. The rotors are of two types, namely, (i) Salient pole rotor and (ii) Smooth cylindrical type rotor.

Salient pole rotor

This type of rotor is used in low and medium speed alternators. It has large diameter and small axial length. The typical lamination of a salient pole rotor is shown in Fig. 5.72. The poles are made of thick steel laminations rivetted together and attached to a rotor by a dovetailed joint. The poles are laminated to reduce the eddy current loss. The overhang of the pole gives necessary mechanical support to the field coil.

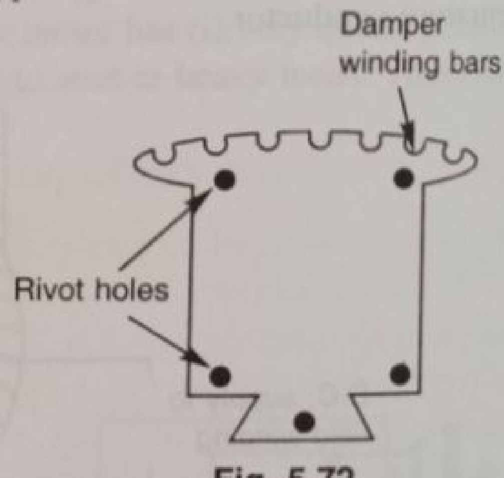


Fig. 5.72

Smooth cylindrical rotor

This type of rotor is used in high speed alternators. To reduce the peripheral speed, the diameter of the rotor is reduced (whereas axial length is increased). Usually, the number of poles of the rotor are 2 or 4. The rotor is made of solid forging of alloy steel. Slots are provided on the outer periphery to accommodate the field winding as shown in the Fig. 5.73.

The smooth cylindrical rotors are used in stream turbine-driven alternators.

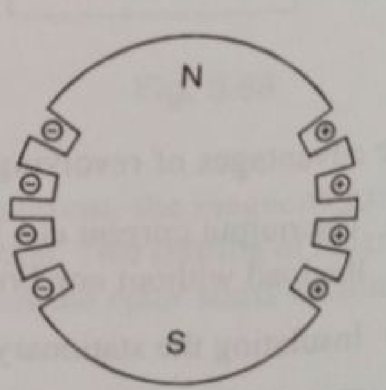


Fig. 5.73

5.42. EMF EQUATION OF AN ALTERNATOR

When the rotor rotates in the stator, the stator windings are cut by the magnetic flux of rotor. Thus an emf is induced in the stator conductors. The expression for the emf induced is obtained as follows.

Let 'Z' number of armature conductors per phase

'T' be the number of turns per phase (Thus $T = \frac{z}{2}$)

'P' be the number of rotor poles

'Φ' be the flux/pole in webers

'N' be the speed of rotation of rotor in RPM

'f' be the frequency of induced emf in hertz.

$$\text{The number of rotations per second} = \frac{N}{60}$$

$$\text{Time taken by the rotor for one revolution} = \frac{60}{N}$$

The flux cut by the conductor = ΦP webers in one revolution of rotor

$$\text{Thus, } d\Phi = \Phi P \text{ and } dt = \frac{60}{N} \text{ seconds}$$

$$\therefore \text{Average emf induced per conductors} = \frac{d\Phi}{dt} = \frac{\Phi P}{60/N} = \frac{N\Phi P}{60} \text{ volts}$$

$$\text{But we have } f = \frac{PN}{120}$$

$$\Rightarrow \quad N = \frac{120\,f}{P}$$

$$\therefore \quad \text{Average emf induced per conductor} = \frac{120\,f}{P} \times \frac{\Phi P}{60} = 2\,f\,\Phi P$$

$$\text{Average emf induced in all the 'Z' conductor per phase} = 2f\,\Phi\,Z \text{ volts}$$

$$T = 4f\,\Phi\,T \text{ volts}$$

$$\text{RMS value of emf induced per phase} = 1.11 \times 2f\,\Phi Z$$

$$= 2.22f\,\Phi Z \text{ volts}$$

$$= 4.44f\,\Phi T \text{ volts}$$