

**Lecture Notes On  
Energy Conversion-II  
For  
5th Semester  
( DIPLOMA Student )**

Prepared by:-

**Binaya Kumar Rout**

Lecturer in Electrical Engg.  
( Department of Electrical Engg.)

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**R.K Institute of Engineering & Technology**

**At:-Apuja.(Kantapada),Niali, Cuttack.**

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## TH.2 ENERGY CONVERSION – II

Name of the Course: Diploma in Electrical Engineering			
Course code:	Th.2	Semester:	5 <sup>th</sup>
Total Period:	60 Periods	Examination:	3 Hrs.
Theory periods:	4 P / Week	Internal Assessment:	20
Tutorial:	---	End Semester Examination:	80
Maximum marks:	100		

### A. Rationale:

Modern industries are mostly equipped with AC machines. So the students are given a scope to gain the concepts of electrical machines like synchronous machines, 3-phase & 1- phase induction motors and fractional horse power motors and other special machines. The students are required to be familiar with constructional features, working principles, starting and speed control methods and performance characteristics with applications of the machines. Numerical solving makes the student to understand the feature more clearly.

### B. Objectives:

After completion of this subject the student will be able:

1. To describe various parts, their material specification with suitable reasoning and working principle of synchronous machines, 3-phase & 1- phase AC motors and fractional horse power and other special machines.
2. To describe their operating principle and working characteristics, torque equation of three phase motors.
3. To describe the losses and efficiency of all machines.
4. To be familiar with starting and speed control of AC motors.
5. To develop problem solving ability on synchronous machines and 3-phase induction motor for better understanding about the concept of machines.
6. To be familiar with different testing methods carried out on such three phase machines.

### C. TOPIC WISE DISTRIBUTION OF PERIODS

Sl. No.	Topics	Periods
1.	Alternator (Synchronous Generator)	14
2.	Synchronous Motor	08
3.	Induction motor	14
4.	Single Phase induction motor	08
5.	Commutator motors	06
6.	Special Electric Machine	05
7.	Three phase transformers	05
	<b>Total</b>	<b>60</b>

## **D. COURSE CONTENT:**

### **1. ALTERNATOR:**

- 1.1. Types of alternator and their constructional features.
- 1.2. Basic working principle of alternator and the relation between speed and frequency.
- 1.3. Terminology in armature winding and expressions for winding factors (Pitch factor, Distribution factor).
- 1.4. Explain harmonics, its causes and impact on winding factor.
- 1.5. E.M.F equation of alternator. (Solve numerical problems).
- 1.6. Explain Armature reaction and its effect on emf at different power factor of load.
- 1.7. The vector diagram of loaded alternator. (Solve numerical problems)
- 1.8. Testing of alternator (Solve numerical problems)
  - 1.8.1. Open circuit test.
  - 1.8.2. Short circuit test.
- 1.9. Determination of voltage regulation of Alternator by direct loading and synchronous impedance method. (Solve numerical problems)
- 1.10. Parallel operation of alternator using synchro-scope and dark & bright lamp method.
- 1.11. Explain distribution of load by parallel connected alternators.

### **2. SYNCHRONOUS MOTOR:**

- 2.1. Constructional feature of Synchronous Motor.
- 2.2. Principles of operation, concept of load angle
- 2.3. Derive torque, power developed.
- 2.4. Effect of varying load with constant excitation.
- 2.5. Effect of varying excitation with constant load.
- 2.6. Power angle characteristics of cylindrical rotor motor.
- 2.7. Explain effect of excitation on Armature current and power factor.
- 2.8. Hunting in Synchronous Motor.
- 2.9. Function of Damper Bars in synchronous motor and generator.
- 2.10. Describe method of starting of Synchronous motor.
- 2.11. State application of synchronous motor.

### **3. THREE PHASE INDUCTION MOTOR:**

- 3.1. Production of rotating magnetic field.
- 3.2. Constructional feature of Squirrel cage and Slip ring induction motors.
- 3.3. Working principles of operation of 3-phase Induction motor.
- 3.4. Define slip speed, slip and establish the relation of slip with rotor quantities.
- 3.5. Derive expression for torque during starting and running conditions and derive conditions for maximum torque. (solve numerical problems)

- 3.6. Torque-slip characteristics.
- 3.7. Derive relation between full load torque and starting torque etc. (solve numerical problems)
- 3.8. Establish the relations between Rotor Copper loss, Rotor output and Gross Torque and relationship of slip with rotor copper loss. (solve numerical problems)
- 3.9. Methods of starting and different types of starters used for three phase Induction motor.
- 3.10. Explain speed control by Voltage Control, Rotor resistance control, Pole changing, frequency control methods.
- 3.11. Plugging as applicable to three phase induction motor.
- 3.12. Describe different types of motor enclosures.
- 3.13. Explain principle of Induction Generator and state its applications.

#### **4. SINGLE PHASE INDUCTION MOTOR:**

- 4.1. Explain Ferrari's principle.
- 4.2. Explain double revolving field theory and Cross-field theory to analyze starting torque of 1-phase induction motor.
- 4.3. Explain Working principle, Torque speed characteristics, performance characteristics and application of following single phase motors.
  - 4.3.1. Split phase motor.
  - 4.3.2. Capacitor Start motor.
  - 4.3.3. Capacitor start, capacitor run motor.
  - 4.3.4. Permanent capacitor type motor.
  - 4.3.5. Shaded pole motor.
- 4.4. Explain the method to change the direction of rotation of above motors.

#### **5. COMMUTATOR MOTORS:**

- 5.1. Construction, working principle, running characteristic and application of single phase series motor.
- 5.2. Construction, working principle and application of Universal motors.
- 5.3. Working principle of Repulsion start Motor, Repulsion start Induction run motor, Repulsion Induction motor.

#### **6. SPECIAL ELECTRICAL MACHINE:**

- 6.1. Principle of Stepper motor.
- 6.2. Classification of Stepper motor.
- 6.3. Principle of variable reluctance stepper motor.
- 6.4. Principle of Permanent magnet stepper motor.
- 6.5. Principle of hybrid stepper motor.
- 6.6. Applications of Stepper motor.

AC Series motor or Universal Motor

→ A dc series motor will rotate in the same direction regardless of the polarity of the supply.

→ One can expect that a dc series motor would also operate on a single-phase ac supply. It is then called as a.c. series motor.

→ ~~It is the~~ However, some changes must be made in a d.c. motor that is to operate satisfactorily on a a.c. supply.

→ The changes effected are:→

(i) The entire magnetic circuit is laminated in order to reduce the eddy current loss.

→ A.c. series motor requires a more expensive construction than a d.c. series motor.

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

→ This reduces the voltage drop across the field winding.

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

(iv) There is considerable sparking between the brushes and commutator when the motor is used on a.c. supply.

→ It is because the alternating flux establishes high currents in the coils short-circuited by the brushes.

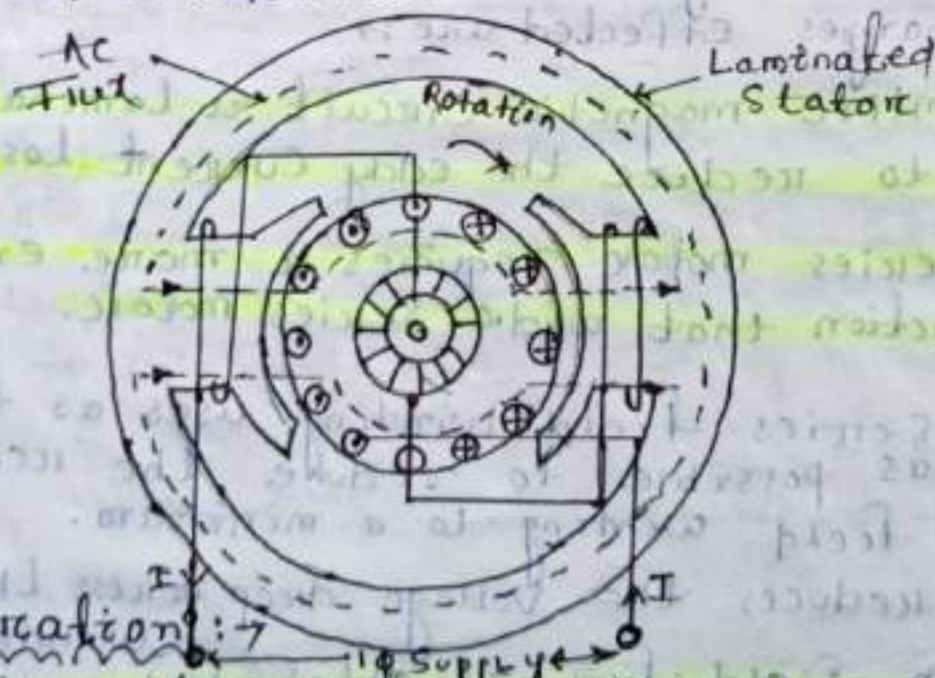
→ When the short-circuited coil breaks contact from the commutator, excessive sparking is produced.

→ This can be eliminated by using high resistance segments.

### Constructions: →

→ The constructions of an a.c. Series motor is very similar to a d.c. Series motor except that above modifications are incorporated.

→ Such a motor can be operated either on a.c. or d.c. supply and the resulting torque-speed curve is about the same in each case. For this reason, it is sometimes called a universal motor.



### Operation: →

→ When the motor is connected to an a.c. supply, the same alternating current flows through the field and armature windings.

→ The field winding produces an alternating flux  $\phi$  that reacts with the current flowing in the armature to produce a torque.

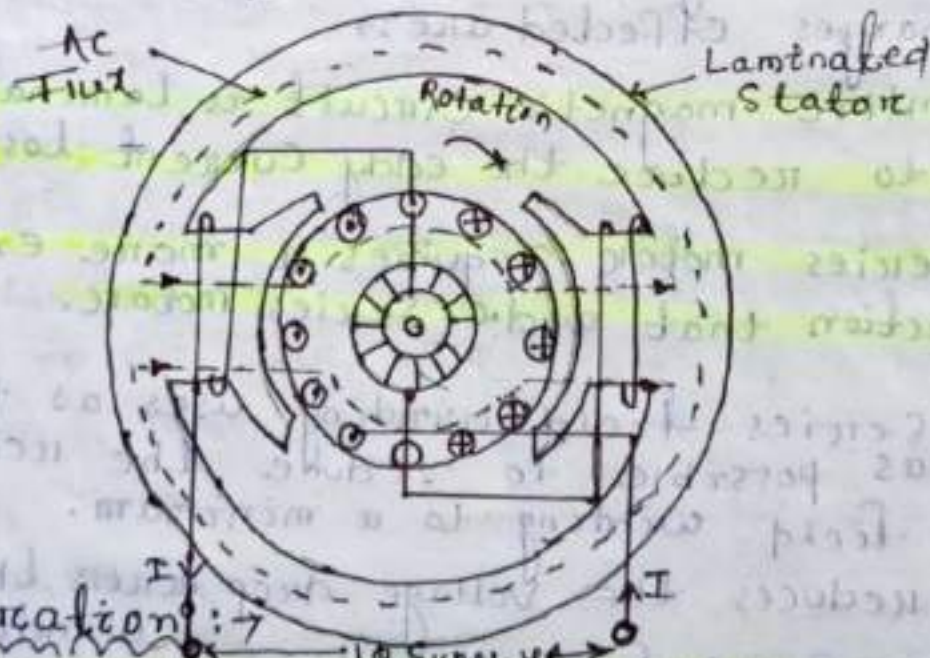
→ Since both armature current and flux reverse simultaneously, the torque always acts in the same direction.

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### Constructions :->

→ The construction of an a.c. Series motor is very similar to a d.c. Series motor except that above modifications are incorporated.

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→ When the motor is connected to an a.c. supply, the same alternating current flows through the field and armature windings.

→ The field winding produces an alternating flux  $\phi$  that reacts with the current flowing in the armature to produce a torque.

→ Since both armature current and flux reverse simultaneously, the torque always acts in the same direction.

It may be noted that no rotating flux is produced in this type of machines.

→ The principle of operation is the same as that of a d.c. series motor.

### Characteristics: →

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

(i) The speed increases to a high value with a decrease in load.

→ In very small series motors, the losses are usually large enough at no load that limit the speed to a "definite value" (1500-19000 rpm)

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

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

### Applications: →

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

(a) High-speed vacuum cleaners

(b) Sewing machines

(c) Electric shavers

(d) Drills

(e) Machine tools, etc.

## Repulsion Motor :->

A Repulsion motor is similar to an a.c. Series motor.

(i) Brushes are not connected to supply but are short-circuited. Consequently, currents are induced in the armature conductors by transformer action.

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

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

## Principle of Operation :->

-> The principle involved in the starting of the motor is illustrated by 2-pole motor.

-> The alternating flux produced by stator or field winding will induce, during one half cycle, voltages in the respective armature conductors as shown.

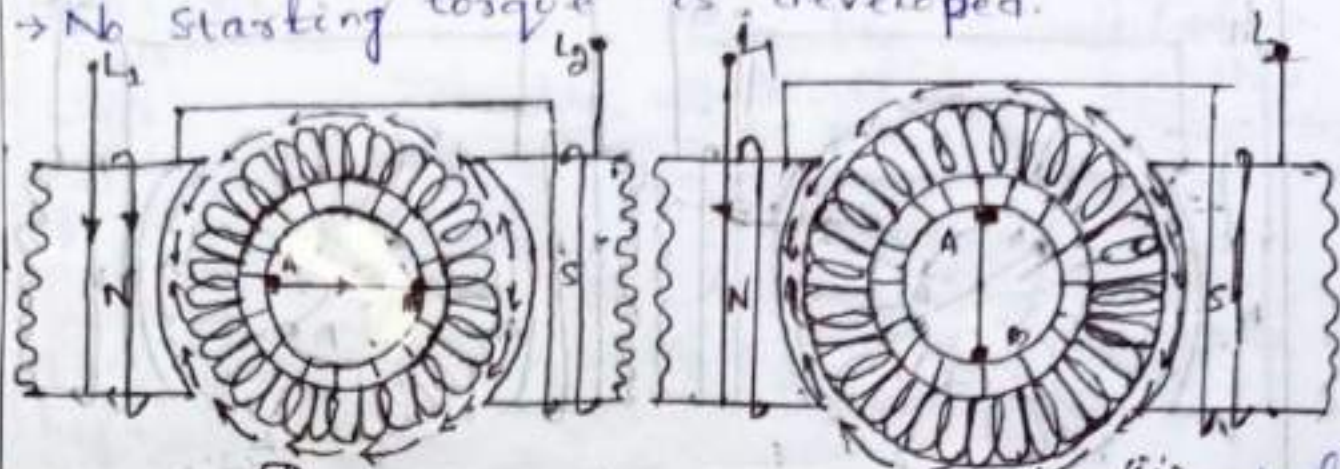
(i) In the brush axis is set in line with the stator-field axis.

-> The induced voltage in the armature conductors are additive on each side of the brushes.

-> Consequently, the net voltage between the brushes is maximum and so is the current through the short-circuited armature.

-> The same is true under the opposite pole therefore, as much torque is developed in one direction as in the other and

The armature remains stationary  
 → No starting torque is developed.



(ii) If the brush-axis is in a plane perpendicular to the stator field axis.

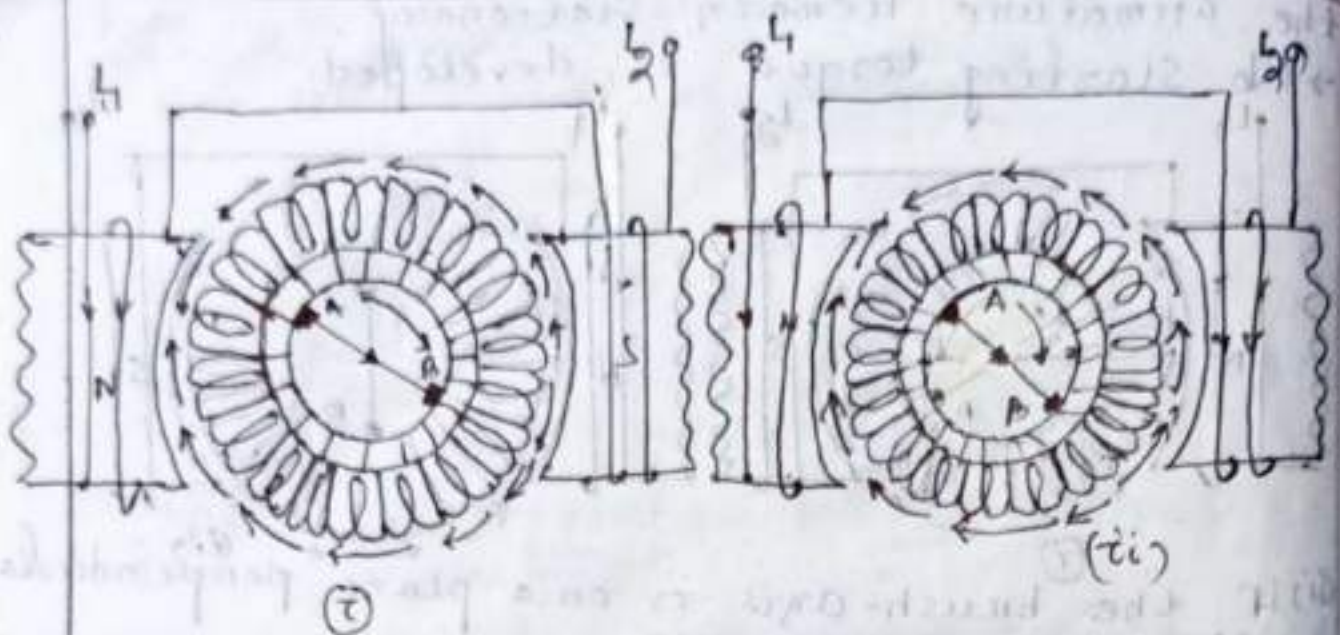
- The voltage in each path will be neutralized.
- As a result, the net voltage between the brushes is zero.
- Therefore, no current flows in the armature circuit and no torque is produced.

(iii) If the plane of the brush-axis is other than  $0^\circ$  or  $90^\circ$  to the plane of the stator field.

→ The direction of rotation would depend upon the direction in which the brushes are shifted from the plane parallel to the field.

→ The brushes are shifted clockwise, and the net torque acts in a clockwise direction.

→ If the brushes are shifted in the anticlockwise direction, the currents in the armature conductors under the poles are reversed and the torque is developed in anticlockwise direction.



(iv) after a repulsion motor has been started in either direction, it will continue to develop torque in that direction and give Series-motor type performance characteristics.

### Repulsion Start Induction-Run motor :-

- The Repulsion Start Induction-Run motor has the same general construction of a repulsion motor,
- The only difference is that in addition to the basic repulsion-motor construction
- It is equipped with a centrifugal device fixed on the armature shaft
- When the motor reaches 75% of its full running speed, the centrifugal device forces a short-circuiting ring to come in contact with the inner surface of the commutator.
- This short-circuits all the commutator bars the rotor then resembles squirrel cage type and the motor runs as a single phase induction motor.

→ At the same time, the centrifugal device raises the brushes from the commutator which reduces the wear of the brushes and commutator as well as makes the operation quiet.

### Repulsion-Induction Motor :-

→ The repulsion-induction motor produces a high starting torque entirely due to repulsion motor action.

→ It functions through a combination of induction motor and repulsion motor.

### Construction :-

Fig shows the connections of a 4-pole repulsion-induction motor for 230-V operation.

(i) It consists of a stator and a rotor.

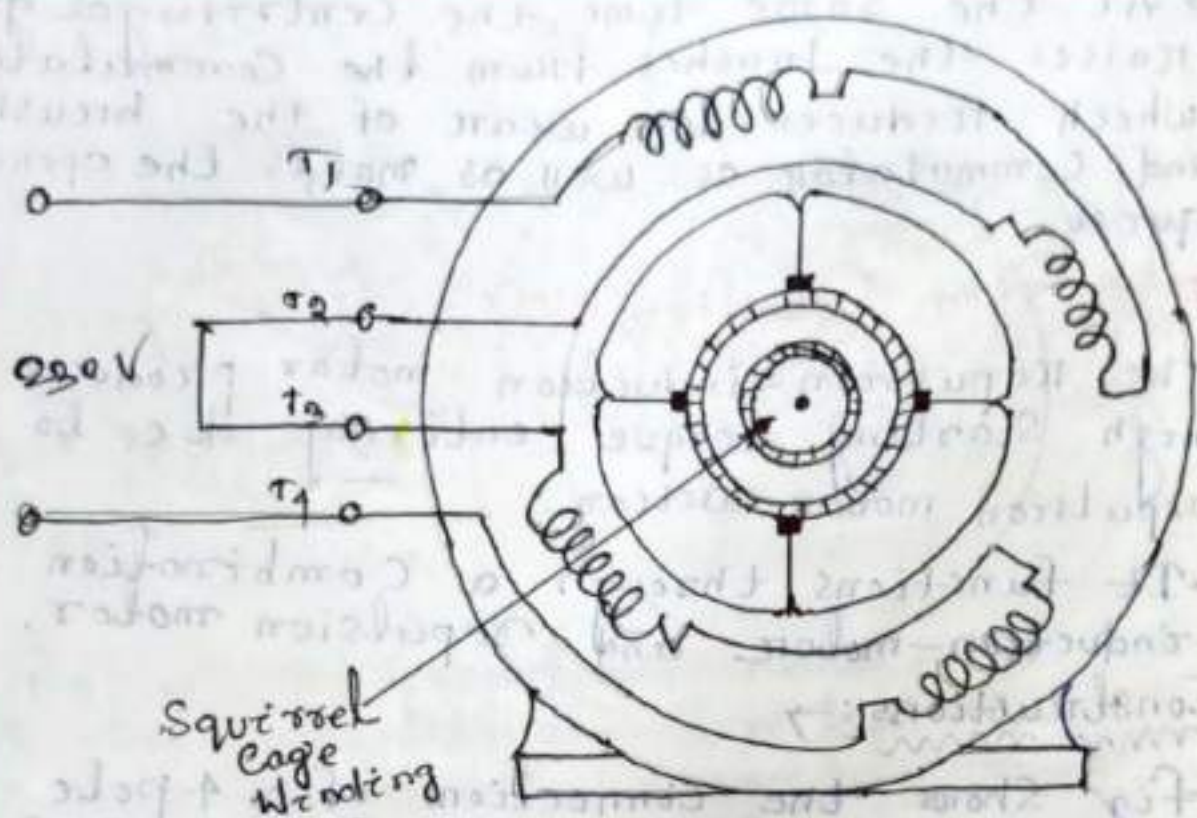
(ii) The stator carries a single distributed winding fed from single-phase supply.

(iii) The rotor is provided with two independent windings placed one inside the other.

→ The inner cage winding is a squirrel cage winding with rotor bars permanently short-circuited.

→ Placed over the squirrel cage winding is a repulsion commutator armature winding.

→ The repulsion winding is connected to a commutator on which ride short-circuited brushes. There is no centrifugal device and the repulsion winding functions at all times.



### Operation :->

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

As the motor speed increases, the current shifts from the outer to inner winding due to the decreasing impedance of the inner winding with increasing speed.

(ii) Consequently, at running speed, the squirrel cage winding carries the greater part of rotor current.

(iii) This shifting of repulsion motor action to induction motor action is thus achieved without any switching arrangement.

(iv) It may be seen that the motor starts as a repulsion motor. When running it

functions through a combination of principle of induction and repulsion.

### Single Phase Synchronous Motors →

→ Very small single-phase motors have been developed which run at true synchronous speed.

→ They do not require d.c. excitation for the motor rotor. Because of these characteristics they are called unexcited single-phase synchronous motors.

- The most commonly used types are -
  - (i) Reluctance Motors.
  - (ii) Hysteresis Motors.

The efficiency and torque-developing ability of these motors is low.

→ The output of most of the commercial motors is only a few watts.

### STARTER →

→ It consists of a steel frame which encloses a narrow cylindrical core made up of thin laminations of silicon steel to reduce hysteresis and eddy current loss.

→ A number of evenly spaced slots are provided on the inner periphery of the rotor.

# Three Phase Induction Motor

## Three phase Induction Motor

→ A ~~star~~ 3-phase Induction motor has a stator and rotor.

→ The stator carries a 3-phase winding is called stator winding while the rotor carries a short circuited winding is called rotor winding.

→ Only the stator winding is fed from 3-phase supply.

→ The rotor winding derives its voltage and power from the externally energized stator winding through electromagnetic induction.

→ As a transformer? a.c. machine in which electrical energy is converted into mechanical energy.

## Construction of 3-phase Induction Motor

→ A 3-phase Induction motor has two main parts (i) Stator, (ii) Rotor

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

## STATOR

→ It consists of a steel frame which enclose a hollow cylindrical core made up of thin laminations of silicon steel to reduce hysteresis and eddy current loss.

→ A number of evenly spaced slots are provided on the inner periphery of the lamination.

→ The insulated conductors are placed in the stator slots and are suitably ~~conn~~ connected to form a balanced 3-phase star or delta connected circuit.

→ The three phase stator winding is wound for a definite number of poles as per requirement of speed.

→ Greater the number of poles, lesser is the speed of the motor and vice-versa.

→ When 3-phase supply is given to the stator winding, a rotating magnetic field of constant magnitude is produced.

→ This rotating field induces currents in the rotor by electromagnetic induction.

### Rotor :->

The rotor, mounted on a shaft, is a hollow laminated core having slots on its periphery.

→ The winding placed in these slots (called rotor winding) ~~is~~

→ Its two type 1- Squirrel cage type.  
2- Wound type.

### Squirrel cage rotor :->

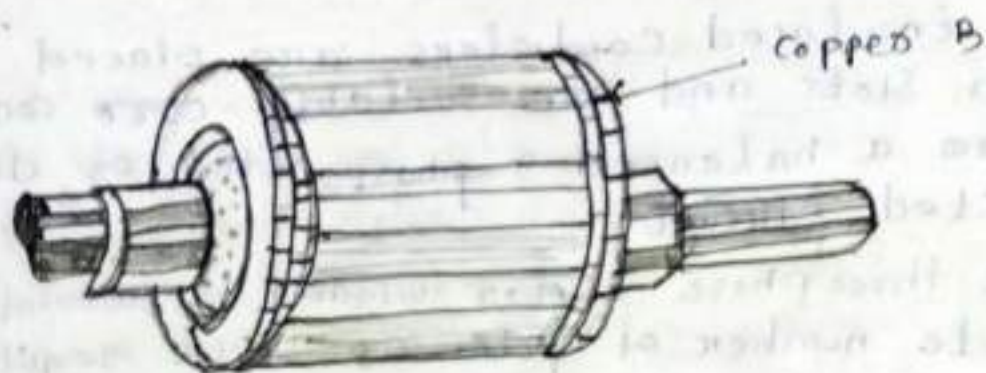
→ It consists of a laminated cylindrical core having parallel slots on its periphery.

→ One copper or aluminium bar is placed in each slot.

→ All these bars are joined at each end by metal rings called end rings.

→ This forms a permanently short-circuited winding which is indestructible.

→ The entire construction resembles a squirrel cage and hence the name.



→ These induction motors which employ squirrel cage rotor called squirrel cage induction motors.

→ Most of 3-phase induction motors use squirrel cage rotor as it has a remarkably simple and robust construction enabling it to operate in the most adverse circumstances.

→ It suffers from the disadvantages of a low starting torque.

→ It is because the rotor bars are permanently short-circuited and it is not possible to add any external resistance to the rotor circuit to have a large starting torque.

### Wound type :-

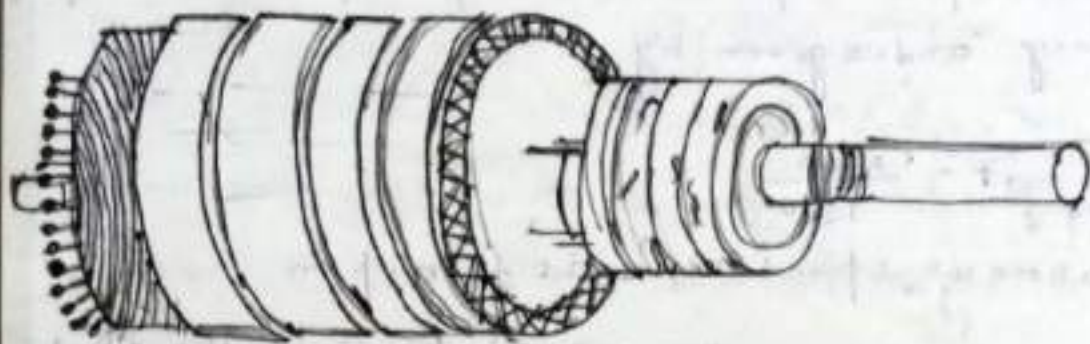
→ It consists of a laminated cylindrical core and carries a 3-phase winding similar to the one the stator.

→ The rotor winding is uniformly distributed in the slots and is usually star connected.

→ The open ends of the rotor winding are brought out and joined to three insulated slip rings mounted on the rotor shaft with one brush resting on each slip ring.

→ The three brushes are connected to a 3-phase star connected rheostat.

→ At starting the external resistances are included in the rotor circuit to give a large starting torque.



- These resistances are gradually reduced to zero as the motor runs up to speed.
- The external resistances are used during starting period only.
- When the motor attains normal speed, the three brushes are short-circuited so that wound rotor runs like a squirrel cage rotor.

### Rotating Magnetic Field:

- When a 3-phase winding is energized from a 3-phase supply a rotating magnetic field is produced. This field is such that its poles do not remain in a fixed position on the stator but go on shifting their position around the stator.
- For this reason it is called rotating field.
- It can be shown that magnitude of this rotating field is constant and is equal to  $1.5 \phi_m$  where  $\phi_m$  is the maximum flux due to any phase.

### Synchronous speed:

- The speed at which the revolving flux rotates is called synchronous speed.

→ its value depend upon the no. poles and the supply frequency and is given by

$$f = \frac{N_s p}{120}$$

Synchronous speed  $N_s = 120 f / p$  r.p.m.

$p$  = no. of poles in the stator

Where

$f$  = supply frequency in Hz

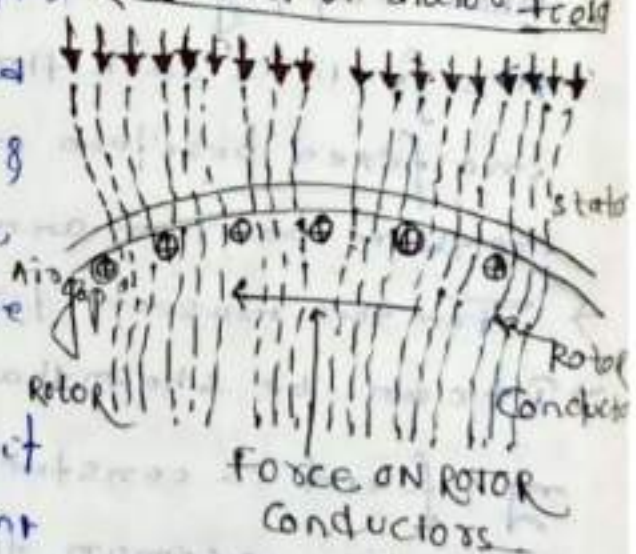
→ Thus for 6-pole, 50 Hz motor,  $N_s = 120 \times 50 / 6 = 1000$  r.p.m. It means that the flux rotates around the stator at a speed of 1000 r.p.m.

### Operation of 3-phase induction motor

→ When 3-phase stator winding is energized from a 3-phase supply rotating magnetic fields set up which rotates around the stator at synchronous speed  $N_s (120 f / p)$  ← Rotation of stator field

→ Due to the relative speed between the rotating flux & the stationary rotor, emf are induced in the rotor conductors.

→ Since the rotor circuit is short circuit current start flowing in the rotor conductors.



→ The current carrying rotor conductors are placed in the magnetic field produced by a stator

- consequently mechanical forces act on the rotor magnetic field conductors.
- The sum of the mechanical forces on all the rotor conductors produces a torque which tends to move the rotor in the same direction as the rotating field.

### → Lenz Law :-

- According to this law the direction of induced current will be such that they tend to oppose the cause producing them.
- Now the cause producing the rotor currents is the relative speed between the rotating field and the stationary rotor conductors.
- Hence to reduce this relative speed, the rotor to slow down.
- Hence the rotor speed the rotor starts running in the same direction as that of stator field and tries to catch it.

### → Slip :-

- We have seen above that rotor rapidly accelerates in the direction of rotating field.
- In practice the rotor can never reach the speed of stator flux.
- If it did there would be no relative speed between the stator field and rotor conductors no induced rotor current and therefore no torque to drive the rotor.
- The friction and windage would immediately

Cause the rotor to slow down.

→ Hence the rotor speed ( $N$ ) is always less than the stator field speed ( $N_s$ ). This difference in speed depend upon load on the motor.

→ The difference bet<sup>n</sup> the synchronous speed  $N_s$  of the rotating stator field and the actual rotor speed  $N$  is called slip.

→ It is usually expressed as a percentage of synchronous speed i.e

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

→ The quantity  $N_s - N$  is sometimes called slip speed.

→ When the rotor is stationary (i.e  $N=0$ )

$$\text{Slip}, s = 1 \text{ or } 100\%$$

→ In an induction motor the change in slip

from no-load to full load is hardly 0.1% to 0.5%. So that it is essentially a constant speed motor.

### Effect of slip on Rotor circuit:

→ When the rotor is stationary  $s=1$

→ Under these conditions the per phase rotor emf  $E_2$  has a frequency equal to that supply frequency.

→ At any slip, the relative speed bet<sup>n</sup> stator

Speed and  $\omega$  therefore is decreased.

- consequently the rotor e.m.f and frequency are reduced proportionally to  $s E_2$  and  $s f$  respectively.
- At the same time per phase rotor reactance  $X_2$  being frequency dependent is reduced to  $s X_2$ .
- When the rotor is at standstill position (i.e. rotor winding energised from 3-phase supply) the voltage induced in the stator conductors is maximum ( $s=1$ ).
- If the rotor revolves at synchronous speed the voltage induced in the rotor conductors is zero ( $\because s=0$ ).
- The above treatment also applies to rotor reactance i.e.
- The rotor resistance is independent of rotor frequency and hence the slip.

### Rotor current:-

- 3 phase induction motor at any slip  $s$ .
- The rotor is assumed to be of round type & star connected.
- Note that rotor e.m.f / phase and rotor reactance / phase are  $s E_2$  and  $s X_2$  respectively. The rotor resistance / phase is  $R_2$  and independent of frequency and therefore depend upon slip.

→ since the motor represents a balanced 2-phase load we need consider on e phase only the conditions on the other two phase being similar.

At standstill :-

$$\text{Rotor current / phase} = I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$$

$$\text{Rotor p.f } \cos \phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

Rotor current frequency :-

→ The frequency of a voltage or current induced due to the relative speed bet'n a winding & a magnetic field is given by the general formula.

Where 
$$\text{Frequency} = \frac{NP}{120}$$

N - Relative speed bet'n magnetic field and the winding

p - No. of poles.

→ For a rotor speed N, the relative speed bet'n the rotating flux and the rotor is  $N_s - N$  consequently the rotor current frequency.

$$\begin{aligned}
 \overline{f} &= \frac{(N_s - N)p}{120} \\
 &= \frac{s N_s p}{120} \\
 &= sf
 \end{aligned}$$

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

$$(\because f = N_s p / 120)$$

Rotor current frequency =

- (i) When the rotor is at stand still or stationary (i.e.  $s = 1$ ) the frequency of rotor current is the same as that of supply frequency ( $f' = sf = 1 \times f = f$ )
- (ii) As the rotor picks up speed the relative speed bet<sup>n</sup> the rotating flux and the rotor decreases, consequently the slip  $s$  and hence rotor current frequency decreases.

# ALTERNATOR (Synchronous Generator)

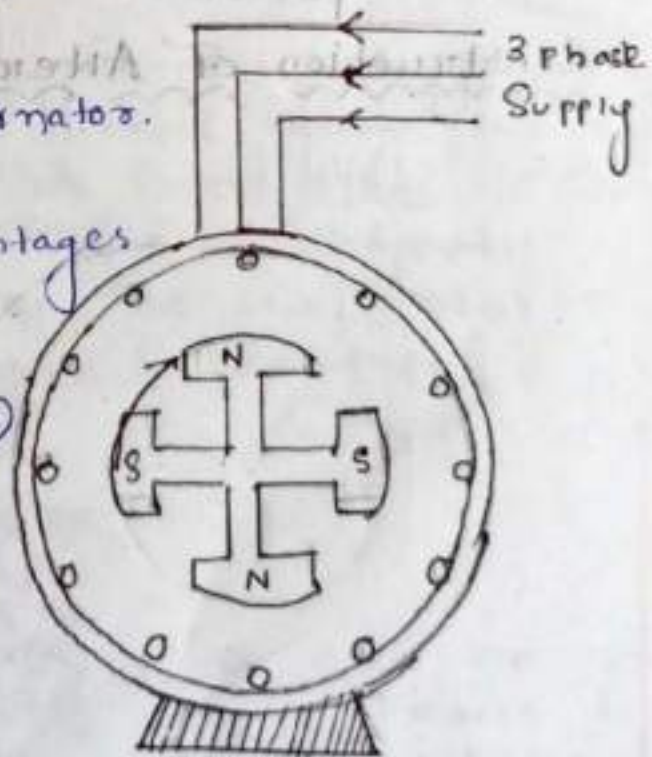
## Introduction :->

- The machine which produce 3-phase power from Mechanical power is called alternator or Synchronous generator.
- These machines are the largest Energy Converter found in the world. They convert mechanical energy into a.c energy.
- An alternator operates on the same fundamental principle electromagnetic induction as a d.c generator. i.e. when a flux linking a conductor change, an e.m.f is induced in the conductor.
- Like d.c generator an alternator also has an armature winding and a field winding.
- The field poles are placed on the stationary part of a machine.

→ No commutator is required in an alternator.

→ It is usually more convenient and advantages to place the field winding on the rotating part (i.e rotor)

→ Armature winding on the stationary part (i.e stator)



Advantages of Stationary armature: →

The field winding of an alternator is placed the rotor and his Connected to d.c supply through two slip ring

→ The 3 phase armature winding is placed on the stator. This arrangement has the following advantages.

- (i) The stationary 3 phase armature can be directly connected to load without going through large, unrelizable slip ring and brushes.
- (ii) It is easier to insubated stationary winding for high voltage for which the alternator are usually design.
- (iii) Due to simple and robust construction of the rotor, higher speed of a rotate dc field is possible.

Construction of Alternator: →



Handwritten notes next to the diagram:

Stator  
Rotor  
Slip ring  
Brushes  
Field winding  
Armature winding



As alternator has 3-phase winding on the stator and 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 3 phase winding is placed in this slot and serves as the armature winding of alternator.

### Rotor

The rotor carries a field winding which is supplied with direct current through two slip rings by a separate d.c. source. This d.c. source generally a small d.c. shunt or compound generator mounted on the shaft of the alternator. Rotor's construct two types:

- (1) Salient pole type.
- (2) Non-salient pole type.

### Salient pole type:

→ In this type salient poles are mounted on a large circular steel frame which is fixed to the shaft of the alternator as shown in fig. (a)

→ Adjacent poles have opposite polarities.

→ Slow and medium-speed alternator (120-900 rpm) such as diesel engines or water turbine have Salient pole type rotors.

→ The Salient Field Poles would cause an excessive windage, loss if driven at high speed and would tend to produce noise.

→ The Salient pole construction cannot be made strong enough to withstand the mechanical stresses to which they may be subjected at higher speed.

→ Salient pole type rotors have large diameters and short axial lengths.

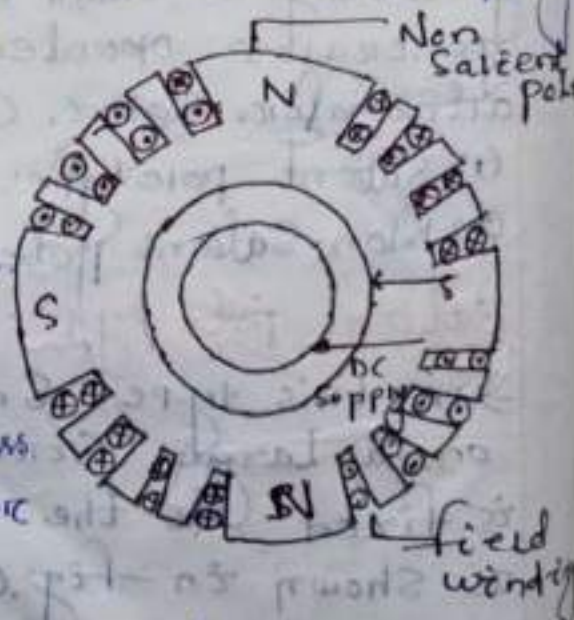
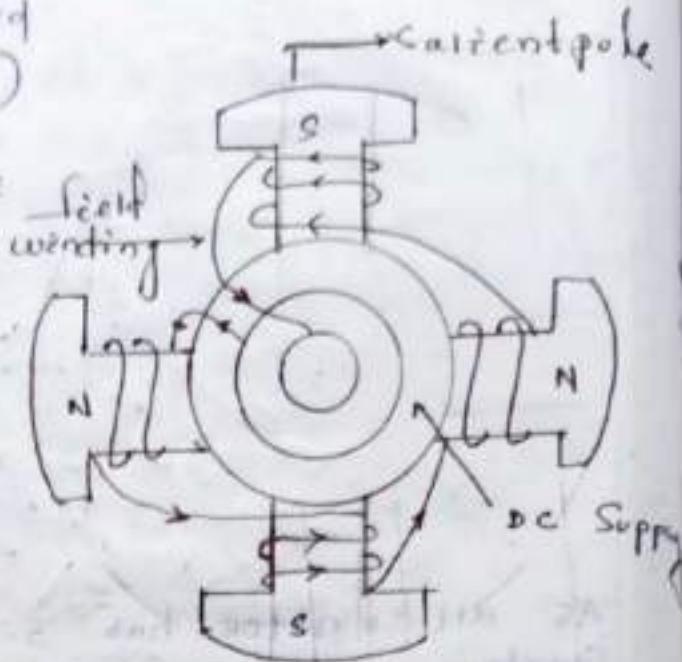
### (ii) Non-salient Pole type :-

→ In this type of the rotor is made of smooth solid forged-steel, radial cylinder having a number of slots along the outer periphery.

→ High speed alternators (1500 or 3000 r.p.m) are driven by steam turbines and use non-salient type rotors due reasons.

→ This type of construction has mechanical robustness and gives noiseless operation at high speed.

→ The flux distribution around the periphery is nearly sinewave and hence a better e.m.f. waveform is obtained than in the



Case of Salient pole type.

→ Steam turbines turn at high speed & a frequency of 50Hz required

→ Turboalternators possess 2 or 4 poles and have small diameters and very long axial lengths.

### Alternator operation

→ The Rotor winding is energized from the d.c. exciter and alternate N & S poles are developed on the rotor.

→ When the rotor is anticlockwise direction a prime mover, the stator or armature conductors are cut by the magnetic flux of rotor poles.

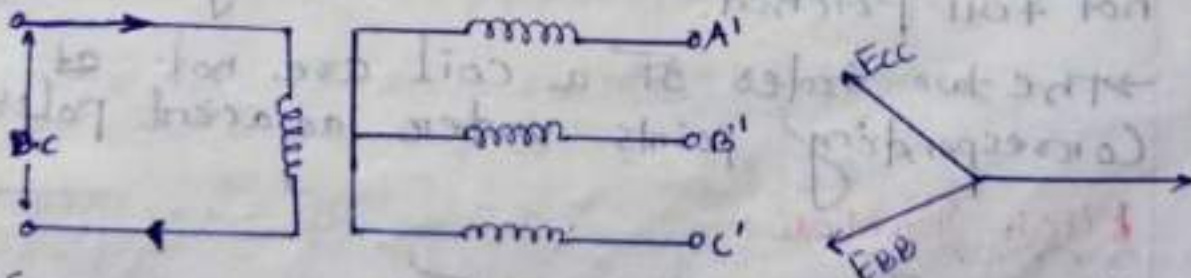
→ Consequently, e.m.f. is induced in the armature conductors due to electromagnetic induction.

→ The direction of induced e.m.f. can be found by Fleming's Right hand rule & frequency is given by

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

N = Speed of rotor in r.p.m.

P = Number of rotor poles.



(Rotor Winding)

(Stator Winding)

(ii)

→ Pitch factor is defined as the ratio of voltage generated by the short pitch winding to that which is generated by the full pitch winding.

## Frequency

The frequency of induced e.m.f in the armature conductors depend upon Speed and the number of poles.

N - Rotor Speed

P - Number of Rotor poles.

F = frequency of e.m.f in Hz

No of cycle / revolution = No of pairs of poles

$$\text{No of revolutions / second} = \frac{N}{60}$$

$$\text{No of cycles / second} = \frac{P}{2} \times \frac{N}{60} = \frac{PN}{120}$$

But number of cycles of e.m.f per second is its frequency.

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

N - is the synchronous motor

→ Alternator is sometimes called synchronous generator.

## Pitch factor & distribution factor

The coils of armature-windings are not full pitched.

→ The two sides of a coil are not at corresponding points under adjacent poles

### Pitch Factor →

$$\text{Pitch factor } k_p = \frac{\text{e.m.f with short-pitch coil}}{\text{e.m.f with full pitch coil}}$$

→ pitch-factor is defined as the ratio of voltages generated by the short pitch winding to that which is generated on the full pitch winding.

## Distribution Factor $\rightarrow$

Distribution factor (kd) =  $\frac{\text{E.m.f with distributed winding}}{\text{E.m.f with concentrated winding}}$

The conductors spread over the surface of the armature ~~spread~~ in slots, their e.m.f differ in phase and the total e.m.f. is the vector sum ~~are not arithmetic sum~~.

## E.m.f equation of an alternator $\rightarrow$

Z = No of conductors on coil sides in series

$\phi$  = Flux per pole in webers

p = Number of rotor poles

N = rotor speed in r.p.m.

In one revolution, each stator conductor is cut by  $p\phi$  webers i.e.

$$d\phi = p\phi, dt = \frac{60}{N}$$

Average e.m.f induced in one stator conductor.

$$\frac{d\phi}{dt} = \frac{p\phi}{60/N} = \frac{p\phi N}{60} \text{ volts}$$

There are Z conductors in series per phase

$$\text{Average e.m.f/phase} = \frac{p\phi N}{60} \times Z$$

$$= \frac{p\phi Z}{60} \times \frac{120f}{p}$$

$$= 2f\phi Z \text{ Volts}$$

R.M.S value of e.m.f/phase

$$= \text{Average value/phase} \times \text{Form Factor}$$

$$= 2f\phi Z \times 1.11 = 2.22f\phi Z \text{ volts.}$$

E.r.m.s/phase

$$= 2.22f\phi Z \text{ volts.}$$

∴ If  $k_p$  and  $k_d$  are the pitch factor and distribution factor of the armature winding then,

$$E_{\text{rms/phase}} = 2.22 k_p k_d z f \Phi \text{ Volts}$$

### Alternator on load: →

→ If there is no current in the armature of the alternator, the only internal voltage in the armature ckt will be generated voltage  $E$

and the terminal voltage  $V$  Machine will be  $E$

However,

When the alternator is loaded, the terminal voltage  $V$  changes due to the three effect.

- (i) voltage drop in armature resistance.
- (ii) voltage drop in armature leakage reactance.
- (iii) voltage drop due to armature reaction.

The voltage drop due to armature reaction is accounted for by assuming a fictitious reactance  $X_a$  in the armature winding.

→ The phasor sum of  $X_L$  and  $X_a$  given synchronous reactance  $X_s$

$$X_s = \sqrt{X_L^2 + X_a^2}$$

→ Synchronous impedance / phase  $Z_s = \sqrt{R_a^2 + X_s^2}$   
 If  $V$  is the terminal voltage / phase and  $E$  is generated emf / phase then

$$E = V + I_a (R_a + jX_s) = V + I_a Z_s$$

## Phasor diagram of Loaded Alternator: →

$E = N \cdot \text{Load e.m.f.} / \text{phase}$

$V = \text{terminal voltage} / \text{phase}$

$I_a = \text{armature current} / \text{phase}$

$Z_s = \text{synchronous impedance} / \text{phase}$

$\phi = \text{Load p.f. angle.}$

### (i) Unity power factor load: →

→ phasor diagram of an alternator for unity p.f. load. Hence  $V$  is taken the reference phasor.

→ The current phasor  $I_a$  in phase with  $V$ .

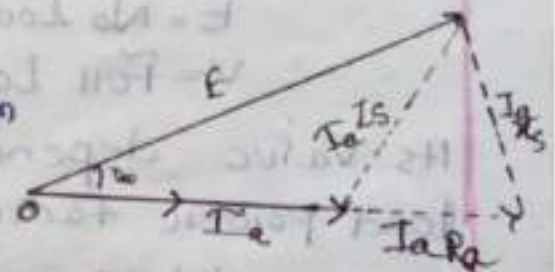
→ The voltage  $I_a R_a$  is in phase with  $V$ . The voltage drop  $I_a R_a$  in phase with  $I_a$ .

→ While the voltage drop  $I_a X_s$  leads  $I_a$  by  $90^\circ$ .

→ The phasor sum of the two giving  $I_a Z_s$ , the phasor sum of  $V$  &  $I_a Z_s$  gives  $E$ .

$$E = \vec{V} + \vec{I_a Z_s}$$

$$= I_a R_a + I_a X_s = I_a Z_s$$



### (ii) Lagging Power Factor Load: →

$$E = \sqrt{(V + I_a R_a)^2 + (I_a X_s)^2}$$

→ Again ' $V$ ' is taken as the reference phasor.

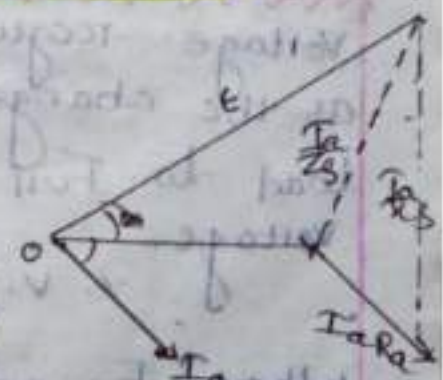
→ The ckt phasor ' $I_a$ ' lags ' $V$ ' by  $\phi$ .

→ The  $I_a R_a$  drop is phase with  $I_a$ , while the drop  $I_a X_s$  leads  $I_a$  by  $90^\circ$ .

→ The phasor sum of the two giving  $I_a Z_s$ ,

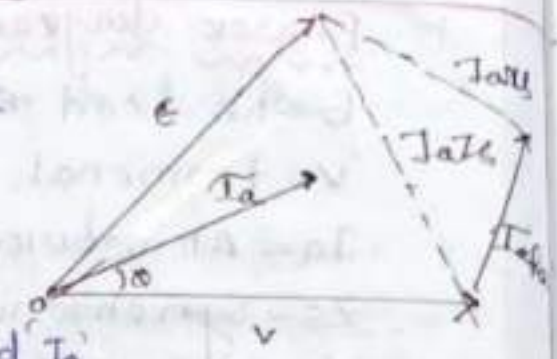
→ The phasor sum of  $V$  &  $I_a Z_s$  gives  $E$ .

$$E = \sqrt{(V \cos \phi + I_a R_a)^2 + (V \sin \phi + I_a X_s)^2}$$



With Leading PF Load →

V is taken as the reference phasor the current phasor  $I_a$  leads V by  $\phi$ . The  $I_a R_a$  drop is in phase with  $I_a$ .



→ While the drop  $I_a X_a$  lead  $I_a$  by  $90^\circ$

→ The phasor sum of V &  $I_a Z_s$  gives E.

→ The phasor sum of the two giving  $I_a Z_s$

Voltage Regulation

$$E = \sqrt{(V \cos \phi + I_a R_a)^2 + (V \sin \phi - I_a X_a)^2}$$

The Voltage regulation of an alternator is defined as the percentage rise in terminal voltage when full load is removed.

% age regulation =  $\frac{E - V}{V} \times 100$

E = No load voltage per phase

V = Full load voltage per phase.

Its value depends upon load current and load power factor.

Voltage Regulation of alternator by Synchronous impedance method

Voltage regulation of an alternator is defined as the change in terminal voltage from no load to full load divided by full load voltage.

% V.R =  $\frac{E_0 - V}{V} \times 100$

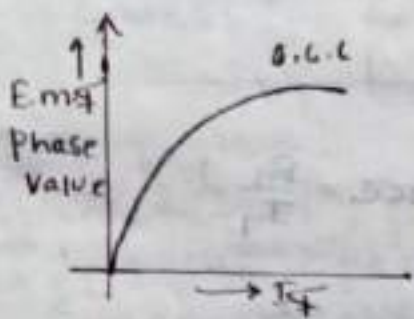
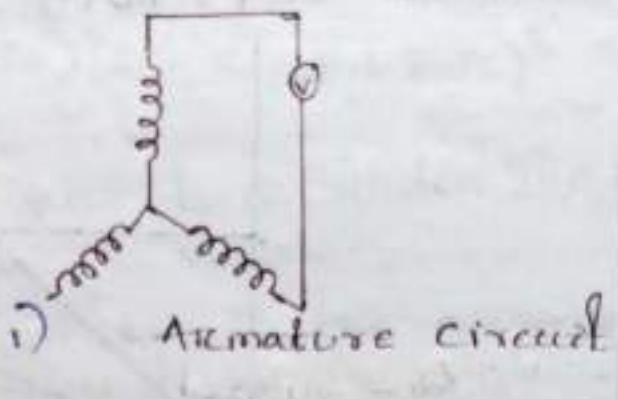
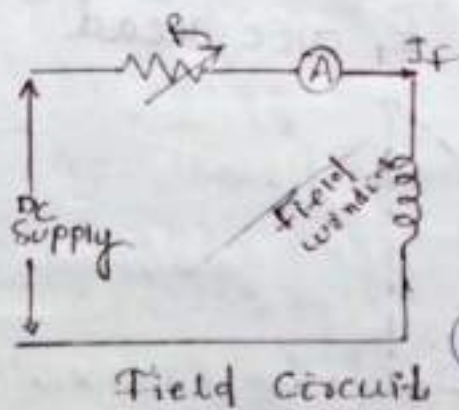
Where  $E_0$  and V are the no-load and full load terminal voltage.

In this method both o.c test and s.c test of alternator is to be performed and armature resistance is to be determined.

## O.C Test

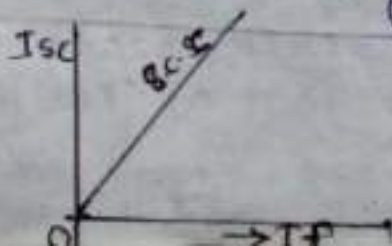
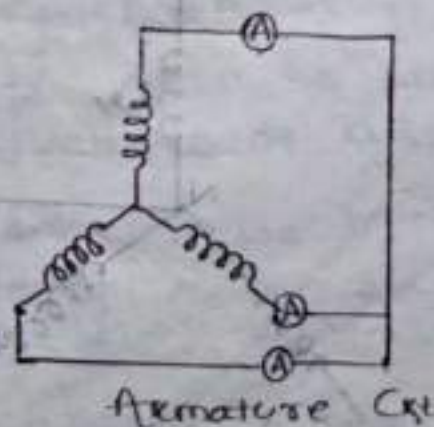
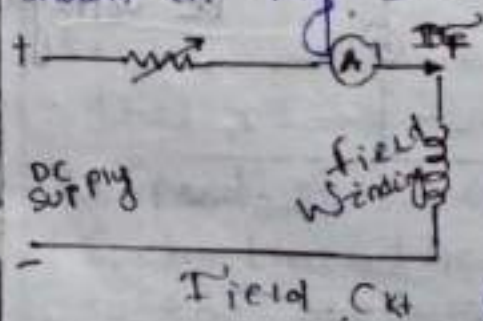
→ In this alternator is run with rated speed no-load, a voltmeter (V) is connected in between two phase which reads the line voltage, the phase voltage ( $E_o$ ) will be now determined by dividing  $V_L$  with the voltage reading.

→ This voltage ( $E_o$ ) will vary according to the field current ( $I_f$ ) which is shown in Fig. 2.



## S.C Test

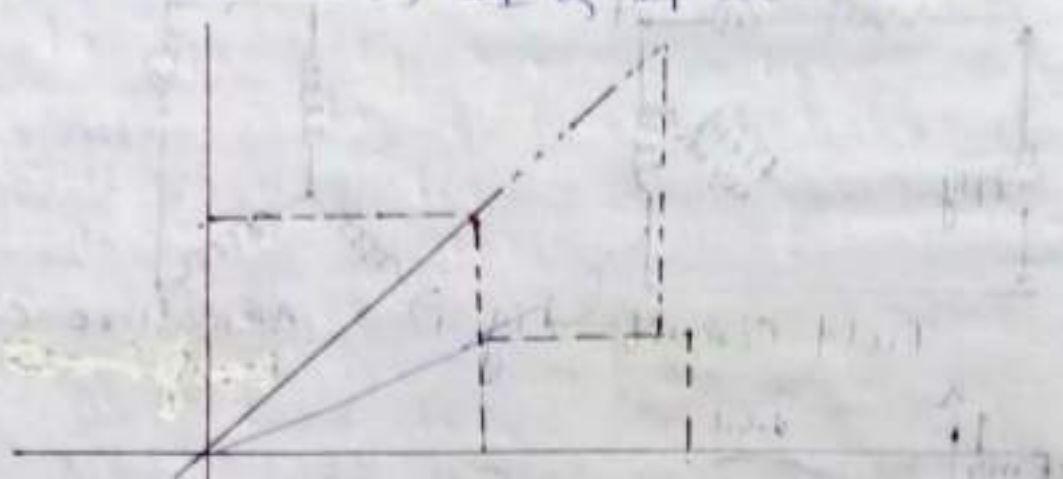
→ In this state the alternator is run at rated speed & the armature terminals are short-circuited through identical ammeters as shown in Fig. 3.



The armature reaction will give rise to  $I_{sc}$  and this  $I_{sc}$  is now varied by the Field current ( $I_f$ )

The Synchronous impedance,  $Z_s$  will be determined by taking the plots of O.C.C. & S.C.C. jointly as shown in Fig 5.

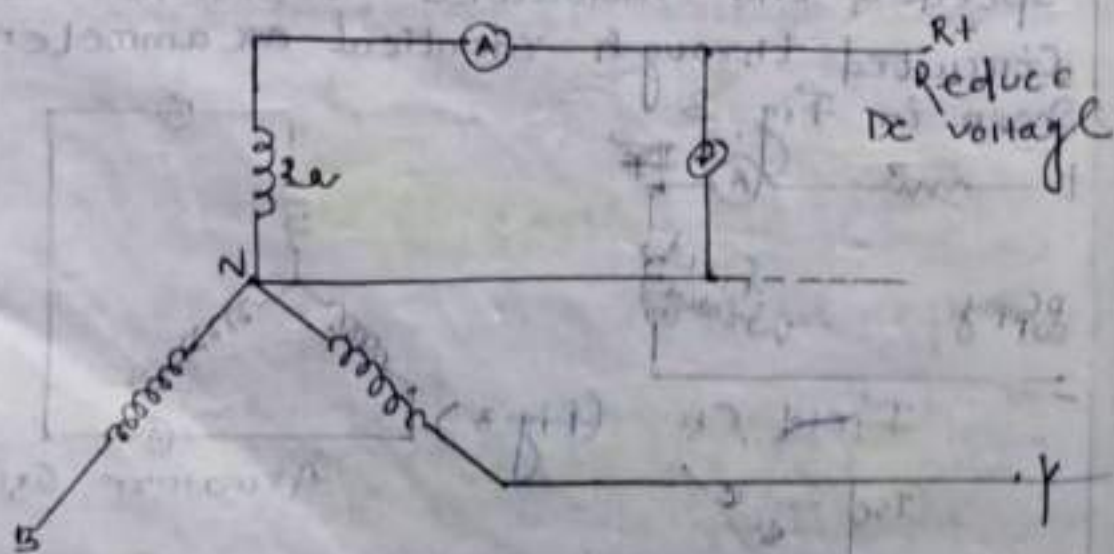
→ From the plot at a particular Field Current ( $I_f$ ) both  $I_1$  &  $E_1$  are read.



$$\therefore Z_s = \text{Synchronous impedance} = \frac{E_1}{I_1}$$

$$\text{i.e. } Z_s = \frac{E_1(\text{O.C.C.})}{I_1(\text{S.C.})}$$

$R_a$  will be determined by using Voltmeter ammeter method.



→ A reduced voltage (d.c) is applied across the armature with alternator is at rest. The voltmeter and ammeter readings are noted

$$\therefore R_a = \frac{V}{I} \text{ which is the d.c value.}$$

$$\therefore R_a(\text{a.c}) = 1.5 R_a(\text{d.c})$$

1.5 is multiplied due to skin effect.

$$\therefore X_s = \sqrt{Z_s^2 - R_a^2} \text{ is found out}$$

$$\therefore E_0 = \sqrt{(V \cos \phi + I_a R_a)^2 + (V \sin \phi + I_a X_s)^2}$$

will be determined

$I_a$  = rated current of armature under Full-load Condition

$V$  = rated terminal voltage of the alternator under Full-load Condition.

$$\therefore V.R = \frac{E_0 - V}{V} \text{ will be found it.}$$

### Parallel operation of Alternator

→ parallel operation of Alternator is called Synchronisation.

→ It is generally done in the generating stations because there are more alternators and they have to be synchronised.

→ The conditions for synchronisation are that

1. The bus bar voltage must be same to that of terminal voltage of alternator

2. Speed of incoming alternator must be such that the frequency must be equal to the busbar.

3. The phase of the alternator voltage must be identical to that of bus bar voltage.

→ Synchro scopes are generally preferred for synchronisation results.

Dt-18-11-2021

## (CH-7) (Single Phase Induction Motor)

- Single phase Induction motor is very similar three phase Squirrel cage Induction motor
- It has a identical Squirrel cage rotor & a single phase winding on the stator.

### Working

- The single phase stator winding produces a magnetic field that pulsates in strength in sinusoidal manner.
- The field polarity reverses after each half cycle but the field doesn't rotate.
- The alternating pulse can't produce rotation in the rotor.
- If the rotor of a single phase motor is rotated in one direction by some mechanical means, it will continue to run in the direction of rotation.
- Once the motor is running at synchronous speed it will continue to rotate even though the single phase current is flowing through the stator winding.
- This method of starting is generally not applicable for the large motor.

### Make Self Starting

- To make a single phase Induction motor self starting we should produce a revolving stator magnetic field.
- This may be achieved by converting a single phase supply into two phase supply through the use of additional winding.
- According to the method of to make the single phase induction.

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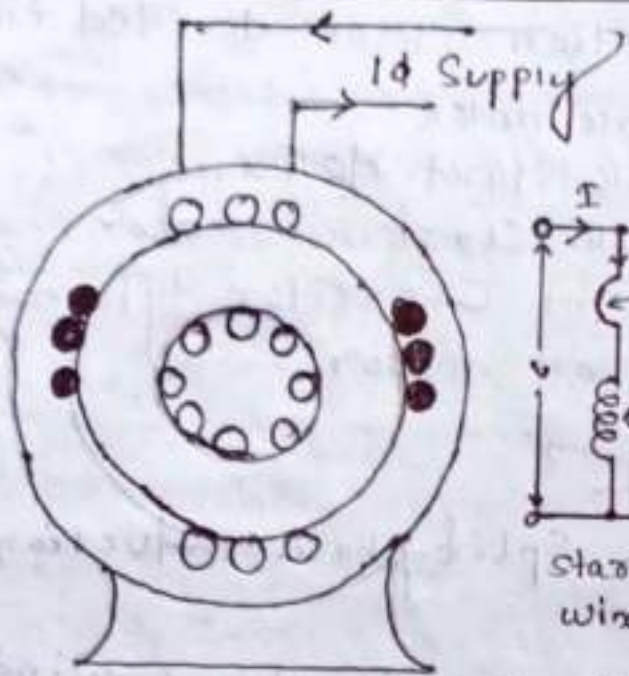
The Single phase Induction motor divided into 5 types

1. Split phase motor
2. Capacitor start motor
3. Capacitor start run motor
4. Permanent capacitor type motor
5. Shaded pole motor

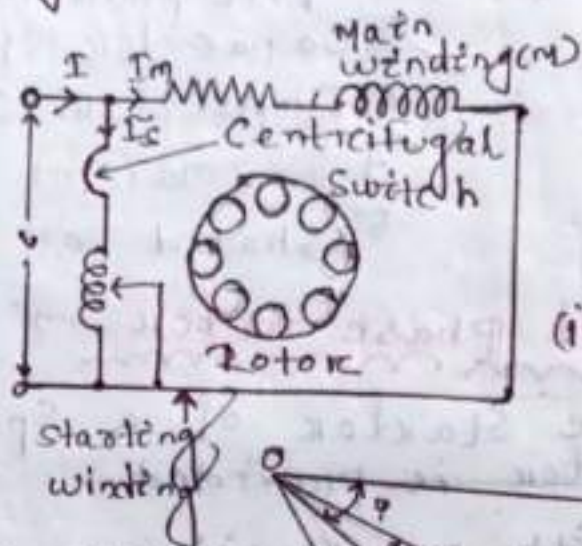
### Split Phase motor :-

- The stator of a split-phase induction motor is provided with an auxiliary or starting winding 'S' in addition to the main or running winding 'M'.
- The starting winding is located  $90^\circ$  electrical from the main winding and operates only during the brief period when the motor starts up.
- The two windings are so designed that the starting winding (S) has a high resistance and relatively small reactance while the main winding (M) has relatively low resistance and large reactance as shown in the schematic connections in fig (ii).
- Consequently the currents flowing in the two windings have a reasonable phase difference  $\phi$  ( $25^\circ$  to  $50^\circ$ ) as shown in fig.
- The starting torque is given by

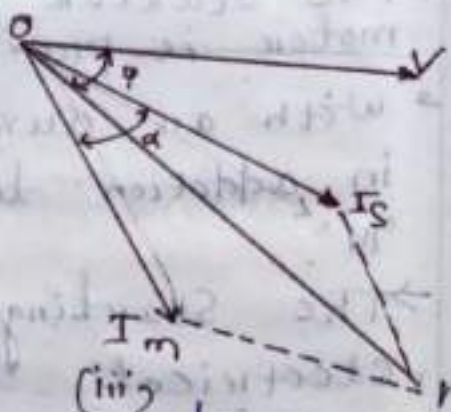
$$T_s = k I_m I_s \sin \phi$$



(i)



(ii)



(iii)

operation : →

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

(ii) Since main winding is made highly inductive while the starting winding highly resistive, the current  $I_m$  and  $I_s$  have a reasonable phase angle  $\alpha$  ( $25^\circ$  to  $30^\circ$ ) between them as shown in fig (iii).

→ A weak revolving field approximating to that of a 2-phase machine is produced which starts the motor.

→ The starting torque is given by

$$T_s = K I_m I_s \sin \alpha$$

Where  $K$  is a constant whose magnitude depends upon the design of the motor.

(ii) When the motor reaches about 75% of synchronous speed, the centrifugal switch opens the circuit of the starting winding.

→ The motor then operates as a single-phase induction motor and continues to accelerate till it reaches the normal speed.

→ The normal speed of the motor is below the synchronous speed and depends upon the load on the motor.

## ② Capacitor Start Motor →

→ The capacitor start motor is identical to a split-phase motor except that the starting winding has as many turns as the main winding.

→ A capacitor  $C$  is connected in series with the starting winding as shown in fig.

→ The value of capacitor is so chosen that  $I_s$  leads  $I_m$  by about  $80^\circ$  (i.e.  $\alpha \approx 80^\circ$ ) which is considerably greater than  $25^\circ$  found in split-phase motor. (fig-ii)

→ Consequently, starting torque ( $T_s = k I_m I_s \sin \alpha$ ) is much more than that of a split-phase motor.

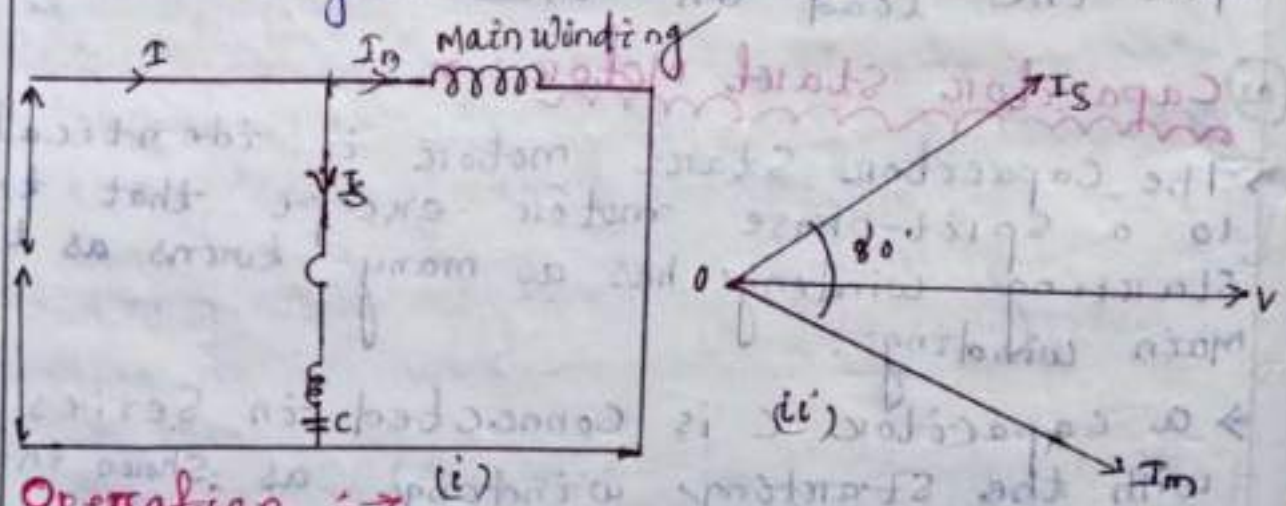
→ Again the starting winding is opened by the centrifugal switch when the motor

attains about 75% of synchronous speed.

→ The motor then operates as a single-phase induction motor and continues to accelerate till it reaches the normal speed.

→ Capacitor-start motors are used where high starting torque is required and where the starting period may be long, e.g. to drive:

- (i) compressors
- (ii) large fans
- (iii) pumps
- (iv) High-inertia loads.



Operation :-

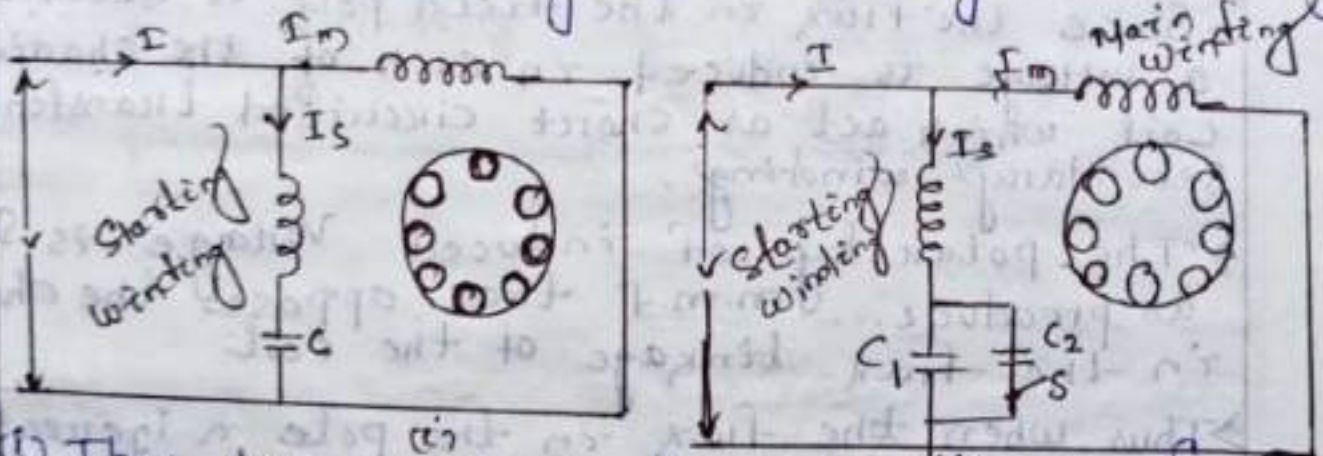
• When the two starter windings are energised from a single-phase supply the main winding carries current  $I_m$  while the starting winding carries current  $I_s$ .

• Since main winding is made highly inductive while the starting winding highly resistive, the current  $I_m$  and  $I_s$  have a reasonable phase angle is near about  $80^\circ$  between them as shown in fig (ii).

### ③ Capacitor-Start Capacitor-Run Motor :->

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

(i) In one design, a single capacitor  $C$  is used for both starting and running as shown in fig.



(i) This design eliminates the need of a centrifugal switch and at the same time improves the power factor and efficiency of the motor.

(ii) In the other design two capacitors  $C_1$  and  $C_2$  are used in the starting winding as shown in fig.

→ The smaller capacitor  $C_1$  required for optimum running conditions, is permanently connected in series with the starting winding.

→ The much larger capacitor  $C_2$  is connected in parallel with  $C_1$  for optimum starting and remains in the circuit during starting. The starting capacitor  $C_2$  is disconnected when the motor approaches about 75% of synchronous speed.

## ④ Shaded-pole motor $\rightarrow$

$\rightarrow$  The shaded pole motor is very popular for starting below 0.05 HP ( $\approx 40W$ ) because of its extremely simple construction. It has salient pole on the stator excited by single phase supply & a squirrel cage rotor.

$\rightarrow$  A portion of each pole is surrounded by a short circuit turn of copper strip called shading coil.

### Operation $\rightarrow$

$\rightarrow$  Since the flux in the field pole is alternating a voltage is induced in each of the shading coil which act as short circuited transformer secondary winding.

$\rightarrow$  The polarity of induced voltage is such as produce m.m.f that opposes the change in the flux linkage of the coil.

$\rightarrow$  Thus when the flux in the pole is increasing the shaded coil current produce an m.m.f opposing the increase.

$\rightarrow$  The flux density of the unshaded portion of the pole is greater than that of the shaded portion.

$\rightarrow$  When the pole flux is decreasing the shading coil current flow to oppose the decrease.

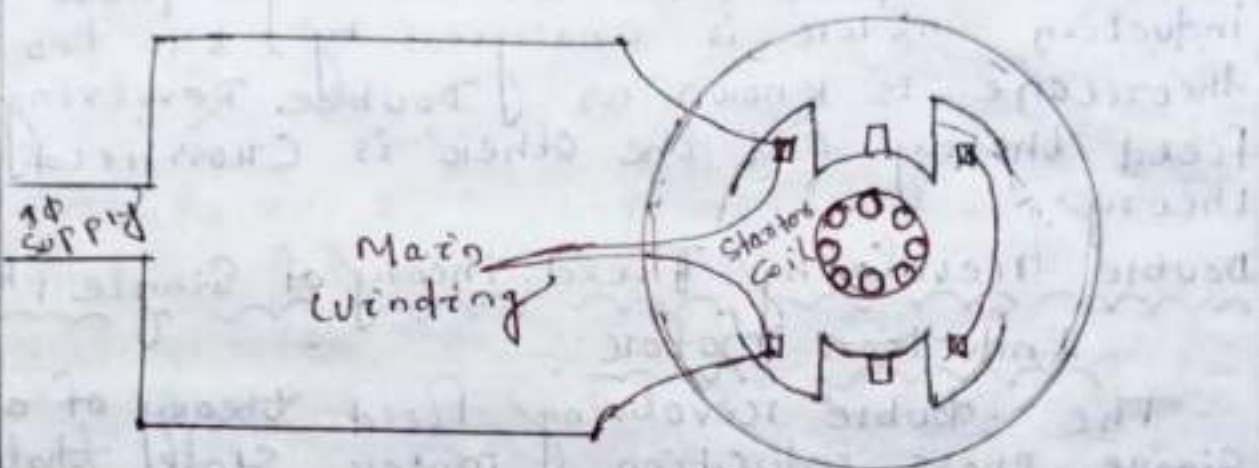
$\rightarrow$  Thus the effect of the shading coil is to produce a shift in the flux from the unshaded portion.

$\rightarrow$  This shift in flux may be considered to be a partiality rotating field and is sufficient to produce in the direction of the shift in the flux.

→ Because of Small Starting torque developed in the motor and relatively large power loss in the shading coil.

→ The shaded pole motor is built in small size.

→ The most common application being to fan.



To change the direction of the rotation of motor

• The Single phase Induction motor has wide range of use both in house and industry working.

• It has one starting winding and one running winding.

• Generally the starting winding has more number of turns. when it get energized it create additive polarity which cause the motor to rotate in clockwise direction.

\* When we connect the phase with the running winding, as the running winding has less number of turns and it creates less polarity. The motor achieves anticlockwise direction of rotation.

\* The performance of the single phase induction motor is analysed by the two theories one is known as Double Revolving field theory and the other is Crossfield theory.

### Double Revolving Field Theory of Single Phase Induction Motor

The double revolving field theory of a single phase induction motor states that a pulsating magnetic field is resolved into two rotating magnetic fields.

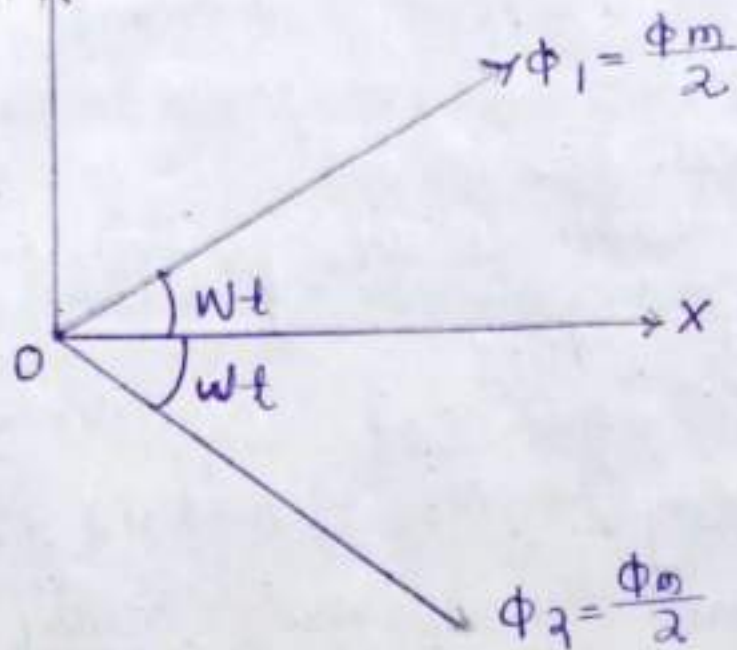
→ They are equal in magnitude but opposite in direction.

→ The induction motor responds to each of the magnetic fields separately.

→ The net torque in the motor is equal to the sum of the torque due to each of the two magnetic fields.

→ The equation for force on an alternating magnetic field is given as the 1st term of the right-hand side of the equation (2) represents the revolving field moving in the +ve direction it is known as forward rotating field.

→ The second term shows the revolving field moving in the -ve direction and is known as the backward rotating field.



→ Consider two rotating magnetic fluxes  $\phi_1$  and  $\phi_2$  each of magnitude  $\frac{\phi_m}{2}$  and rotating in opposite directions with angular velocity " $\omega$ "

$$\text{Totally } x\text{-component} = \frac{\phi_m}{2} \cos \omega t + \frac{\phi_m}{2} \cos \omega t = \phi_m \cos \omega t$$

$$\text{Totally } y\text{-component} = \frac{\phi_m}{2} \sin \omega t - \frac{\phi_m}{2} \sin \omega t = 0$$

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

Thus the resultant flux vector is  $\phi = \phi_m \cos \omega t$  acting along the X-axis.

- The direction in which the single phase motor is started initially known as the +ve direction.
- Both the revolving field rotate at the synchronous speed  $\omega_s = 2\pi f$  in the opposite direction.
- The pulsating magnetic field is resolved into two rotating magnetic fields. Both are equal in magnitude and opposite in direction but at the same frequency.

### Ferraris Principle: →

Ferraris devised a motor using electromagnet at right angle and power by alternating current that were 90° out of phase.

- Thus producing a revolving magnetic field.
- The direction of motor could be reversed by reversing the polarity of one of the currents.

### Cross field theory: →

- Cross field revolving theory is the theory which discusses the cause of non self starting of single phase induction motor.
- If the single-phase stator winding is excited and the rotor of the motor is rotated by an auxiliary means and the starting device is then removed.
- The motor continues to rotate in the direction in which it started.

## Permanent Capacitor type motor:

- It has a cage rotor and stator.
- The stator has two windings - main and auxiliary winding.
- It has only one capacitor in series with starting winding.
- It has no starting switch.

## Advantages of permanent split capacitor motor:

- No centrifugal switch is needed.
- It has higher efficiency and pull-out torque.

## Applications of permanent split capacitor motor:

- It finds applications in fans and blowers in heaters and air conditioners.
- It is also used to drive office machinery.