AC MOTORS

Subject Name: Electrical Fundamentals

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Approved By:

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2	Squirrel cage and slip ring rotor contruction
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5	Power stage diagram of an IM
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10	Double field revolving theory
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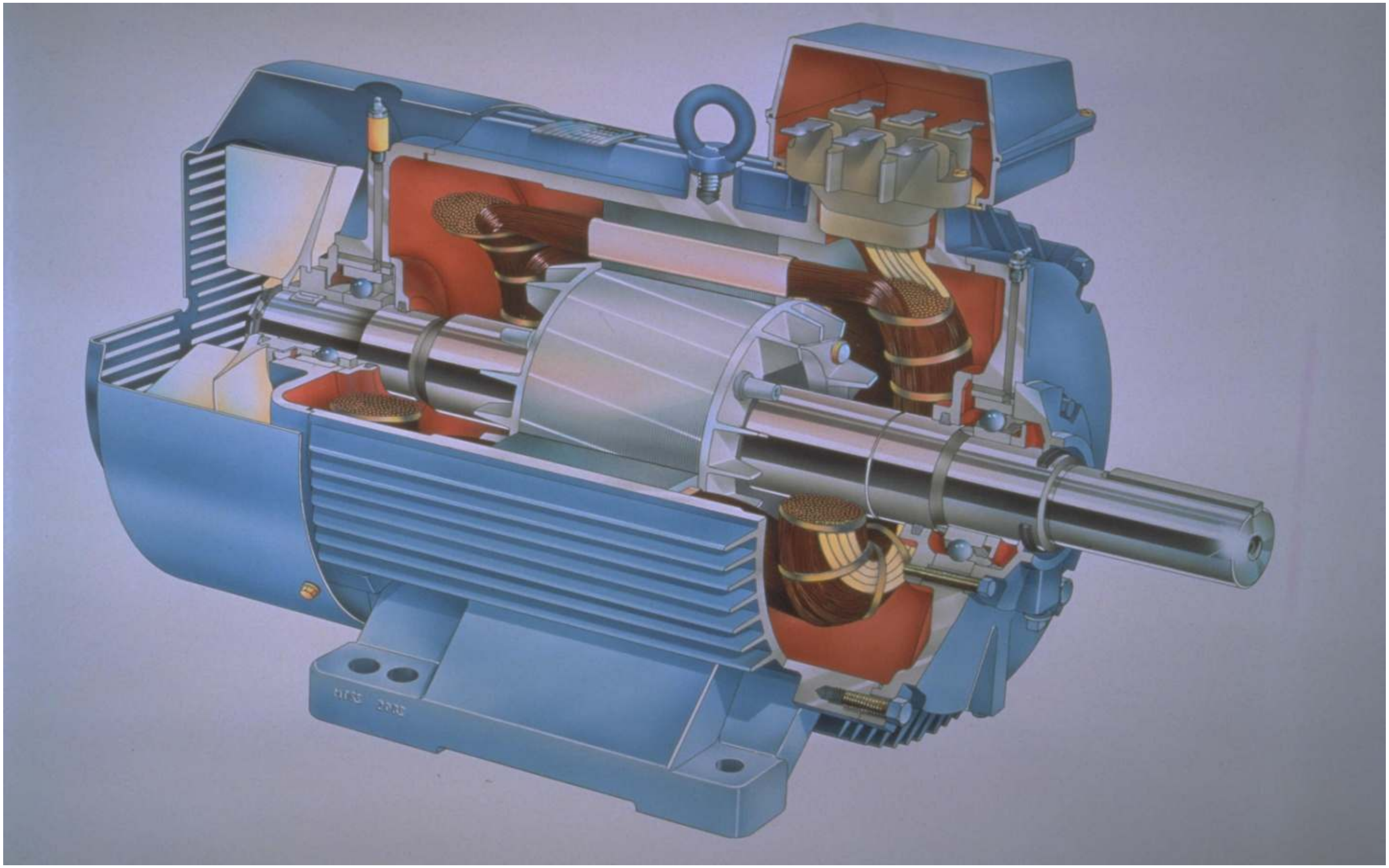
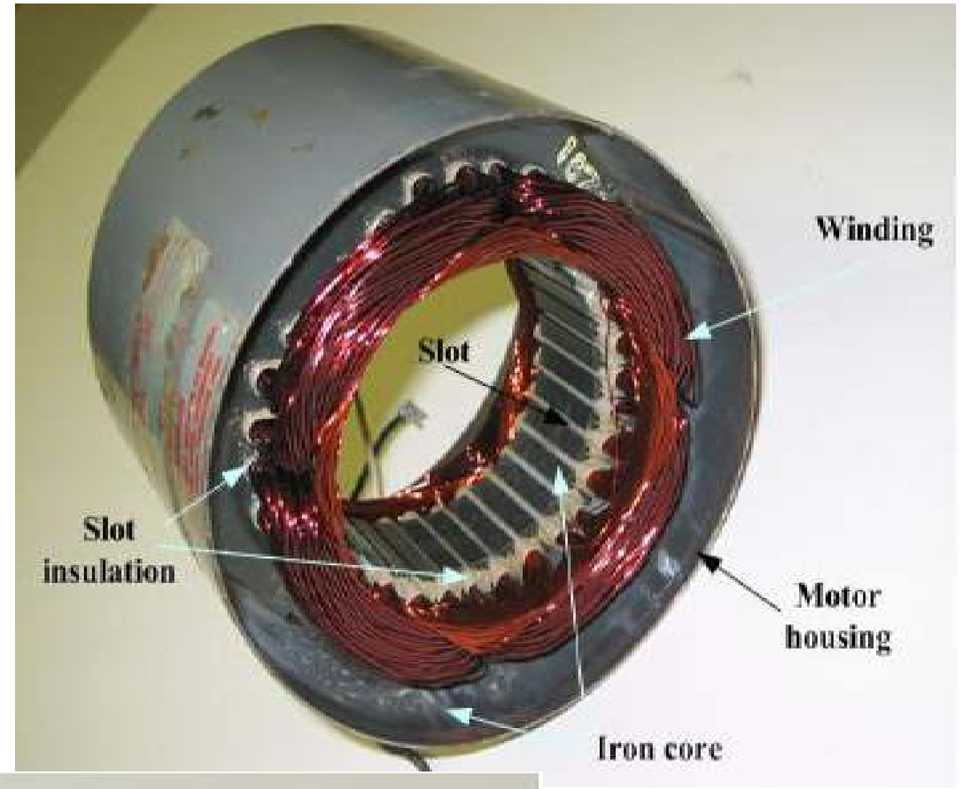
3-phase Induction Motor



Construction

- An induction motor has two main parts

    1. Stator
    2. Rotor



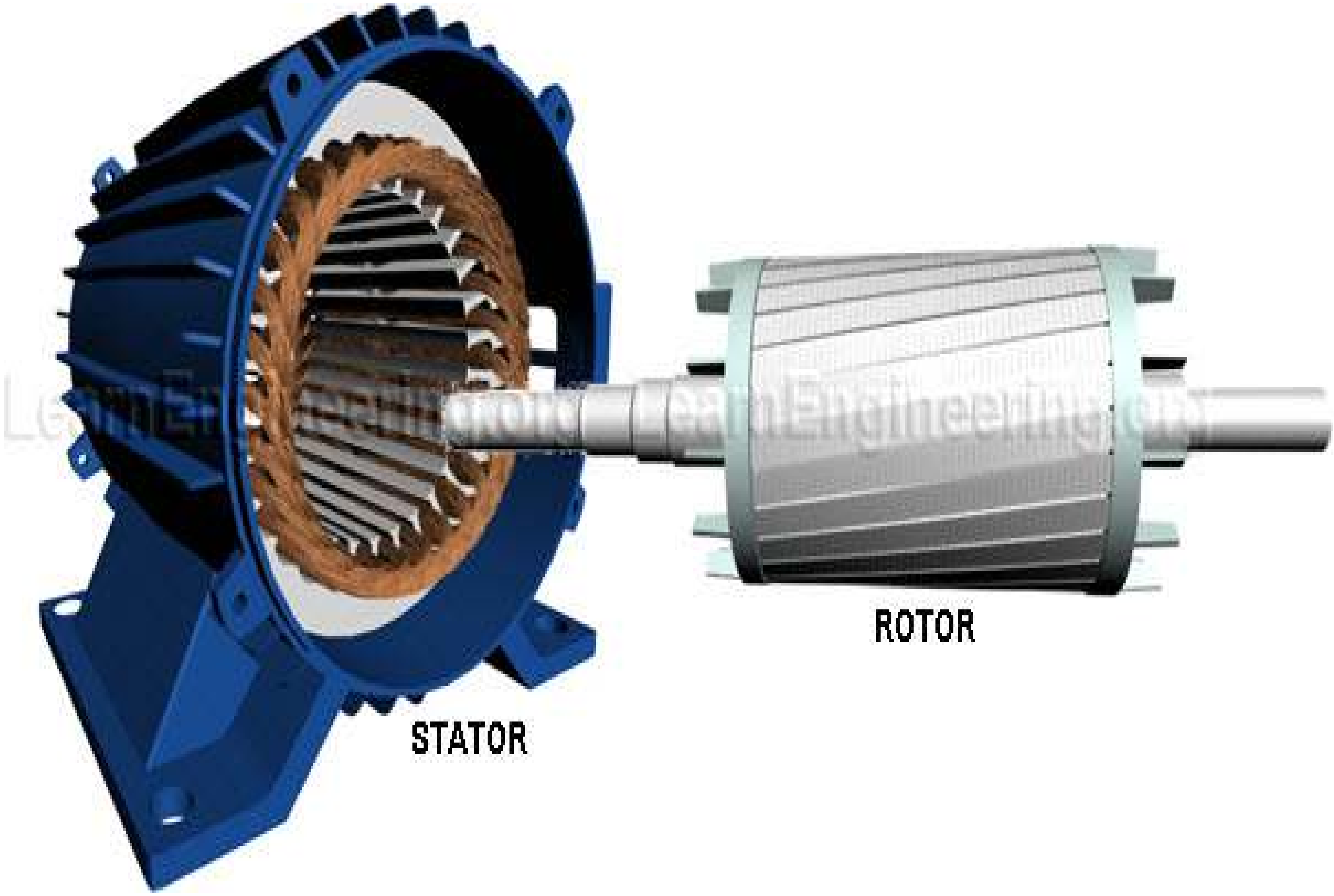
Construction

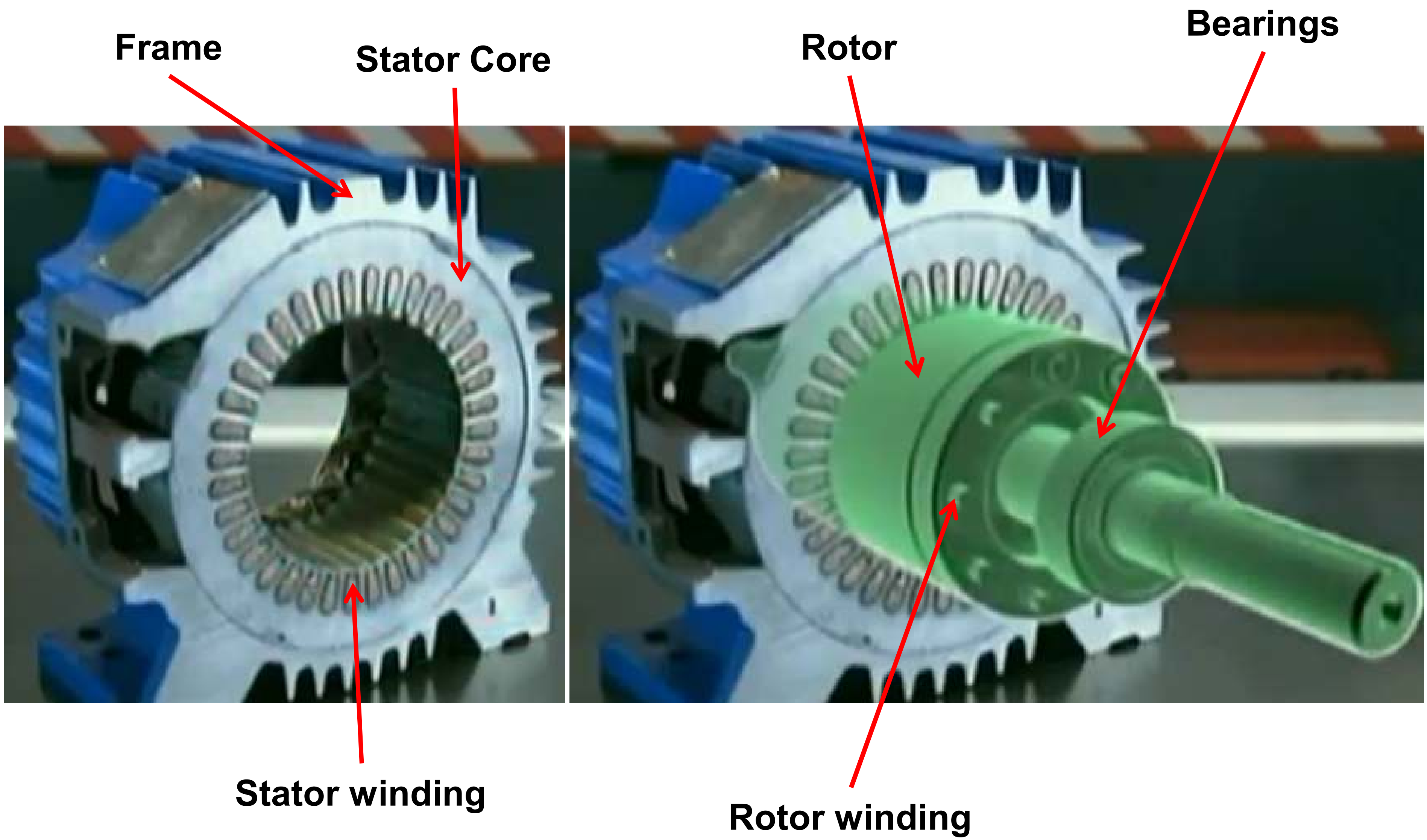
- A three phase Induction motor essentially consists of two parts:

1. STATOR
2. ROTOR

STATOR

- A Stator is a stationary part and Rotor is the rotating part.
- The Stator is built up of high-grade alloy steel lamination to reduce eddy-current losses.
- The laminations are slotted on the inner periphery and are insulated from each other.
- The insulated stator conductors are placed in these slots.
- The Stator conductor are connected to form a three-phase winding.
- The three phase winding may be Star or Delta connection.


ROTOR
STATOR


Frame
Stator Core
Rotor
Bearings
Stator winding
Rotor winding

Stator

Parts	Material used	Work	Remarks
Stator Frame	Cast Iron	Provide Support	No Flux Passes
2 End covers	Cast Iron	Provide Support	
Stator Core	Laminated Silicon Steel	Hold windings	Provide flux Path
Distributed winding	Copper	Generate flux	High Conductivity
Bearings		Smooth rotation of shaft	


FRAME
STEEL LAMINATIONS


S


www.stator-rotor.com

www.stator-rotor.com

www.stator-rotor.com

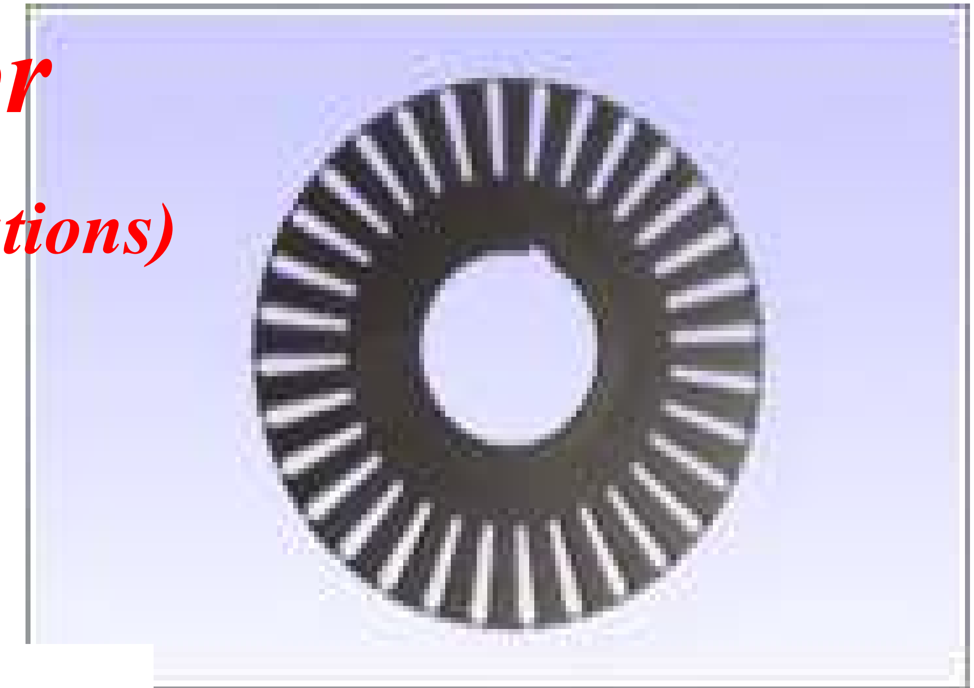

ROTOR

- The Rotor is built up of thin laminations of the high-grade alloy steel material.
- The laminated cylindrical core is mounted directly on the shaft or a spider carried by the shaft.
- There are two type of Induction Motor Rotor :

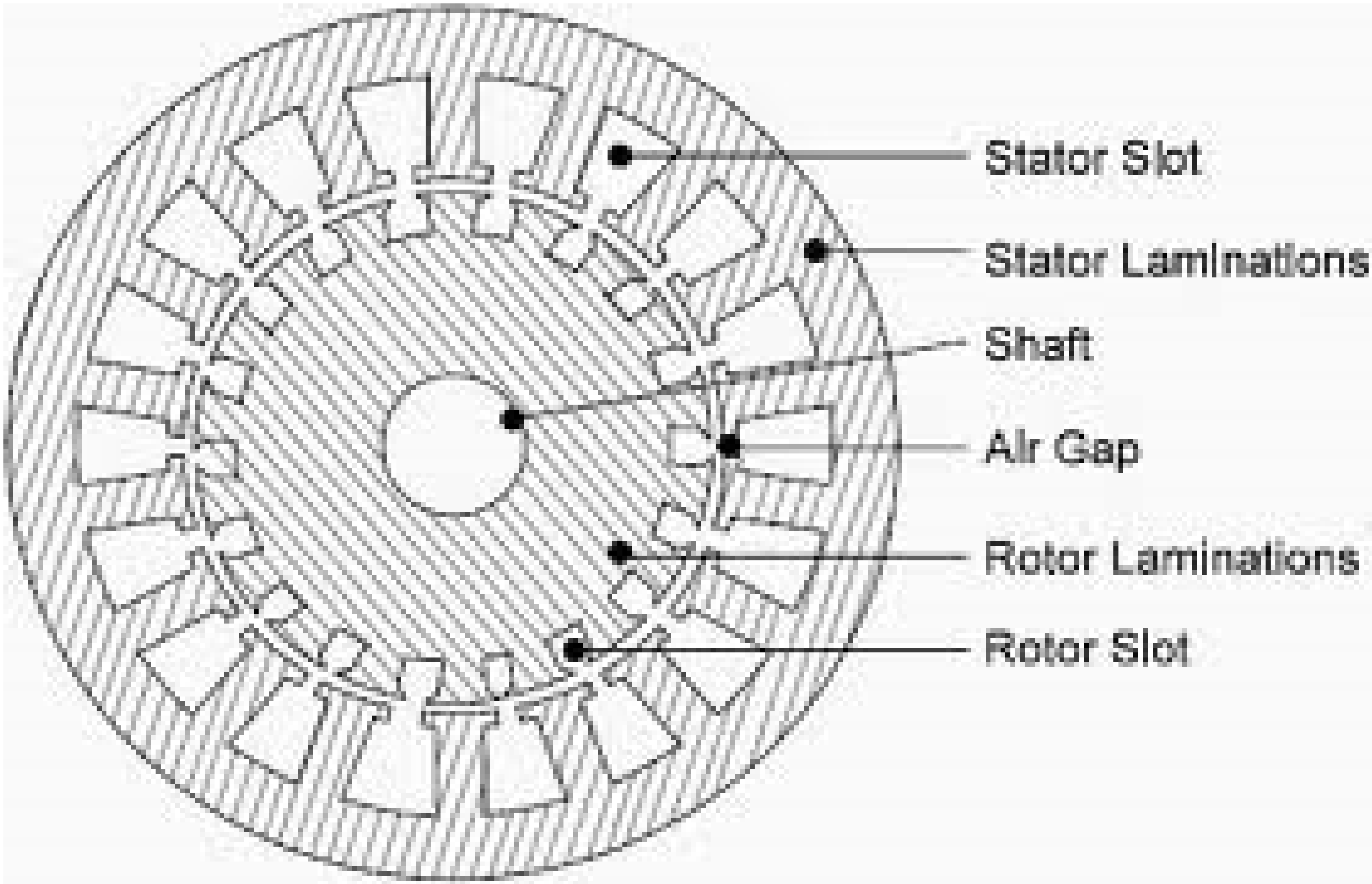
1. Squirrel-cage rotor or simply cage rotor.
2. Phase wound or wound rotor. Motor using this type of rotor are also called slip-ring motor.

Rotor

(Laminations)

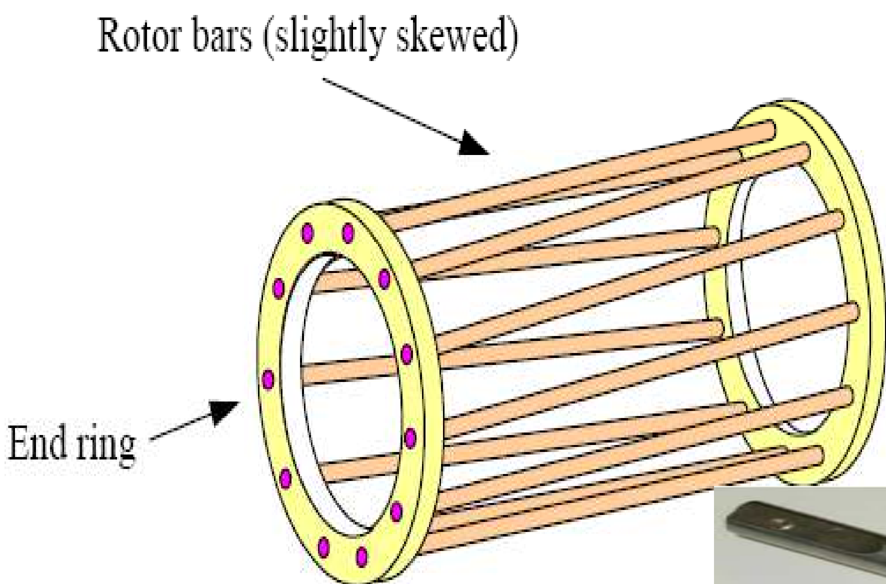



IRON LAMINA

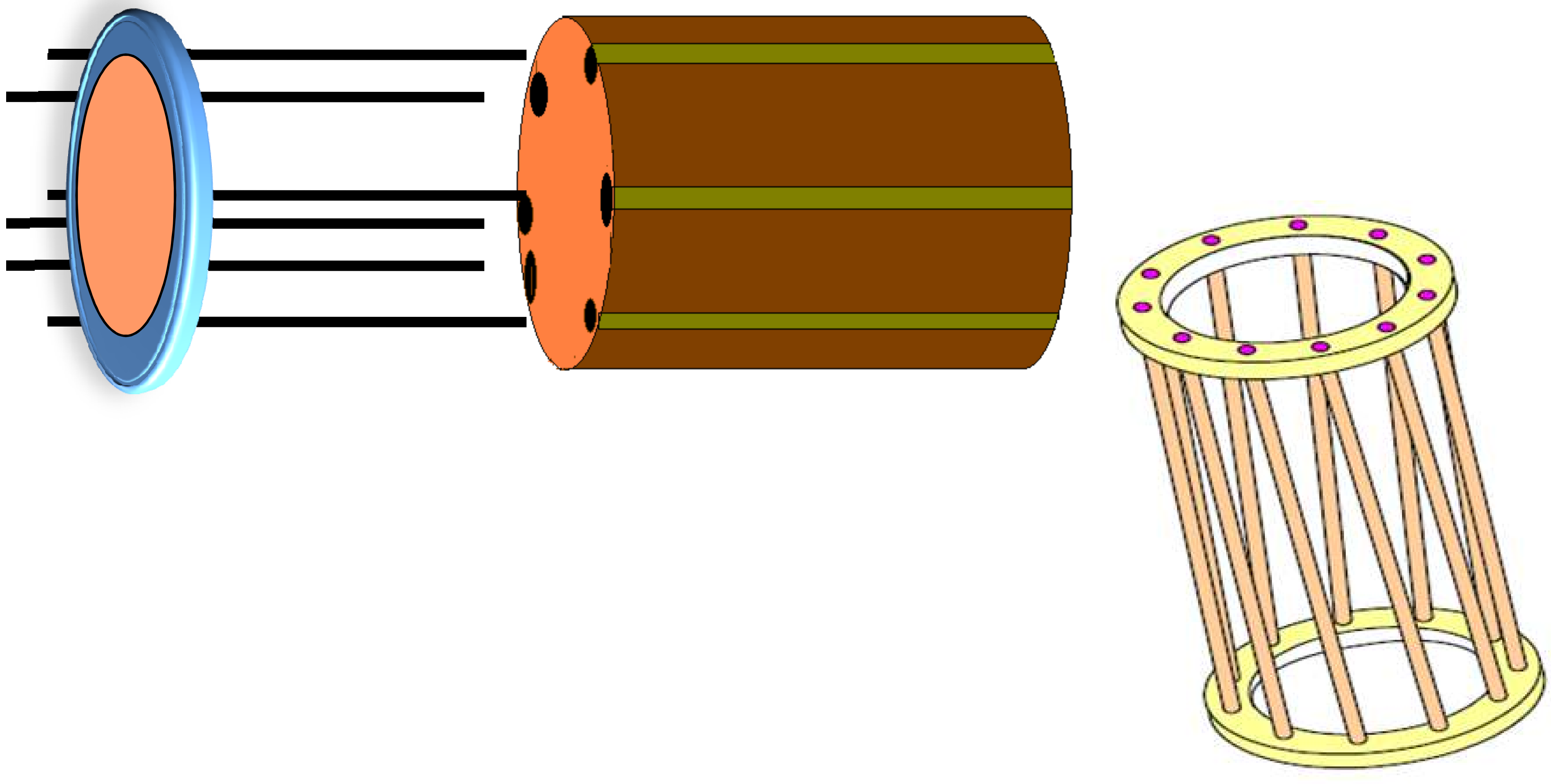

Stator Slot
Stator Laminations
Shaft
Air Gap
Rotor Laminations
Rotor Slot

Rotor

Types:
1. Squirrel-cage rotor
2. wound-rotor



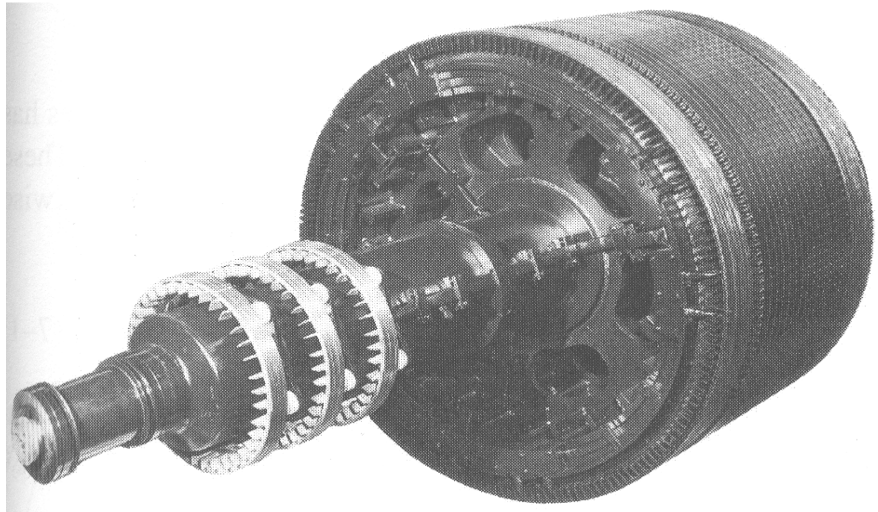
Squirrel-cage rotor

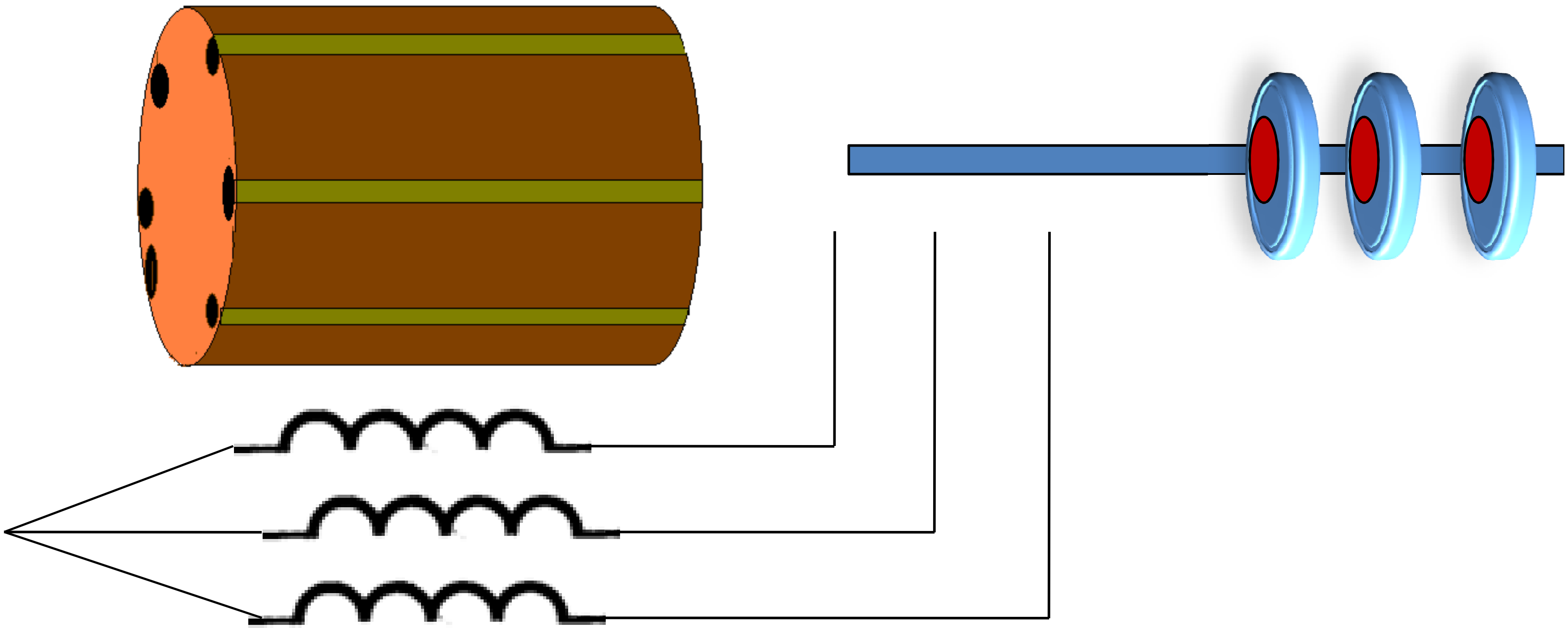


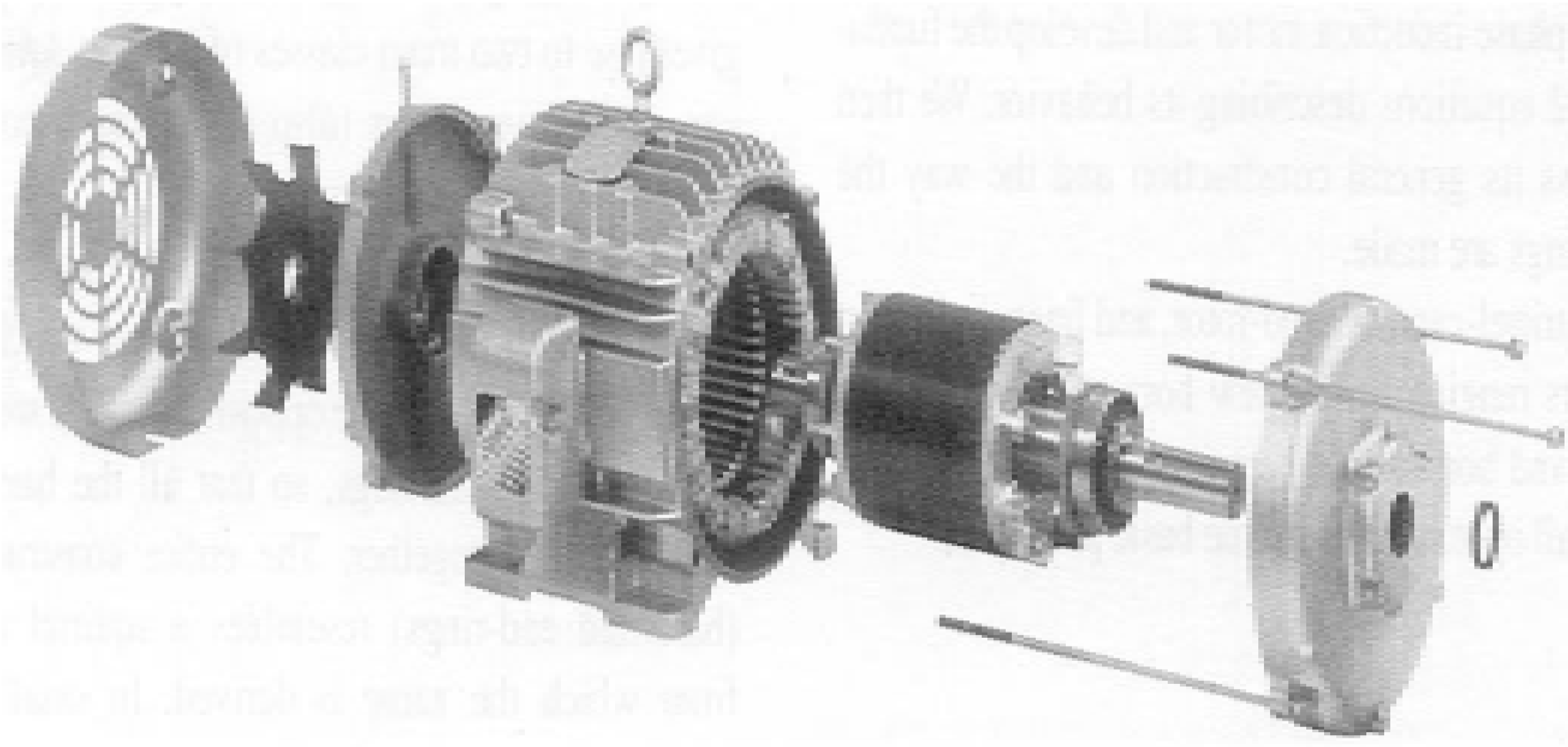
➢Advantages of Squirrel Cage IM

1. Absence of brushes reduce the risk of sparking
2. Smooth Operation
3. More uniform torque is produced and the noise is rduced during operation
4. Less maintained
5. Higher efficiency and higher power factor
6. Locking tendency of the rotor is reduced. During locking the rotor and stator teeth attract each other due to magnetic action

Wound-rotor(Slip Ring)



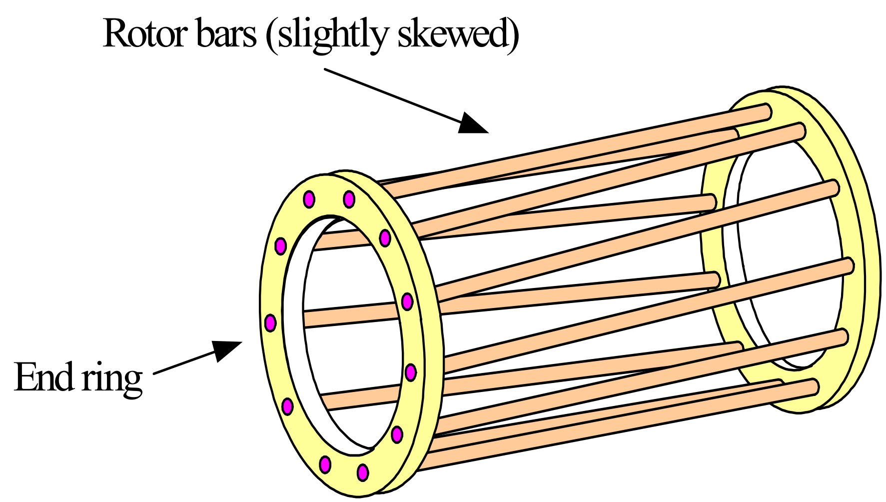




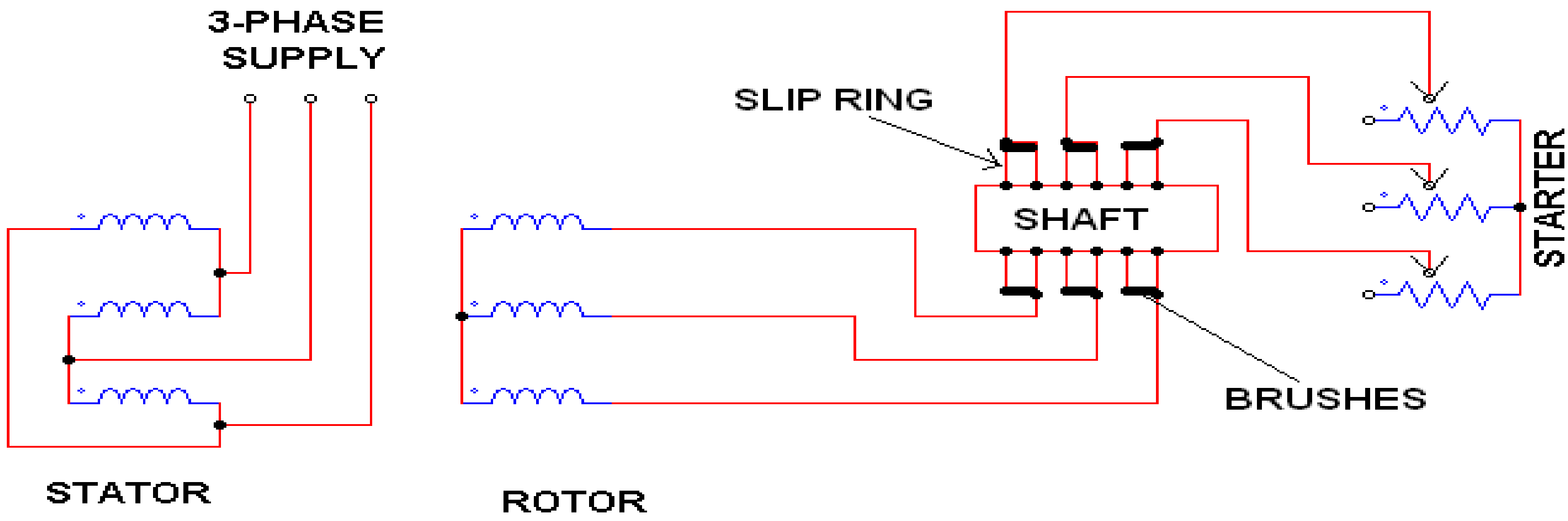
- In induction Machine Rotor windings (Bars) have current by only induction

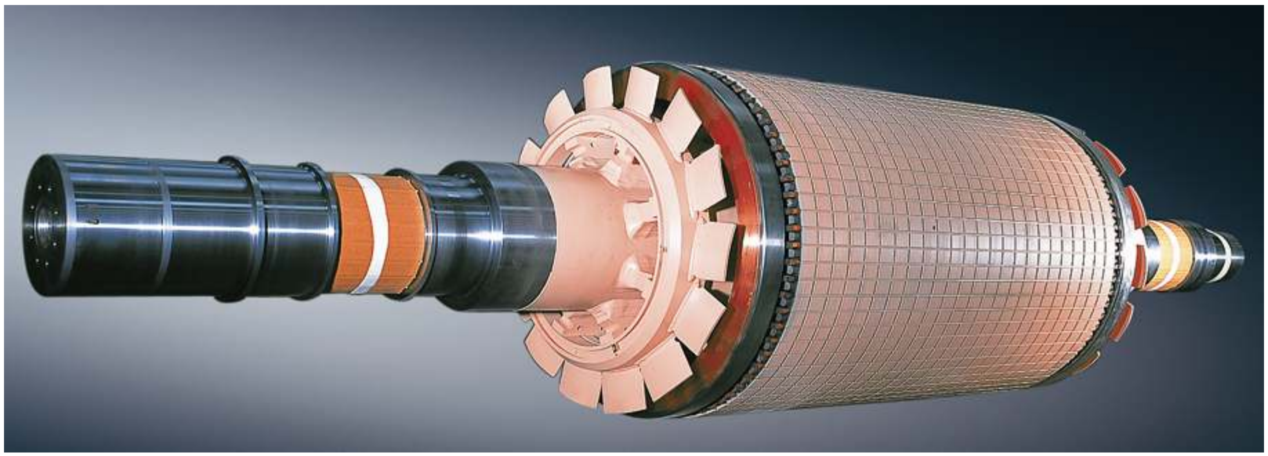
1. Squirrel-Cage Rotor

➢ The conductors and the end rings form a cage of the tyre which was once commonly used for keeping squirrels.



2. Wound Rotor or Slip Ring Rotor





- Rotor winding is exactly similar to Stator

- To increases the starting torque and decrease the starting current from the supply

- To control the speed of motor

❖ Comparison of Squirrel cage and Wound Rotor

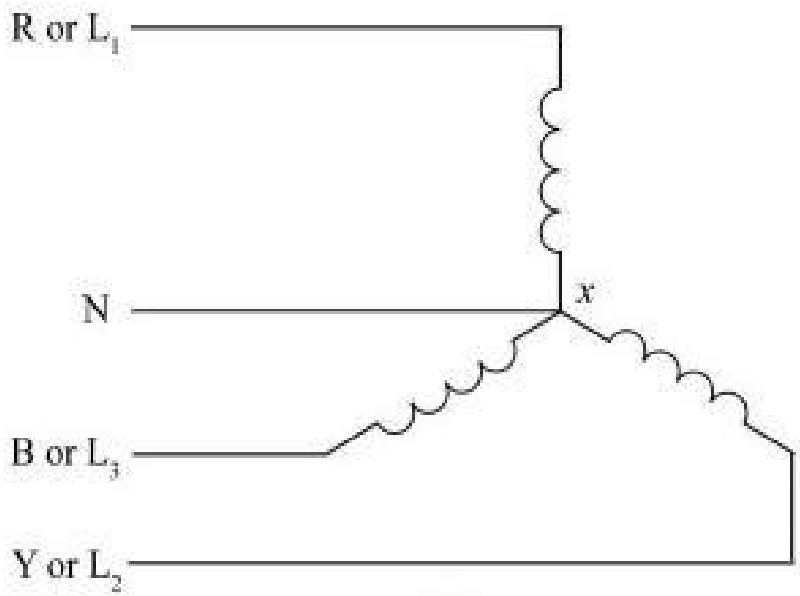
Slip ring Rotor	Squirrel Cage Rotor
Rotor consists of 3-phase winding similar to stator winding	Rotor consist of bars which are shorted at the ends with the help of end rings
Construction is complicated	Construction is simple
External resistance is added	As permanently shorted, External resistance can't be added
Slip ring and brushes are presents	Slip ring and brushes are not presents
Rotor are costly	Rotor are cheap
Maintenance are required	Maintenance free
Higher starting Torque	Moderate Starting Torque
Speed control is possible	Speed control Not possible
Rotor Cu-loss is high so efficiency is low	Rotor Cu-loss are less, so efficiency is high
Use for lifts, hoists, cranes, elevators, compressor etc..	Use in lathes, drilling machine, fan, blower, water pumps, grinder, etc..

ROTATING MAGNETIC FIELD(R.M.F)

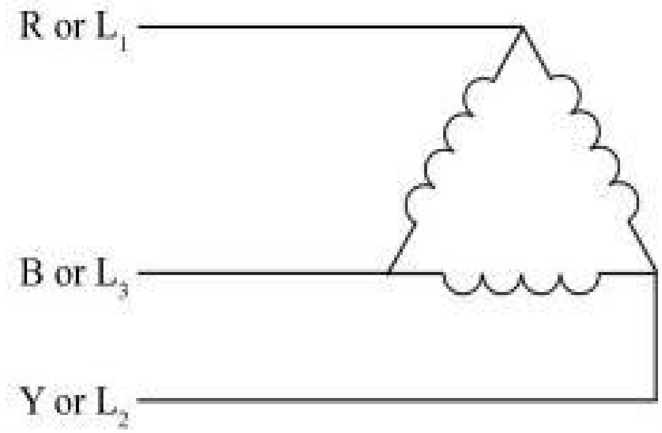
- 3-Phase IM is based on the principle of rotating magnetic fields.

PRODUCTION OF R.M.F.

- Stationary part: Stator
- 3-phase winding is connected in star or delta
- Each winding are displaced from each other by 120 degree.



(a)



(b)

- 3-phase current are displaced from each other by 120^0 electrical degree.
- Each alternating phase current produces its own flux which is sinusoidal.

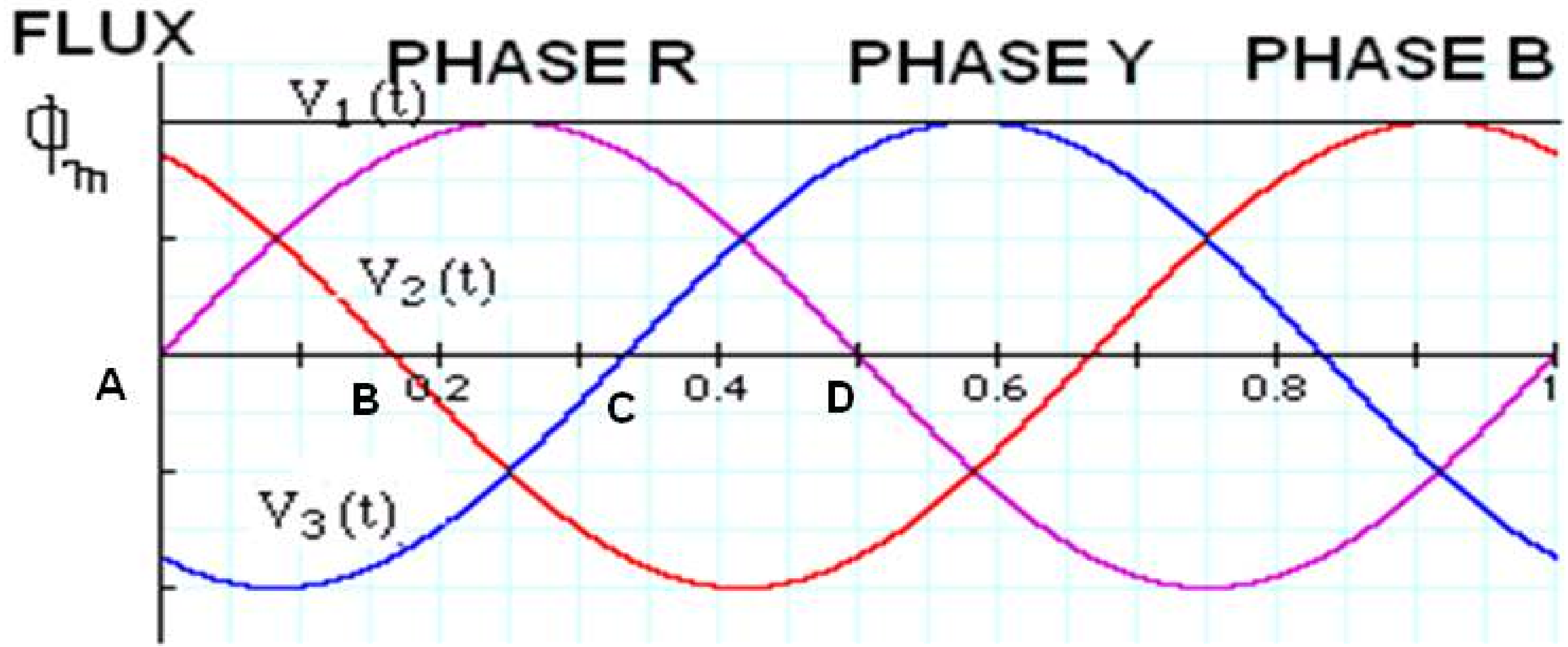
$$\varphi_R = \varphi_m \mathrm{Sin}(\omega t) = \varphi_m \mathrm{Sin}\ \theta$$

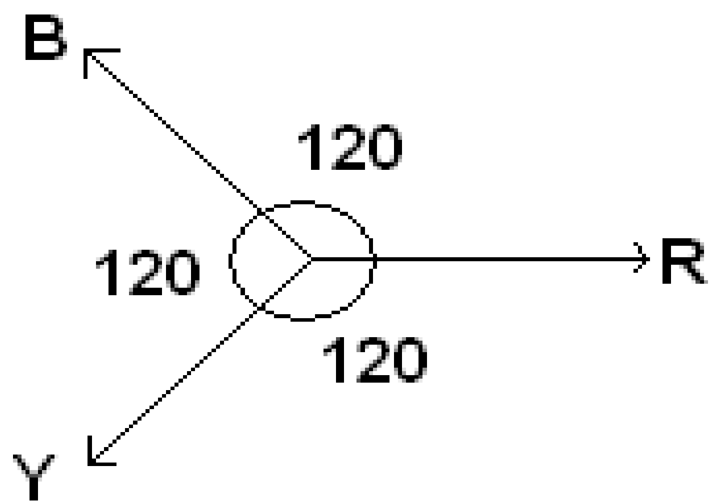
$$\varphi_Y = \varphi_m \mathrm{Sin}(\omega t - 120^0) = \varphi_m \mathrm{Sin}(\theta - 120^0)$$

$$\varphi_B = \varphi_m \mathrm{Sin}(\omega t - 240^0) = \varphi_m \mathrm{Sin}(\theta - 240^0)$$

- Resultant flux $\acute{Ø}_T$

$$\overline{\varphi_T} = \overline{\varphi_R} + \overline{\varphi_Y} + \overline{\varphi_B}$$


FLUX
PHASE R
PHASE Y
PHASE B
V1 (t)
V2 (t)
V3 (t)
A
B
C
D
0.2
0.4
0.6
0.8
1


B
120
120
120
R
Y

A. $\theta = 0$
B. $\theta = 60$
C. $\theta = 120$
D. $\theta = 180$

CASE-A: $\theta = 0$

$$\varphi_R = \varphi_m \text{Sin } 0 = 0$$

$$\varphi_Y = \varphi_m \text{Sin}(0 - 120^0) = -0.866\,\varphi_m$$

$$\varphi_B = \varphi_m \text{Sin}(0 - 240^0) = 0.866\,\varphi_m$$

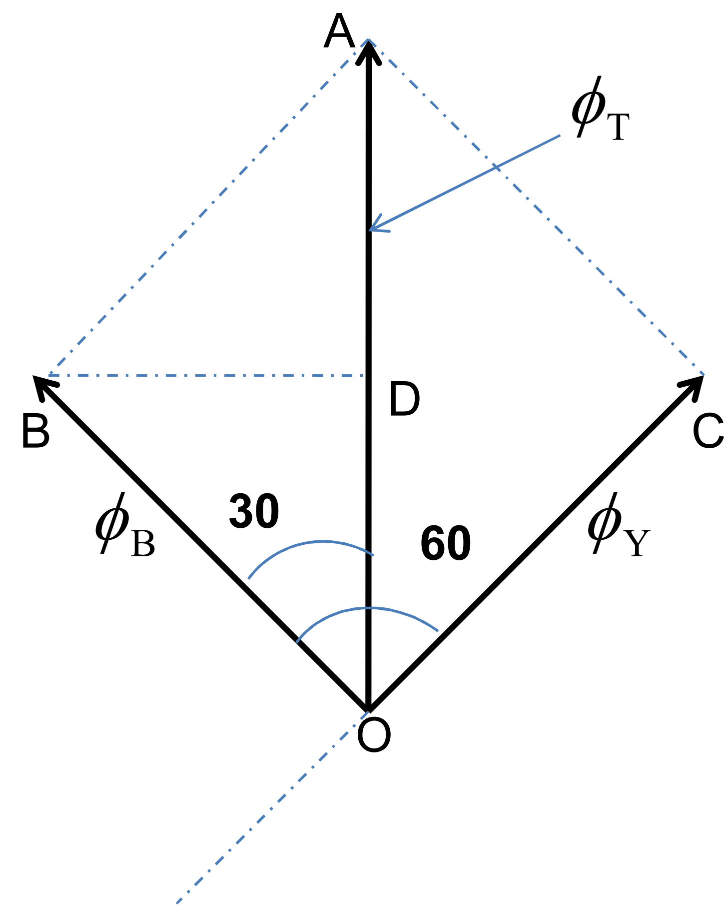
$$OD = DA = \frac{\phi_T}{2}$$

$$\angle BOD = 30$$

$$COS30 = \frac{OD}{OB} = \frac{\varphi_T \div 2}{0.866\,\varphi_m}$$

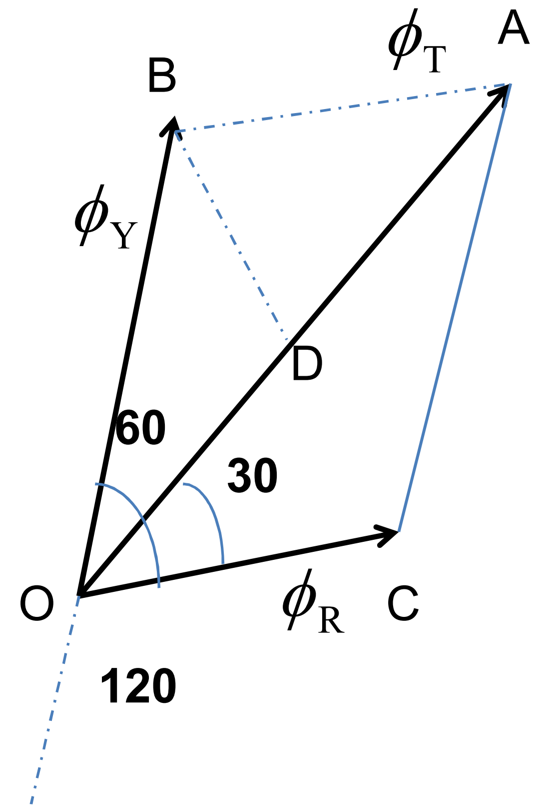
$$\varphi_T = 2 \times 0.866\,\varphi_m \times \cos 30$$

$$\varphi_T = 1.5\,\varphi_m$$



A. $\theta = 0$
B. $\theta = 60$
C. $\theta = 120$
D. $\theta = 180$

CASE-B: $\theta = 60$



$$\varphi_R = \varphi_m \mathrm{Sin}60 = 0.866\varphi_m$$

$$\varphi_Y = \varphi_m \mathrm{Sin}(60 - 120)$$
$$= -0.866\varphi_m$$

$$\varphi_B = \varphi_m \mathrm{Sin}(60 - 240) = 0$$

$$\varphi_T = 1.5\,\varphi_m$$

A. $\theta = 0$
B. $\theta = 60$
C. $\theta = 120$
D. $\theta = 180$

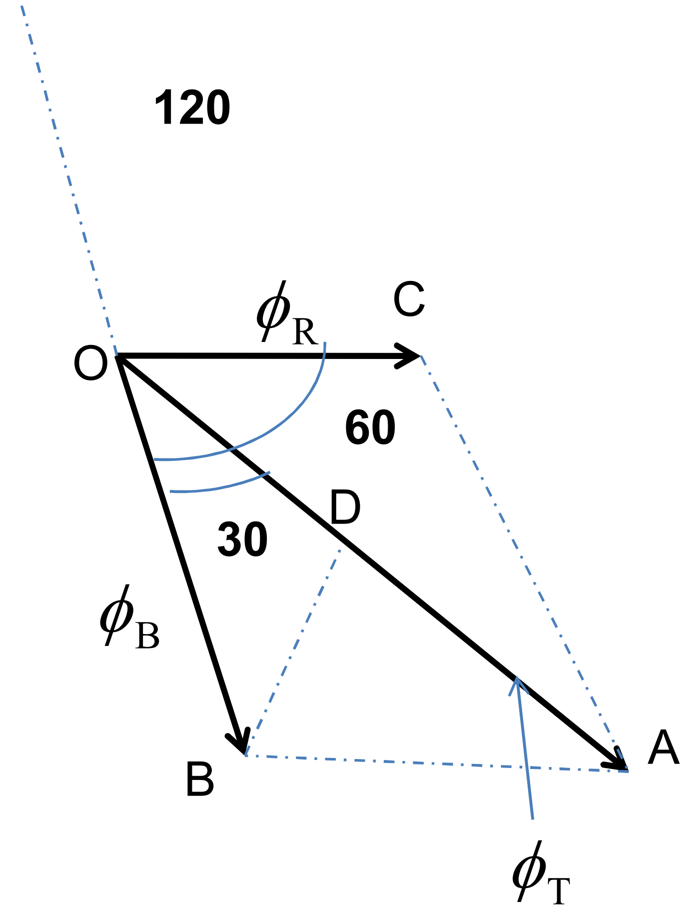
CASE-C: $\theta = 120$

$$\varphi_R = \varphi_m \text{Sin}120$$
$$= 0.866\, \varphi_m$$

$$\varphi_Y = \varphi_m \text{Sin}(120 - 120)$$
$$= 0$$

$$\varphi_B = \varphi_m \text{Sin}(120 - 240)$$
$$= -0.866\, \varphi_m$$

$$\varphi_T = 1.5\, \varphi_m$$



A. $\theta = 0$
B. $\theta = 60$
C. $\theta = 120$
D. $\theta = 180$

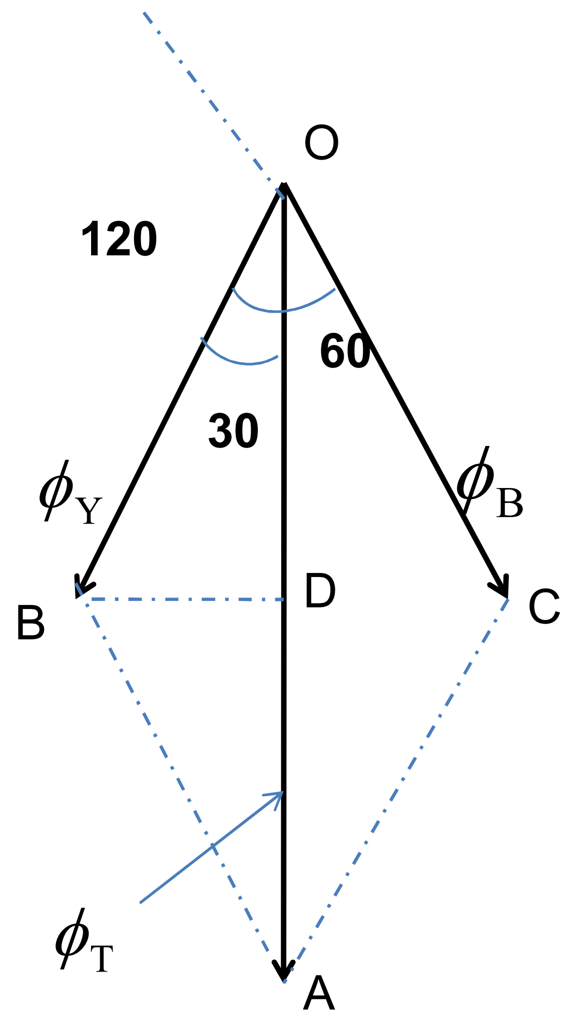
CASE-D: $\theta = 180$

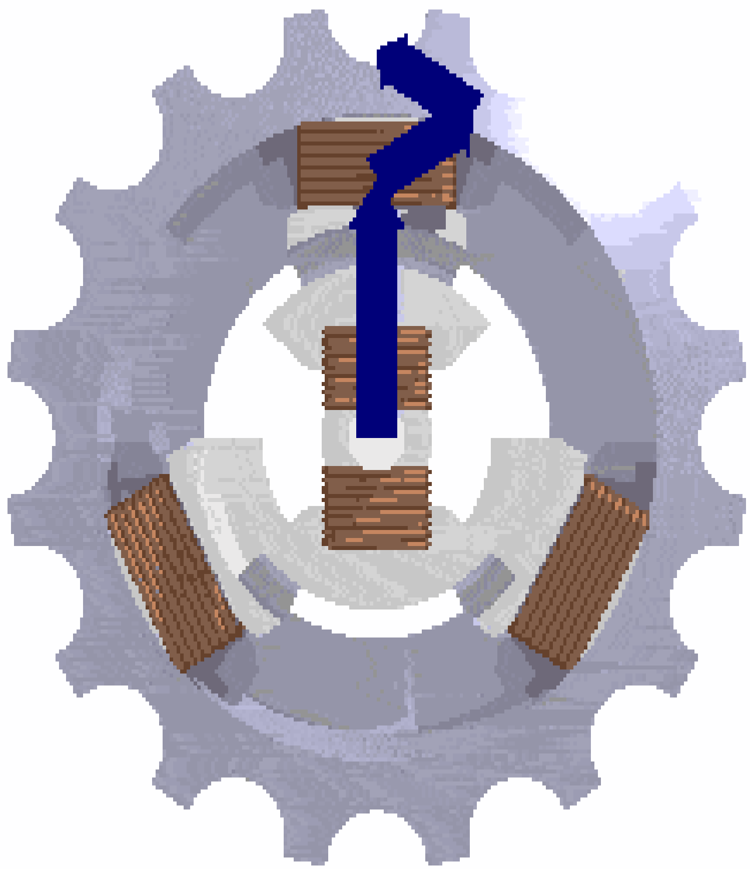
$$\varphi_R = \varphi_m \mathrm{Sin}180 = 0$$

$$\varphi_Y = \varphi_m \mathrm{Sin}(180 - 120)$$
$$= 0.866\varphi_m$$

$$\varphi_B = \varphi_m \mathrm{Sin}(180 - 240)$$
$$= -0.866\varphi_m$$

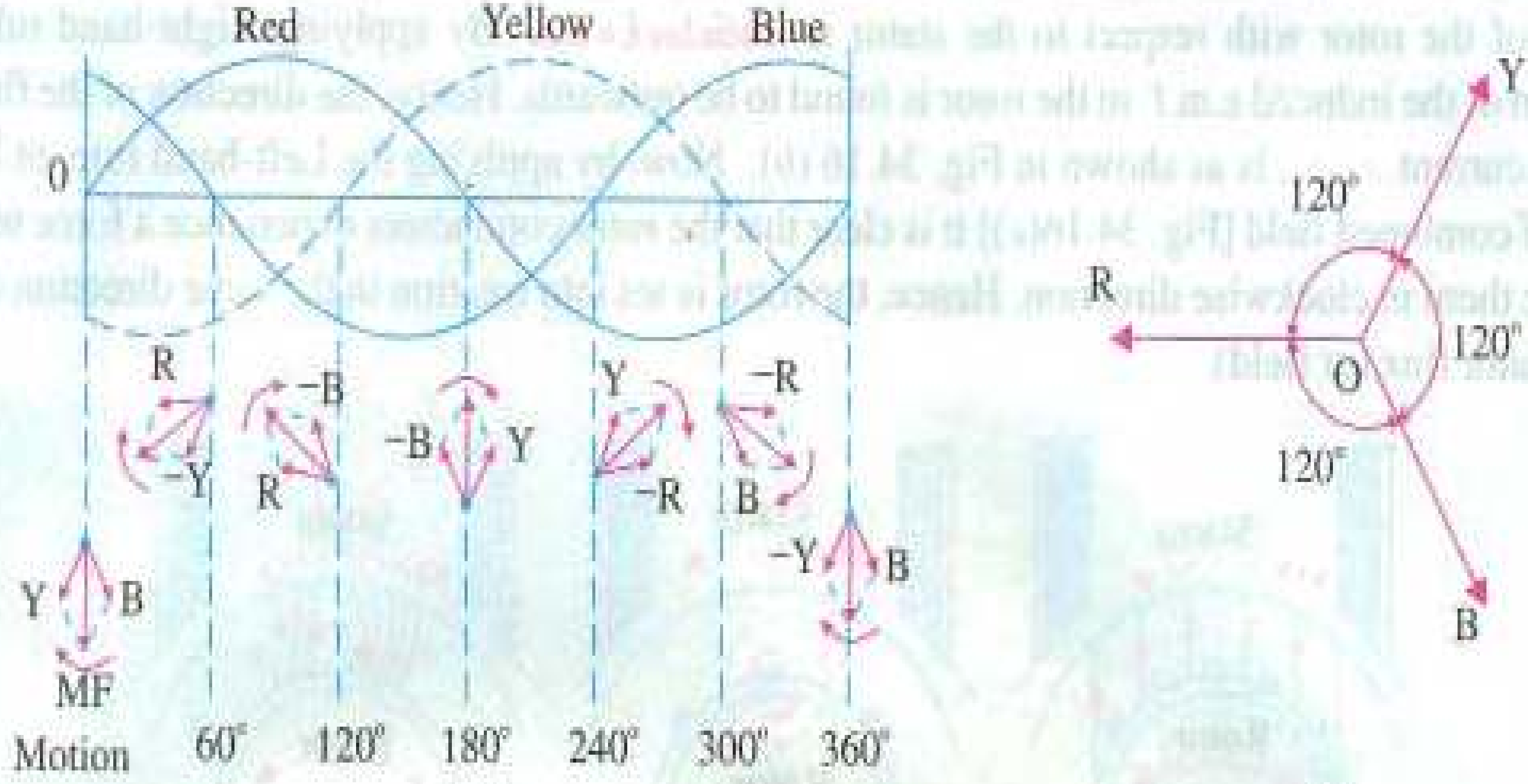
$$\varphi_T = 1.5\,\varphi_m$$





Rotating Magnetic Field

Vector sum of Rotating Magnetic Field



Red
Yellow
Blue
0
R
−Y
−B
R
−B
Y
Y
−R
−R
B
−Y
B
Y
B
MF
Motion
60°
120°
180°
240°
300°
360°
Y
120°
R
120°
O
120°
B

(*a*) (*b*)

Speed and Slip

- IM can't run at synchronous Speed.
- Let consider for a moment that is rotor is rotating at synchronous speed.
- Under this condition there would be no cutting of flux by the rotor conductor and there would be no generated voltage no current and no torque.
- So, rotor speed is slightly less than synchronous speed.
- The difference between the synchronous speed and actual speed is called slip speed.

Ns = Synchronous Speed in r.p.m.
Nr = Actual Rotor speed in r.p.m.

Slip Speed = (Ns-Nr) r.p.m.

- Per-unit slip is usually called the Slip,

$$\text{Slip (S)} = \frac{\mathrm{N_S} - N_r}{N_S} \text{ per unit (p.u)}$$

$$\text{Percentage Slip} = \frac{\mathrm{N_S} - N_r}{N_S} \times 100$$

Frequency of Rotor Voltage and Current

- Frequency of current and voltage in the stator must be same as the supply frequency.

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

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

- Rotor frequency is given by,

$$f_r = \frac{P \times (N_s - N_r)}{120}$$

Now,

$$\frac{f_r}{f} = \frac{N_s - N_r}{N_s}$$

$$\frac{f_r}{f} = S$$

$$f_r = S \times f$$

Case:1 Rotor is Stationary

(Nr=0)

$$S = \frac{N_s - N_r}{N_s} = 1$$

$$f_r = f$$

Case:2 Rotor is rotate at synch. Speed

(Nr=Ns)

$$S = \frac{N_s - N_r}{N_s} = 0$$

$$f_r = 0$$

Rotor Current

➢ Stand Still Condition:

E20=e.m.f. induced per phase of the rotor at stand still
R2 = Rotor resistance per phase
X20 = Reactance per phase of the rotor at stand still = $2\Pi f_1 L_2$
Z20 = Rotor Impedance per phase at stand still
I20 = Rotor Current per phase at stand still

$$Z_{2o} = R_2 + jX_{20}$$

$$I_{20} = \frac{E_{20}}{Z_{20}}$$

Power Factor at Stand Still

$$Cos\phi_{20} = \frac{R_2}{Z_{20}} = \frac{R_{20}}{\sqrt{R_2^2 + X_{20}^2}}$$

➢ Rotor Current at Slip(S):

- Induced e.m.f. per phase in the rotor winding at slip(s) is,

$$E_{2s} = SE_{20}$$

- Rotor winding resistance per phase =R2
- Rotor winding reactance per phase at Slip(S),

$$X_{2s} = 2\pi f_2 L = 2\pi(Sf_1)L = SX_{20}$$

- Rotor winding reactance per phase at slip(S)

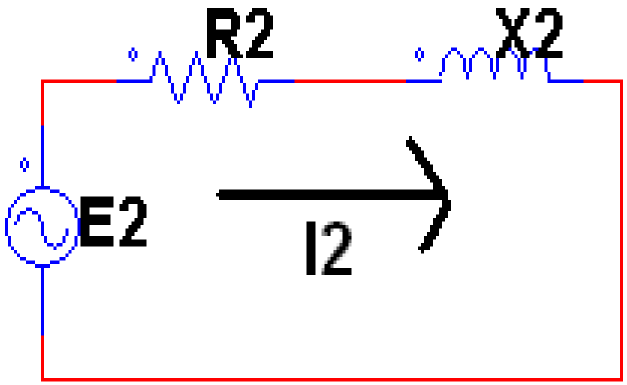
$$Z_{2s} = R_2 + jX_{2s} = R_2 + jSX_{20}$$

- Rotor Current at Slip(S) is

$$I_{2s} = \frac{E_{2s}}{Z_{2s}}$$

- Power Factor at Slip(S) is

$$Cos\phi_{2s} = \frac{R_2}{Z_{2s}}$$



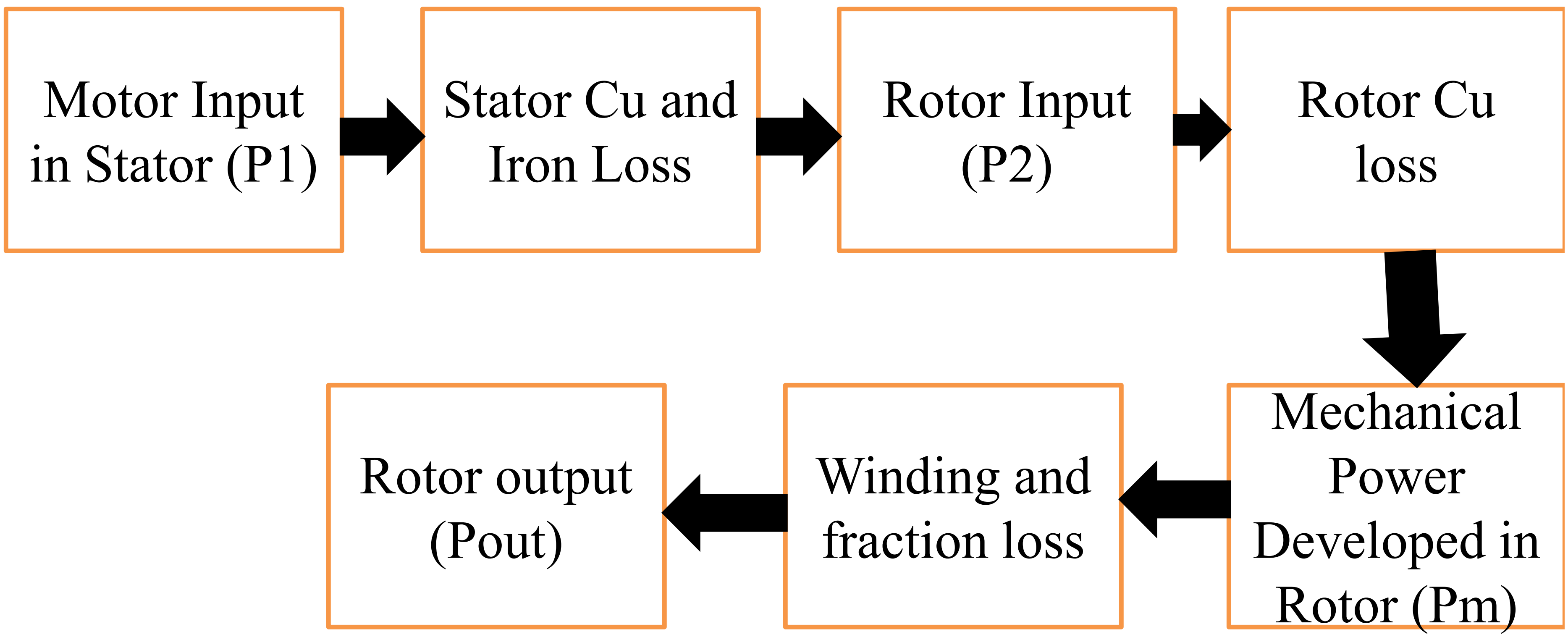
$$I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$$

$$I_{2r} = \frac{E_{2r}}{Z_{2r}} = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

$$Cos\phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

$$Cos\phi_2 = \frac{R_2}{Z_{2r}} = \frac{R_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

POWER STAGE DIAGRAM OF AN IM



Total Rotor Cu-loss = $3I_2^2R_2$

TORQUE EQUATION

- Torque developed in IM on following factor:

1. The Part of rotating magnetic field which reacts with rotor and is responsible to produce induced e.m.f. in rotor.
2. The magnitude of rotor current in running condition
3. The power factor of rotor circuit in running condition

$$T \; \alpha \; \varphi \times I_{2r} \times \cos \varphi_{2r}$$

Ø = flux responsible to produce induced e.m.f
I2r = Rotor running Current
CosØ2r = Running power factor of rotor

- The flux(Ø) produced by stator is proportional to E1 i.e. Stator Voltage

$$\varphi \; \alpha \; E_1$$

- Ratio of stator turns to rotor turns i.e. k

$$\frac{E_2}{E_1} = k$$

$$E_2 \; \alpha \; \phi$$

While,

$$I_{2r} = \frac{E_{2r}}{Z_{2r}} = \frac{SE_{2r}}{\sqrt{R_2^2 + (SX_2)^2}}$$

$$\text{Cos}\,\phi_{2r} = \frac{R_2}{Z_{2r}} = \frac{R_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

Now put all value of I_{2r}, Cos$Ø_{2r}$ and Ø in Torque equation,

$$T \;\alpha\; E_2 \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}} \frac{R_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

$$T \;\alpha\; \frac{SE_2^2 R_2}{R_2^2 + (SX_2)^2} N - m$$

$$T = \frac{kSE_2^2 R_2}{R_2^2 + (SX_2)^2} N - m$$

For 3-phase IM

$$k = \frac{3}{2\pi N_s}$$

Ns = Synchronous Speed in r.p.s.=Ns/60

$$T = \frac{3}{2\pi N_s} \frac{SE_2^2 R_2}{R_2^2 + (SX_2)^2} N-m$$

- Starting Torque:

At N=0 ; S=1

$$T_{st} = \frac{3}{2\pi N_s} \frac{E_2^2 R_2}{(R_2^2 + X_2^2)} N-m$$

- Changing R2, starting Torque can be controlled.
- Changing R2 at start is possible in case of slip ring IM only.

Condition For Maximum Torque

- Torque depend on slip at which motor is running
- Supply voltage to the motor is usually rated and constant also fixed ratio between E1 and E2.
- So, E2 is constant
- Similarly R2 , X2 and Ns are Constant for IM.
- For Maximum Torque➔ Torque is only control by Slip(S).

$$\frac{dT}{dS} = 0$$

Now,

$$T = \frac{kSE_2^2 R_2}{R_2^2 + (SX_2)^2}$$

Here R2 , X2 and K are Constant

Now,

$$\frac{dT}{dS} = 0$$

$$S^2 X_2^2 - R_2^2 = 0$$

$$S^2 = \frac{R_2^2}{X_2^2}$$

$$S = \frac{R_2}{X_2} \text{ Neglecting (-ve) slip}$$

- This is the slip at which torque is maximum and is denoted as (Sm)

$$S_m = \frac{R_2}{X_2}$$

Magnitude of Max. Torque

$$S_m = \frac{R_2}{X_2}$$

- Now put value in torque equation.

$$T_m = \frac{kS_m E_2^2 R_2}{R_2^2 + (S_m X_2)^2}$$

$$= \frac{k\left(\frac{R_2}{X_2}\right) E_2^2 R_2}{R_2^2 + \left(\frac{R_2^2}{X_2} X_2\right)^2}$$

$$T_m = \frac{kE_2^2}{2X_2} \text{ N - m}$$

- Max. Torque is inversely proportional to the rotor reactance.
- It is directly proportional to the square of the rotor induced e.m.f. at stand still.
- It is not depend on the rotor resistance R2.

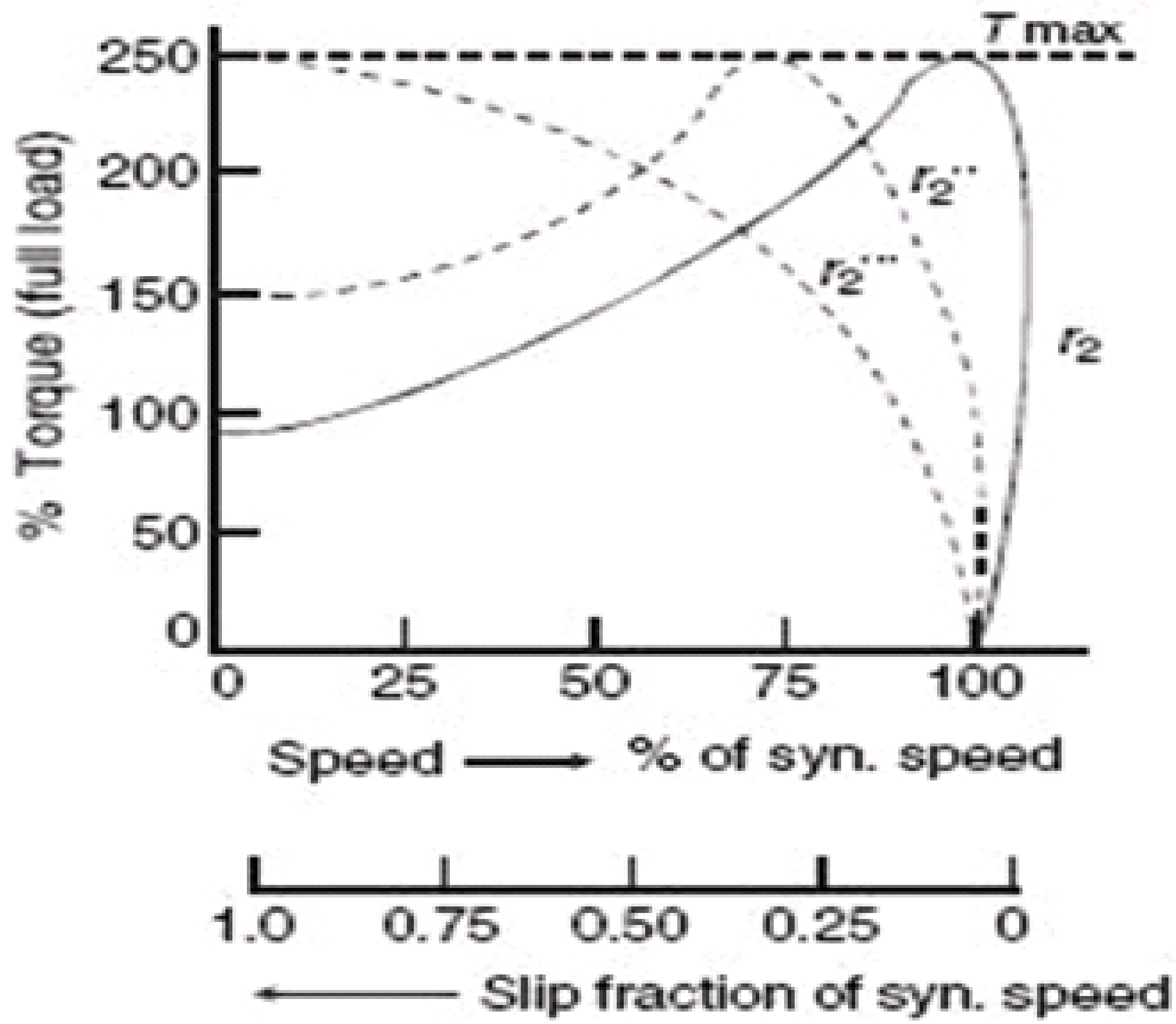
Torque-Slip and Torque-Speed characteristics.

We know that,

$$T = \frac{kSE_2^2 R_2}{R_2^2 + (SX_2)^2}$$

- R2 and X2 are Constant. So, Torque depend upon Slip(S)

1. Low-Slip Region
2. Medium-Slip Region
3. High-Slip Region



T max
250
200
150
100
50
0
% Torque (full load)
r2''
r2'''
r2
0
25
50
75
100
Speed ⟶ % of syn. speed
1.0
0.75
0.50
0.25
0
⟵ Slip fraction of syn. speed

Losses in Induction Motor

1. Constant Losses

   - Core Losses
   - Mechanical Losses

2. Variable Losses

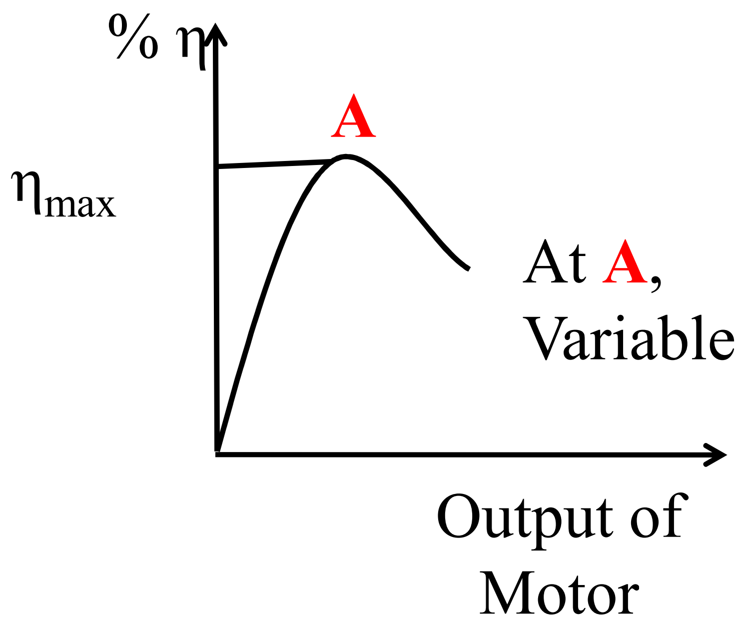
   - Copper Losses in Stator
   - Copper Losses in Rotor

Total Rotor Cu-loss = $3I_2^2R_2$

Efficiency of an Induction Motor

➢ The Ratio of net power available at the shaft (Pout) and the net electrical power input (Pin) to the motor is called as overall efficiency of an induction motor

$$\% \eta = \frac{P_{out}}{P_{in}} \times 100$$



At **A**,

Variable loss = Constant loss

Working principle:-

- **The single-phase induction motor operation can be described by two methods:**

1)Double revolving field theory 2)Cross-field theory.

- **Double revolving theory is perhaps the easier of the two explanations to understand**

●Double revolving field theory:-

- **A single-phase ac current supplies the main winding that produces a pulsating magnetic field.**
- **Mathematically, the pulsating field could be divided into two fields, which are rotating in opposite directions.**
- **The interaction between the fields and the current induced in the rotor bars generates opposing torque .**

Double revolving field theory:-

- **The interaction between the fields and the current induced in the rotor bars generates opposing torque.**
- **Under these conditions, with only the main field energized the motor will not start.**
- **However, if an external torque moves the motor in any direction, the motor will begin to rotate.**

●Double revolving field theory:-

- **The pulsating filed is divided a forward and reverse rotating field**
- **Motor is started in the direction of forward rotating field this generates small (5%) positive slip**

$Sr = Ns - Nr/Ns$

- **Reverse rotating field generates a larger (1.95%) negative slip**

$Sb = Ns + Nr/Ns$

- **Construction of single phase induction motor:-**

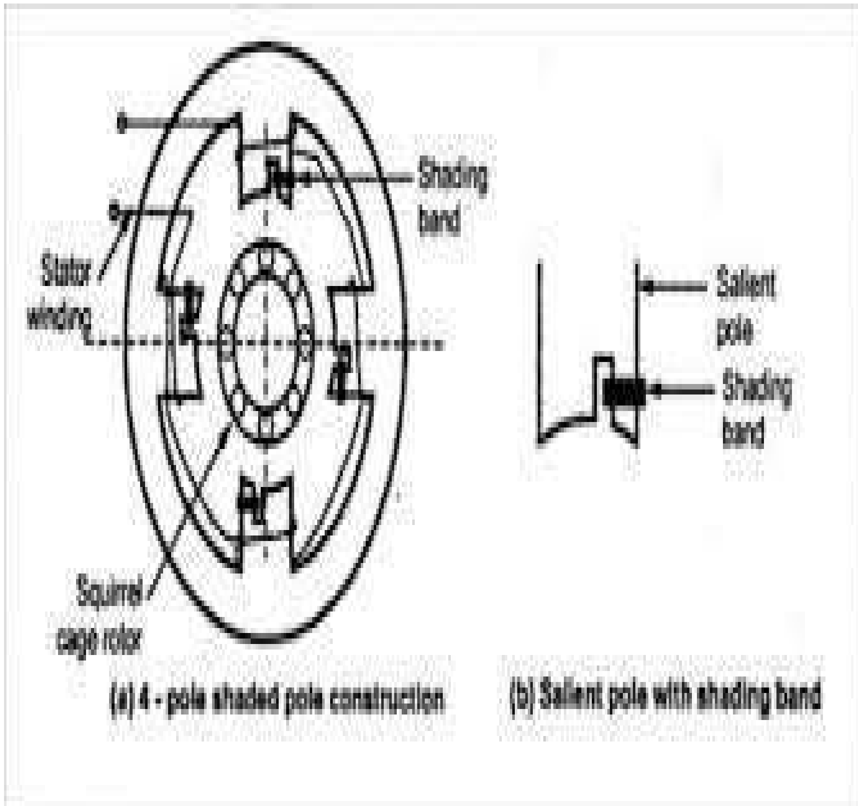
Construction of a **single phase IM** is similar to 3-

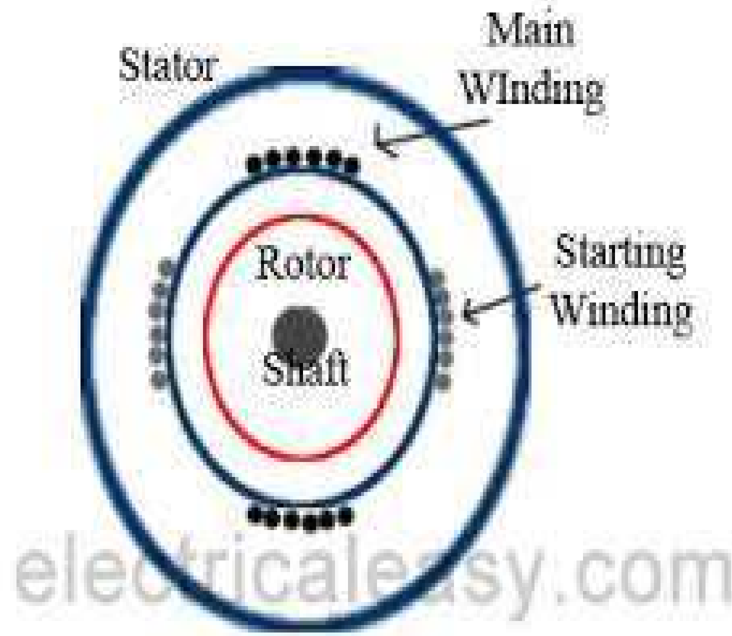
phase squirrel cage induction motor. The **rotor** used here is same as that used in 3 phase squirrel cage Induction motor and it is very simple in design, robust in construction. The rotor is not insulated from the core. The slots on rotor are either semi-closed type or totally closed type. Rotor windings are perfectly symmetrical

- **Construction of single phase induction motor:-**

Single phase motor can be wound for any even number of poles i.e two, four, six, etc. This type of motor normally have two **Stator** windings. In motors that operate with both windings energized ,the winding with more wire (more turns) is known as main winding and the other is called auxiliary winding. In case of this motor synchronous speed equation is (N

- **Construction of single phase induction motor:-**





- **Types of single phase induction motor:-**

According to the method used for it's starting single phase I.M. can be classified into following types:-

1)Split phase motor/ Resistance start motor
2)Capacitor start motor
3)Capacitor start-Capacitor run motor
4)Two value capacitor motor
5)Shaded pole motor

- **Split phase motor:-**

A split phase induction motor consist of two main parts:-

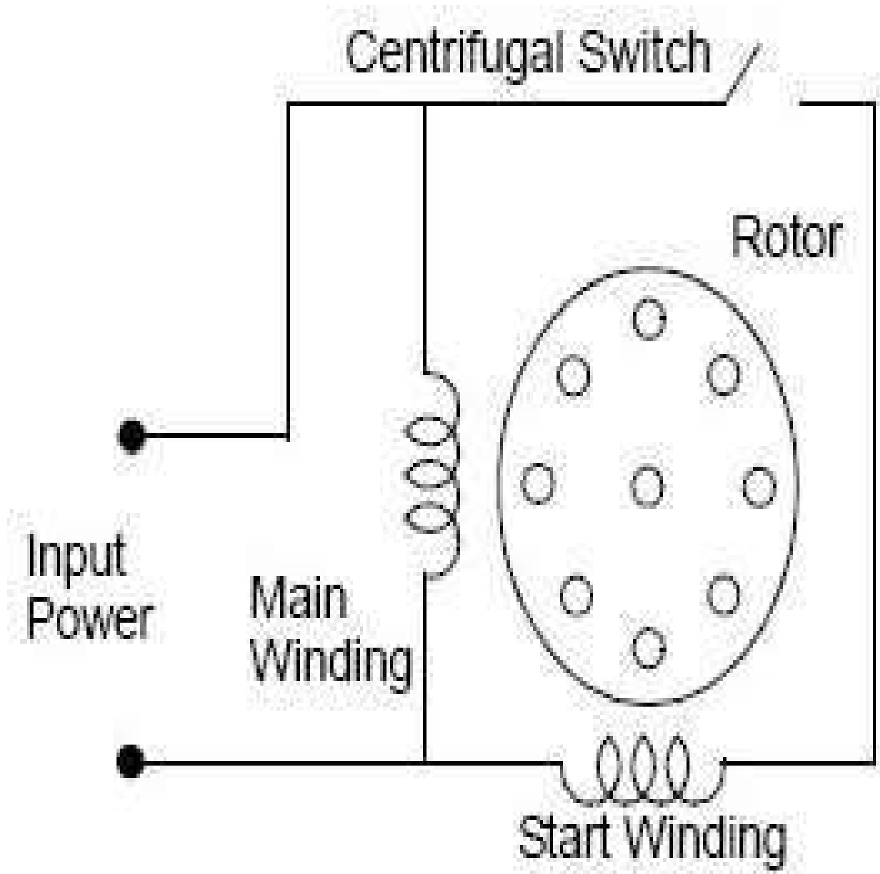
1) Stator 2) Rotor

The stator is provided with single phase windings

a)Main winding b)Auxiliary winding

The two winding are placed 90 degree electrical apart & are connected in parallel across the single phase AC supply. Whereas the auxiliary winding has a high resistance & low reactance.

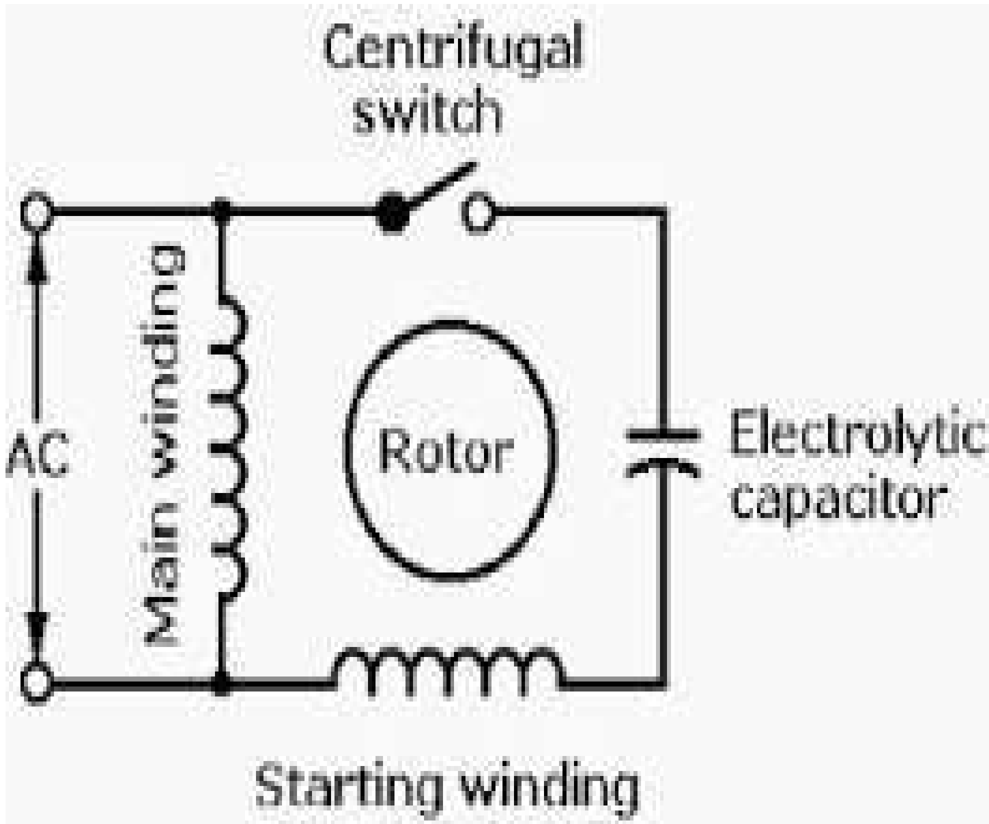
- **Split phase motor:-**



- **Capacitor Start Motor:-**
- **In these motors, a capacitor is connected in series with the starting winding , which takes leading current & hence produce high starting torque.**
- **The capacitor motor can be classified as :-**

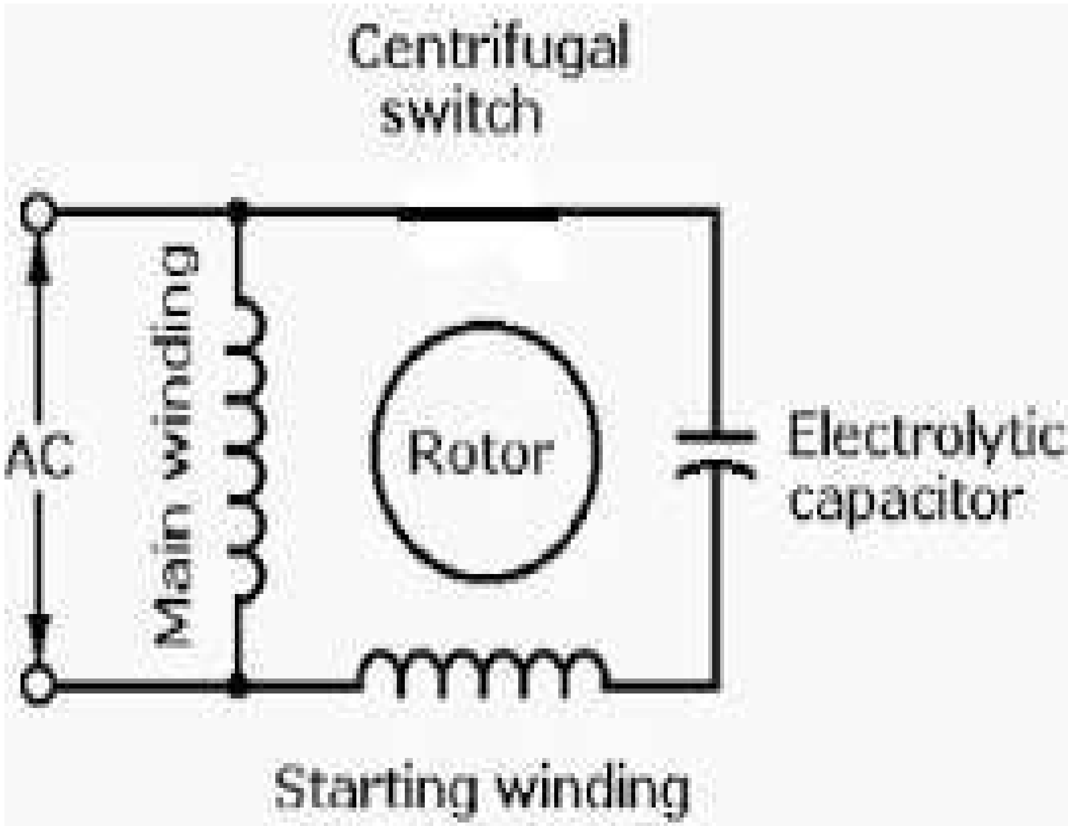
1. **capacitor start**
2. **capacitor start & capacitor run**
3. **Two value capacitor motor**

- **Capacitor start motor:-**
- **In this motor the capacitor is connected in series with the starting winding which takes leading current.**
- **As the capacitor is used only at start , it is rated for intermittent duty & the cost of which decreases.**
- **A relatively small ac electrolytic type capacitor is used.**
- **This motor has high starting torque, about 1.5 times the full-load torque.**


Centrifugal switch
AC
Main winding
Rotor
Electrolytic capacitor
Starting winding

- **Capacitor start & Capacitor run motor:-**

- **In this motor there is no centrifugal switch, so the capacitor remains in the circuit & helps to improve the power factor under running condition.**
- **The power factor of this motor under running condition is high.**
- **The operation is also quiet & smooth.**
- **The torque under running condition is also higher than the capacitor start &**


Centrifugal switch
AC
Main winding
Rotor
Electrolytic capacitor
Starting winding

- **Two value capacitor type motor:-**

This types of motor employs two capacitor 1)Start capacitor(Cs)

2)Run Capacitor(Cr)

The Start capacitor is rated for short rating & is used for starting.

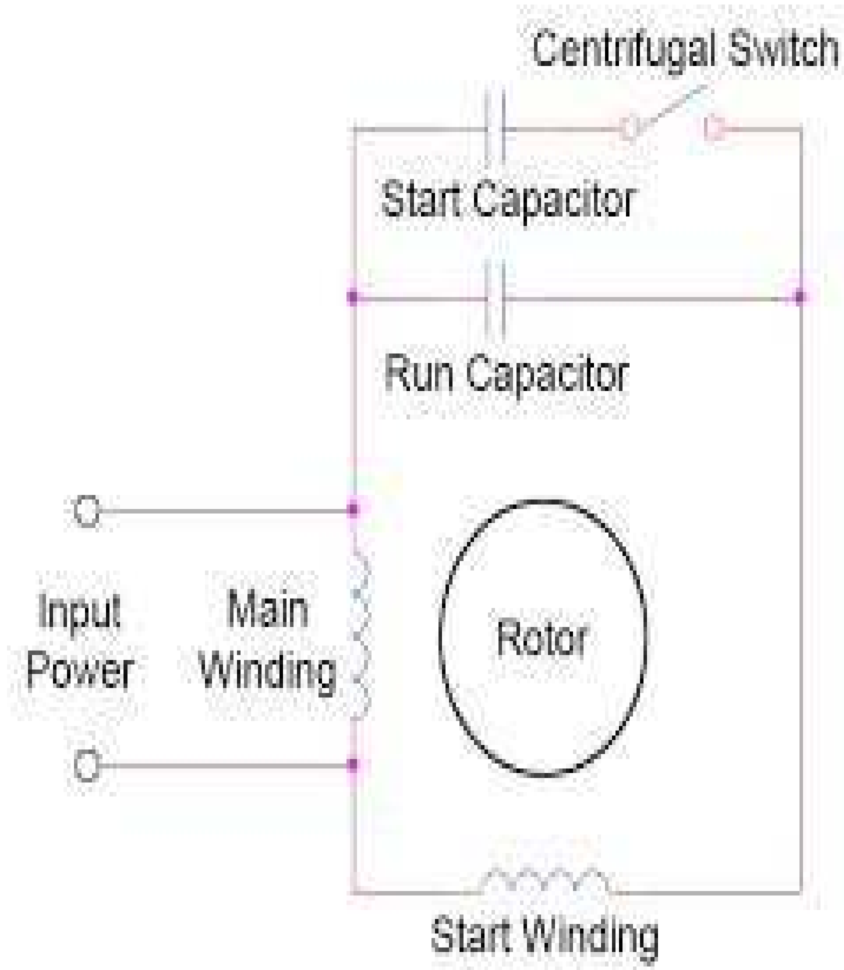
The Run capacitor is rated for continuous duty as it is used under

- **Two value capacitor type motor:-**

A centrifugal switch is used to disconnect the start capacitor when the motor has reached about 70 to 80% of its full load speed.

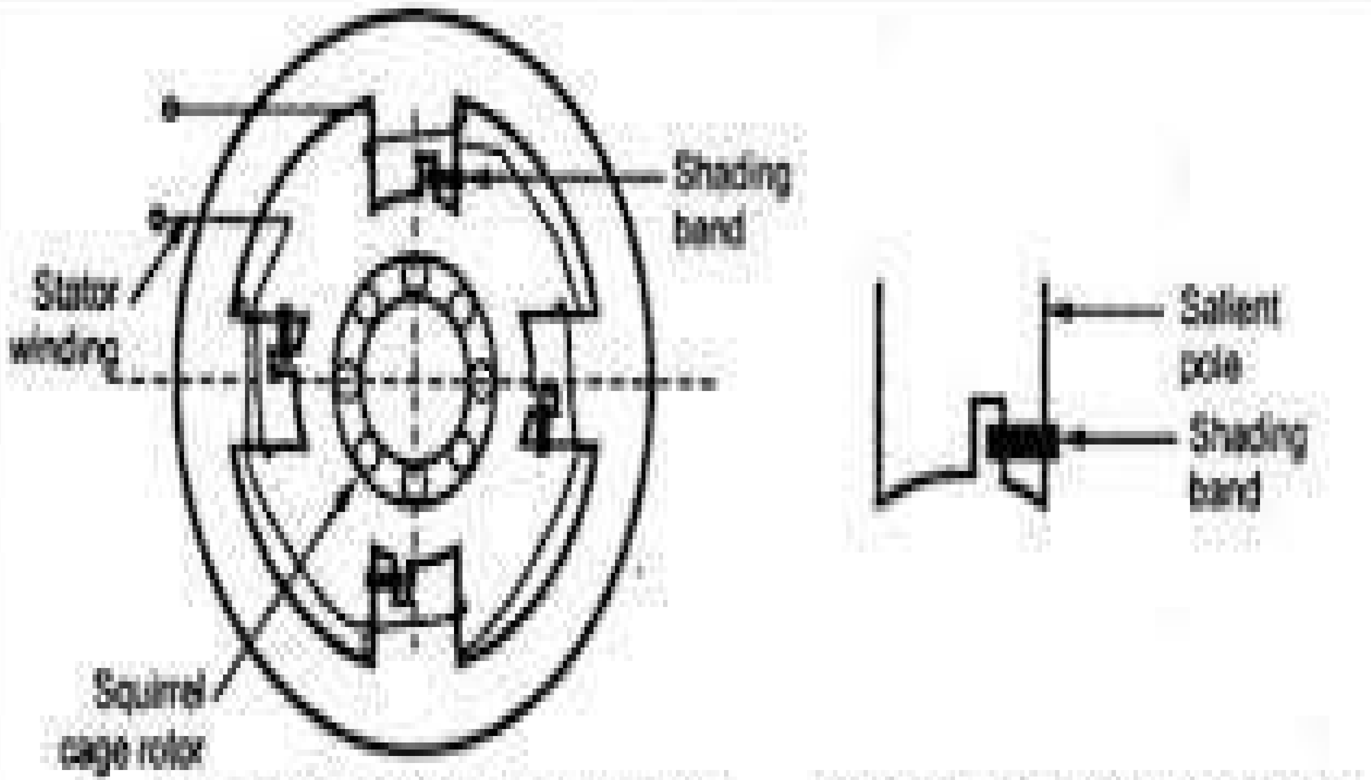
This motor is useful where the motor has start against heavy loads.

The starting torque is about 2 to 2.5 times its full load torque.



Centrifugal Switch
Start Capacitor
Run Capacitor
Input
Power
Main
Winding
Rotor
Start Winding

- **Shaded pole motor:-**
- **A shaded pole motor has a stator consisting of salient poles & a squirrel cage rotor.**
- **The main winding is wound on the entire pole section.**
- **When the ac supply is given to the stator winding of shaded pole motor , due to shading provided on the salient poles, a rotating magnetic field is produced.**



(a) 4 - pole shaded pole construction

(b) Salient pole with shading band


Thank you ...