

# Three Phase Induction Motor

*Unit 4*

# Introduction

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- \* A poly phase induction motor consists of two major parts, the stator and rotor
- \* When stator is excited with a.c voltage, rotating field is set up
- \* This field produces an EMF in the rotor winding by mutual induction principle, which in turn circulates current when the rotor is short circuited
- \* This current interacts with the field produced by the stator winding, thereby producing torque which is responsible for the rotation of rotor.

# Construction

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## **Stator :**

- ★ Consists of core and winding .
- ★ It is of cylindrical in structure , made of laminated sheet metal, build up of laminations.
- ★ Laminations are of thickness 0.35mm to 0.5mm
- ★ Stator core internal diameter and length are the main dimensions of induction motor

## **Rotor:**

- ★ Types: Squirrel Cage and Wound Rotor
- ★ Squirrel cage rotors, consists of uninsulated bars of aluminium or copper that are joined together at both ends by rings of similar conducting material
- ★ Rotor core is made up of laminated sheet of steel with thickness of 0.5 mm

# Construction

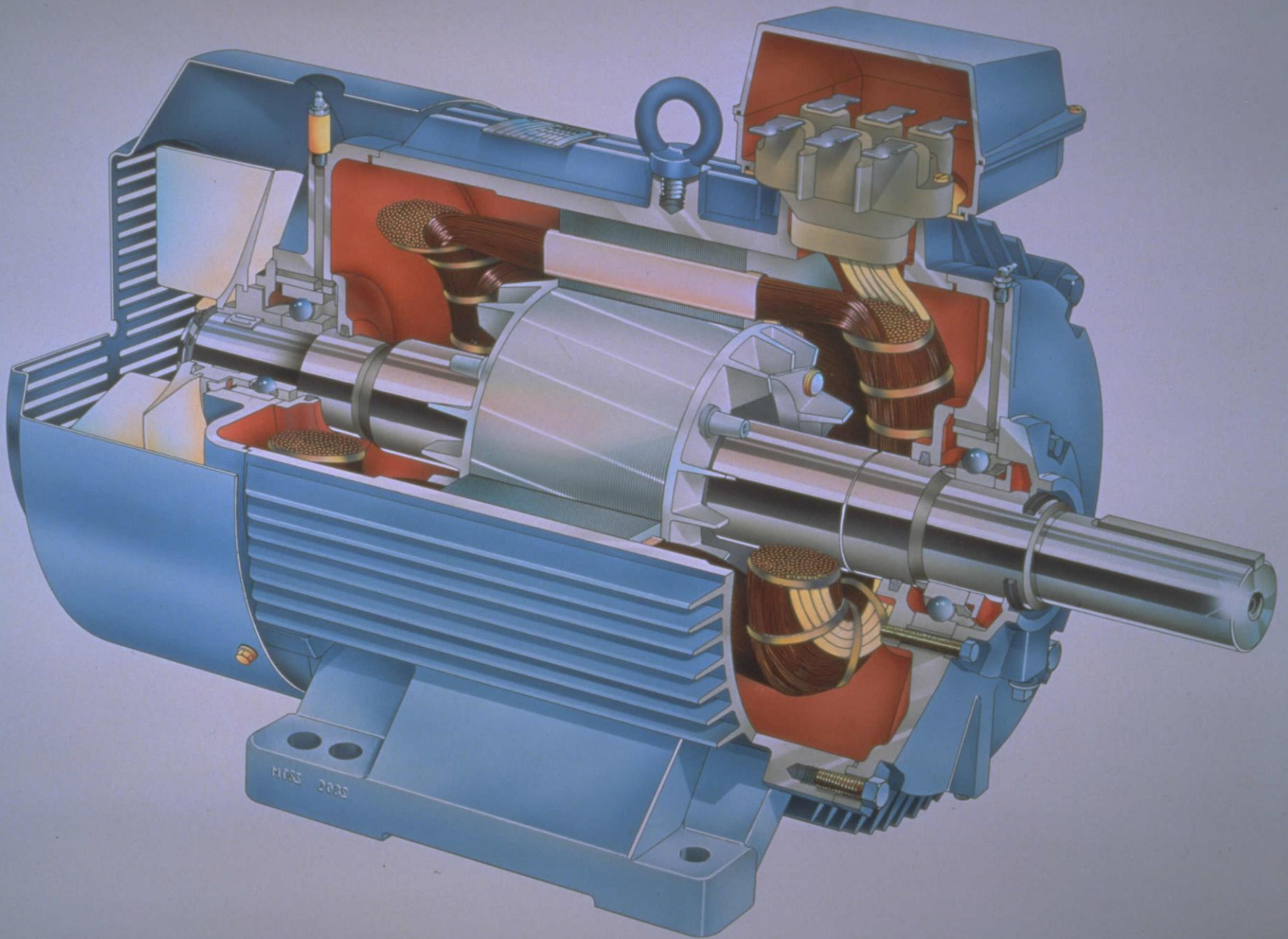
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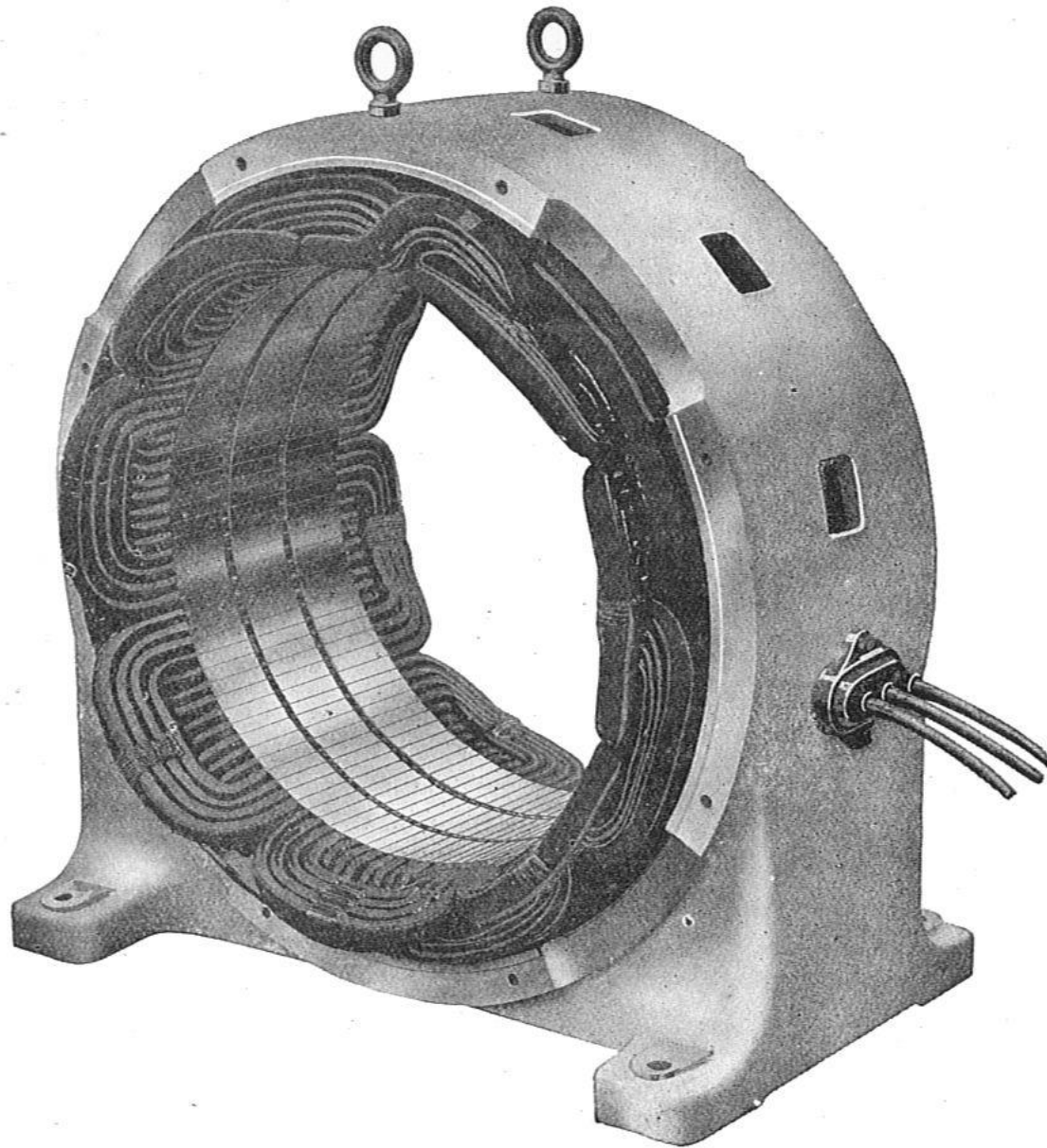
- ★ Aluminium bars and endrings are cased directly over the rotor core
- ★ When copper bars are employed , rotor bar are inserted on the slots from the end of the rotor and end rings are joined to them by bracing
- ★ Wound rotor – consists of core, winding, sliprings and brushes.
- ★ Rotor core is made of laminations and it carries a three phase winding
- ★ One end of each phase are connected to form a star point
- ★ Other end of each phase are connected to three slip rings

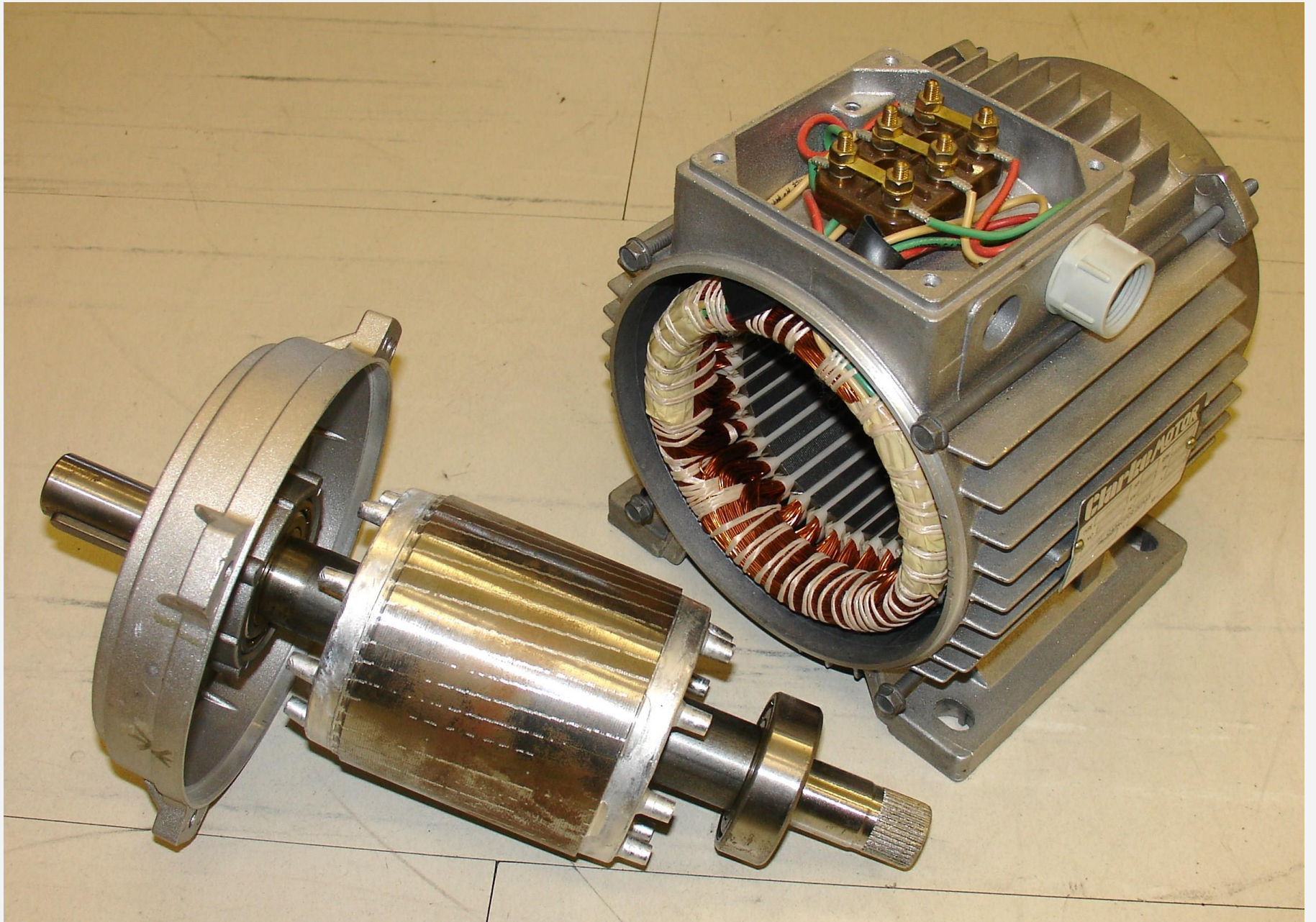
# Construction

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- \* Slip rings are mounted on the rotor shaft and they are insulated from the rotor and from each other
- \* Carbon brushes are mounted over the slip rings , facilitate the connection from rotor winding to the external resistances

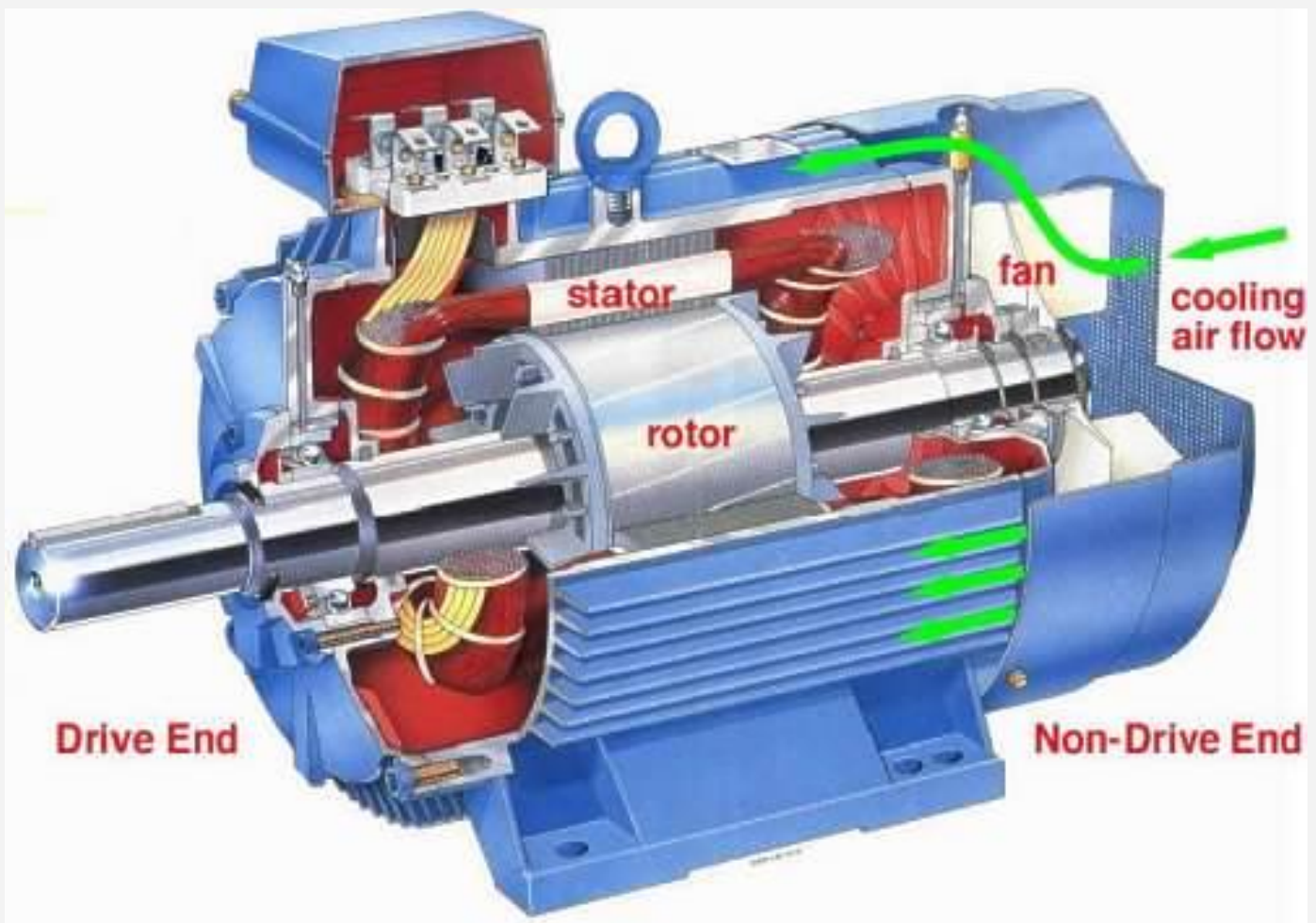




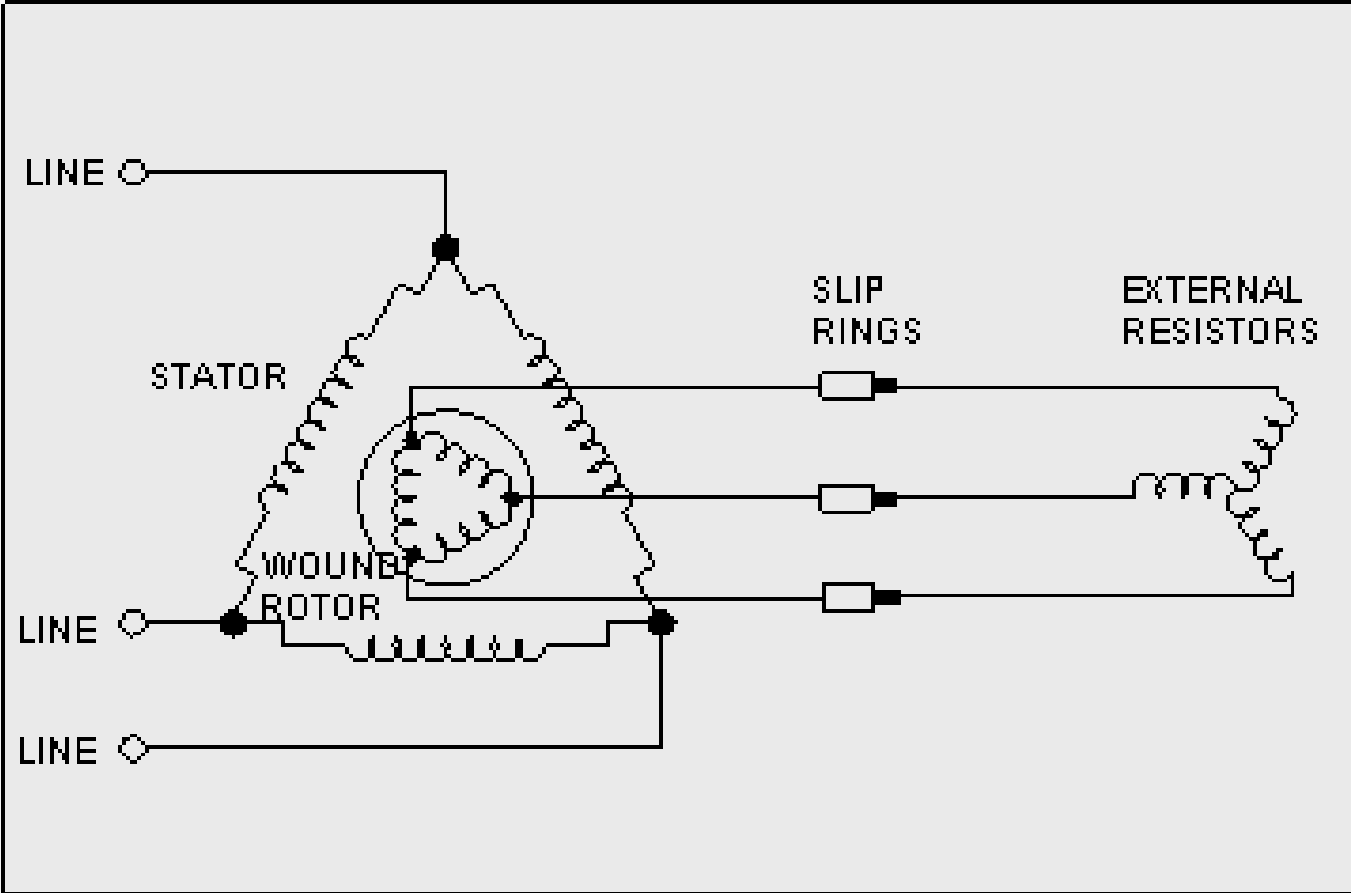


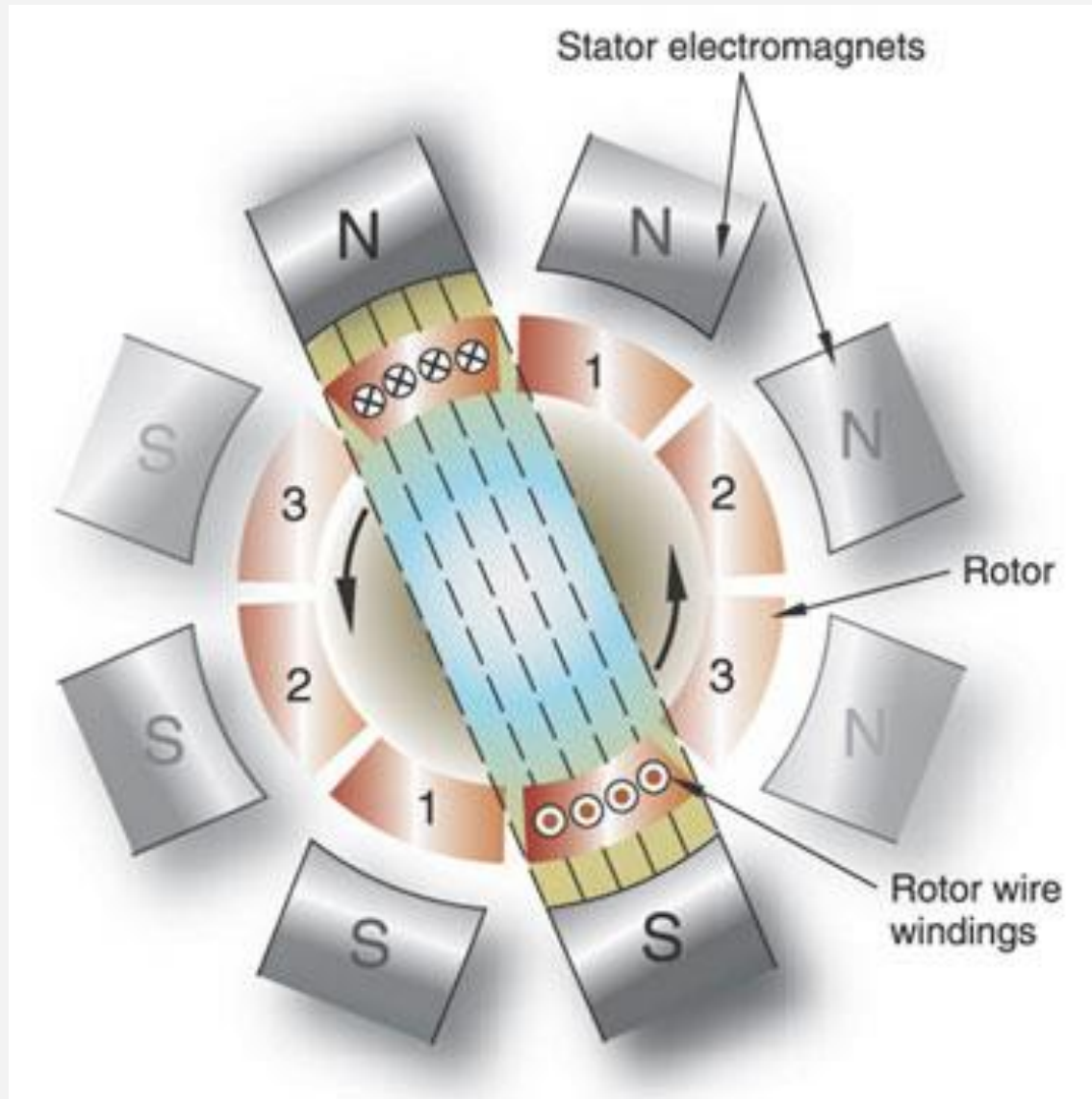


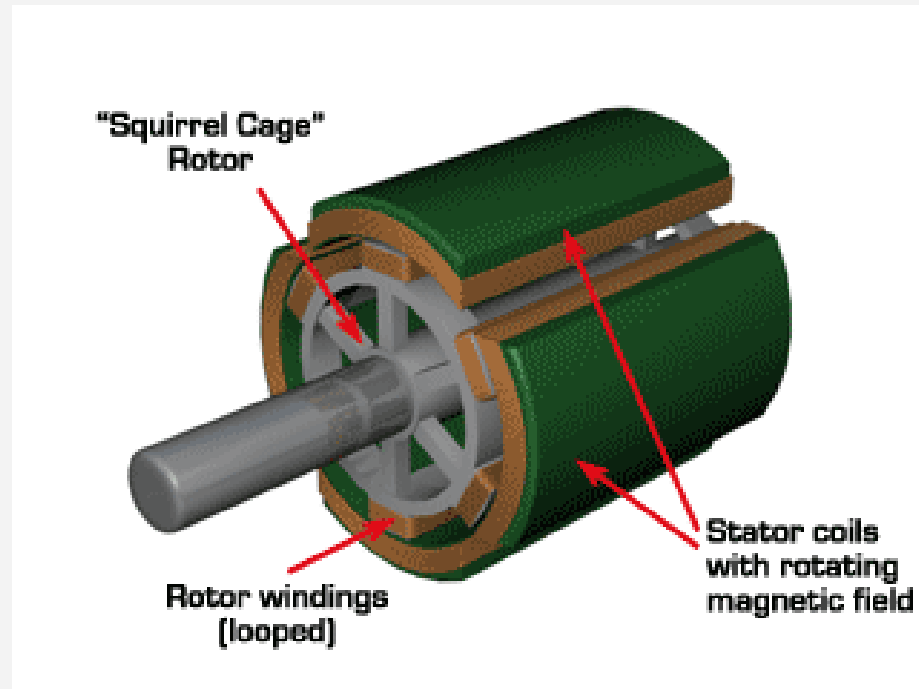












# Advantages of Squirrel Cage Rotor over Wound Rotors

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- i. No slip rings, brushes, short circuiting devices are required
- ii. Higher efficiency
- iii. Cheaper and rugged in construction
- iv. Has better space factor, shorter over hang, smaller copper loss
- v. Has bare end rings, larger space for fans, thus cooling is better
- vi. Better power factor, pull out torque and overload capacity

# OUTPUT EQUATION

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Output equation for A.C machines is,

$$\text{Input kVA, } Q = C_o \cdot D^2 L n$$

$$\text{where, } C_o = 1.1 K_w \cdot B_{av} \cdot ac \times 10^{-3}$$

$$Q = \frac{\text{kW}}{\eta \cdot \cos\phi}$$

The rating of induction motor is given in Horse Power

$$\therefore Q = \frac{\text{HP} \times 0.746}{\eta \cdot \cos\phi}$$



## CHOICE OF SPECIFIC MAGNETIC LOADING

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- i. **Power Factor:** with higher values of  $B_{av}$  in the gap , results in large magnetizing current , giving low power factor. However in I.M  $B_g$  should be such that there is no saturation in any part of the magnetic circuit
- ii. **Iron loss:** an increased in  $B_{av}$  result in increased in iron loss an decreased in efficiency
- iii. **Over load capacity :** with increase in  $B_{av}$ , flux per pole is large. Turns per phase and no of tursn becomes less. Reduction in leakage reactance. Thereby gives maximum output for same voltage. So machines has larger over load capacity

# CHOICE OF SPECIFIC ELECTRIC LOADING

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- i. **Copper loss and temp rise:** large value of  $a_c$  , needs greater amount of copper , results in higher copper losses and large temperature rise
- ii. **Voltage:** for high voltage machines , less value of  $a_c$  should be chosen, because it needs large space for insulation .
- iii. **Overload capacity:** larger value of  $a_c$  , results in large number of turns per phase. Which in turn increase the leakage reactance of the machine, reduces the overload capacity of the machine.

## SPECIFIC MAGNETIC & ELECTRIC LOADING:

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### ▶ $B_{av}$ Specific magnetic loading:

- ▶ Depends on power factor, iron loss and overload capacity. For 50Hz machine,  $B_{av} = 0.3$  to  $0.6T$ .
- ▶ For machines used in cranes, rolling mills etc., need large overload capacity  $B_{av} = 0.65T$

### ▶ ac :Specific electric loading:

- ▶ Depends on copper loss, temp rise, voltage rating and overload capacity.
- ▶ Varies between 5000 to 45000 ac/m.

# MAIN DIMENSIONS

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- \* Separation of D and L depends on the ratio of  $L/\tau$  ( length of core to pole pitch)
  - \*  $L/\tau = 1.5$  to 2 for minimum cost
  - \*  $L/\tau = 1.0$  to 1.25 for good power factor
  - \*  $L/\tau = 1.5$  for good efficiency
  - \*  $L/\tau = 1$  for over all design
- \* Generally  $L/\tau = 0.6$  to 2;  $\tau = \sqrt{0.18L}$
- \* Diameter of the stator bore and hence diameter of rotor is also limited by  $V_a$ .
- \*  $V_a$  up to 60m/s can be employed
- \* Stator - provided ventilating ducts ( $L \geq 125\text{mm}$ ) of 10mm width

# STATOR WINDING

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- ✦ In general double layer lap type winding with diamond shaped coils is generally used for stators
- ✦ Small motors with a small no of slots and having large no of turns per phase may use single layer mush windings
- ✦ Three phase of the winding may be connected in either star or delta depending upon starting methods employed.
- ✦ Squirrel cage induction motors - star delta starters

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### **Stator turns per phase:**

- \* Flux /pole  $\Phi_m = B_{av} \tau L = B_{av} \pi DL/P$
- \* Stator voltage / phase =  $E_s = 4.44 K_{ws} \cdot f \cdot \Phi_m \cdot T_s$
- \* Therefore stator turns / phase  
 $T_s = E_s / (4.44 K_{ws} \cdot f \cdot \Phi_m)$

### **Stator conductors:**

- \* X-sectional area of stator conductors can be estimated from the knowledge of current density, kVA rating and stator phase voltage.

$$\delta_s - 3 \text{ to } 5 \text{ A/mm}^2 : I_s = Q / (3E_s \times 10^{-3})$$

$$a_s = I_s / \delta_s \text{ and } d_s = \sqrt{4 a_s / \pi}$$

- \* Round conductors are used for smaller diameter.
- \* If diameter is more than 2mm, use bar and strip conductors for better space factor for slots

# STATOR CORE

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- ✦ Made of laminations of thickness of 0.5mm
- ✦ Design of stator core involves shape of slots, no. of slots, dimensions of teeth and depth of slot

## Shape of slot :

- ✦ Open and Semi-closed slots may be used
- ✦ When *open slots* are used, winding coils can be formed and insulated completely before they are inserted in the slots. Easy for repair. Avoids excessive slot leakage
- ✦ *Semi-closed slots* are usually preferred of I.M because  $K_g$  will be less, results in less magnetizing current, also results in low tooth pulsation loss and less noise operation
- ✦ *Tapered coils* are used in semi closed slots

# STATOR CORE

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- ✦ In small motors round conductors are used
- ✦ In large and medium size motors strip conductors are preferred
- ✦ In both case tapered slot with parallel sided tooth arrangement is preferred, because it gives maximum slot area for particular flux density.

## **Number of slots :**

- ✦ Depends on tooth pulsation loss, leakage reactance , ventilation, magnetizing current , iron loss and cost.
- ✦ In general no. of slots should be chosen as an integral
- ✦ For open type slots, slot pitch at the gap – 15 to 25mm
- ✦ For semi closed slots, the slot pitch may be less than 15mm



# STATOR CORE

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$$Y_{ss} = \text{Gap surface} / \text{Total no of slots} = \pi D / S_s$$

$$\text{Then } S_s = \pi D / Y_{ss}$$

$$\left\{ \begin{array}{l} \text{Total no. of} \\ \text{stator conductors} \end{array} \right\} = \text{No. of phases} \times \left\{ \begin{array}{l} \text{Conductors} \\ \text{per phase} \end{array} \right\}$$

$$\left\{ \begin{array}{l} \text{Total no. of} \\ \text{stator conductors} \end{array} \right\} = 3 \times 2T_s = 6T_s$$

$$\left\{ \begin{array}{l} \text{Conductors} \\ \text{per Slot} \end{array} \right\} Z_{ss} = \frac{\text{Total Stator Conductors}}{\text{No. of stator slots}}$$

$$\left\{ \begin{array}{l} \text{Conductors} \\ \text{per Slot} \end{array} \right\} Z_{ss} = \frac{6T_s}{S_s}$$

$Z_{ss}$  – Even for double layer winding

# STATOR CORE

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## Area of stator slots :

- ★ Once no. of conductors per slot has been obtained, approximate area of the slot can be calculated
- ★ Area of the slot = (Copper area/slot)/Space factor  
=  $Z_{ss} \times a_g$  / Space factor
- ★ Space factor - 0.25 to 0.4
- ★ High voltage machines have lower space factors owing to large thickness of insulation.
- ★ After obtaining the area of the slot, the dimensions of the slot should be adjusted
- ★ Tooth width and the slot width at gap surface should be approx equal

# STATOR CORE

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- ✦ The width of the slot should be so adjusted such that  $B_t = 1.3$  to  $1.7$  T.
- ✦ In general ratio of slot depth / slot pitch- 3 to 6

## Length of mean turn

- ✦  $L_{mts} = 2L + 2.3\tau + 0.24$

## Stator teeth:

- ✦ The dimensions of the slot determines the value of  $B_t$ .
- ✦ High value of  $B_t$  is not desirable, as it leads to a higher iron loss and greater magnetizing MMF.
- ✦  $B_t$  should not exceed  $1.7$  T.

# STATOR CORE

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$$\text{Minimum tooth area/pole} = \frac{\Phi_m}{1.7}$$

$$\text{Total area/pole} = \left[ \begin{array}{c} \text{No. of slots} \\ \text{per pole} \end{array} \right] \times \text{Net iron length} \times \text{Width of tooth}$$

$$\text{Total area/pole} = \frac{S_s}{P} L_i \cdot W_{ts}$$

$$(W_{ts})_{\min} = \frac{\Phi_m}{1.7 \cdot \frac{S_s}{P} \cdot L_i}$$

- ★ The minimum width of stator teeth is near the air gap surface or 1/3<sup>rd</sup> of height of the slots
- ★ A check for minimum tooth width using the above equation should be applied before finally deciding the dimensions of stator slot

# STATOR CORE

## Depth of the stator core :

- ★ Depends on flux density in the core,  $B_{CS}$  - 1.2 to 1.5 T
- ★ Flux passing through the stator core is half of the flux per pole.

Therefore,

$$\text{Flux in the stator core, } \phi_c = \frac{\phi_m}{2}$$

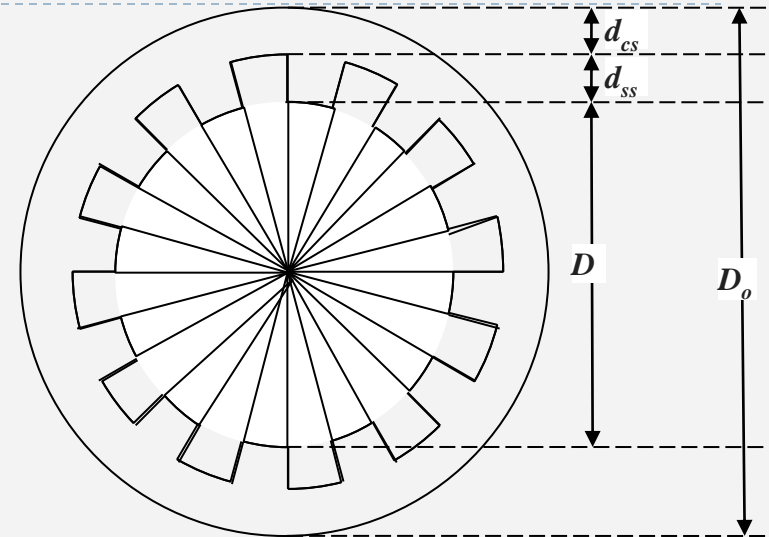
$$\text{Area of the stator core} = \frac{\text{Flux through Core}}{\text{Flux density in stator core}} = \frac{\phi_m}{2B_{CS}} \rightarrow (1)$$

$$\text{also, Area of the stator core} = L_i \times d_{CS} \rightarrow (2)$$

Equating (1) and (2)

$$\text{Depth of core, } d_{CS} = \frac{\phi_m}{2B_{CS} \cdot L_i}$$

$$\text{Outside diameter of stator core, } D_o = D + 2(d_{ss} + d_{cs})$$



Cross Section of Stator Core

# LENGTH OF THE AIR GAP

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$l_g$  - decided by considering the following factors:

- \* Power factor
- \* Overload capacity
- \* Pulsation loss
- \* Unbalanced magnetic pull
- \* Cooling
- \* Noise

## Power factor:

- \* MMF required to send the flux through the air gap is **proportional** to the product of B and  $l_g$
- \*  $l_g$  – determines the magnetizing current drawn by the machine.
- \* Magnetizing current inversely proportional to power factor

# LENGTH OF THE AIR GAP

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## Overload capacity:

- ✦  $l_g$  affects the value of zig-zag leakage reactance which forms a large part of total leakage reactance .
- ✦ If  $l_g$  is larger, then zig-zag leakage flux will be less and so leakage reactance will be **less**, results in **increase** in overload capacity

## Pulsation loss:

- ✦ With larger length of air gap, the variation of reluctance due to slotting is small.
- ✦ The tooth pulsation loss, which is produced due to variation in reluctance of air gap, is reduced accordingly.
- ✦ Therefore, the pulsation loss is less with large air gaps.

# LENGTH OF THE AIR GAP

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## Unbalanced magnetic pull

- ✦ If the  $l_g$  is small, then even for small deflection or eccentricity of the shaft would produce large irregularity in  $l_g$ .
- ✦ It is responsible for the production of UMP, which has the tendency to bend the shaft still more at a place where it is already bent resulting in fouling of rotor with stator.
- ✦ If  $l_g$  is large, a small eccentricity would not be able to produce noticeable UMP.

## Cooling:

- ✦ If  $l_g$  is large, cylindrical surfaces of rotor and stator are separated by a large distance.
- ✦ This would afford better facilities for cooling at the gap surfaces especially when a fan is fitted for circulation of air

## Noise:

- ✦ The principal cause of noise in I.M is the variation of reluctance of the path of the zig-zag leakage as small as possible, can be done by increasing  $l_g$ .



# Relations for length of air gap

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- i. For small I.M ,  $l_g = 0.2 + 2\sqrt{DL}$  mm
- ii. Alternate formula for small Induction Motors,  
 $l_g = (0.125 + 0.35 D + L + 0.015V_a)$  mm
- iii. For general use,  $l_g = (0.2 + D)$  mm
- iv. For machines with journal bearings  
 $l_g = 1.6 \sqrt{D} - 0.25$  mm  
D,L and  $V_a$  are in meters

D in mm	$l_g$ in mm
0.15	0.35
0.20	0.50
0.25	0.60
0.30	0.70
0.45	1.30
0.55	1.80
0.65	2.50
0.80	4.00

# DESIGN OF SQUIRREL CAGE INDUCTION ROTOR

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- ✦ The squirrel cage rotor consists of laminated core, rotor bars and end rings
- ✦ The rotor bars and end rings are made of Al or Cu
- ✦ Diameter of the rotor is slightly lesser than the stator to avoid mechanical friction between the stationary stator and rotating rotor
- ✦ Rotor diameter  $D_r = \text{Stator Bore}(D) - 2l_g$

# DESIGN OF ROTOR BARS AND SLOTS

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- ★ For a three phase machine , the rotor bar current is given by the equation,

$$\text{Rotor bar current } I_b = (6T_s \cdot I_s) K_{ws} \cos\Phi / S_r$$

$$\approx 0.85(6T_s \cdot I_s) / S_r$$

- ★ Performance of an induction motor is greatly influenced by the resistance of the rotor
- ★ Higher rotor resistance has higher starting torque but lesser efficiency
- ★ Rotor resistance is the sum of resistance of the bars and the endrings
- ★ The cross section of the rotor bars and end rings are selected to meet both requirements of  $T_{st}$  as well as efficiency

# DESIGN OF ROTOR BARS AND SLOTS

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- ▶ Current density of the rotor bar,  $\delta_b$  - 4 to 7 A/mm<sup>2</sup>
- ▶ Area of each rotor bar,  $a_b = I_b / \delta_b$  mm<sup>2</sup>
- ▶ In case of squirrel cage motor the X-sectional area of bars will take the shape of the slot and insulation is not used between bars and rotor core.
- ▶ The rotor slots for squirrel cage rotor may be either closed or semi closed types.

## **Advantages of closed slots:**

- \* Low reluctance
- \* Less magnetizing current
- \* Quieter operation
- \* Large leakage reactance and so starting current is limited

## **Disadvantage of closed slots:**

- \* Reduced overload capacity

# DESIGN OF ROTOR BARS AND SLOTS

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## Rules for Selecting Rotor Slots:

- i. No. of stator slots should never be equal to rotor slots.  
 $S_r$  is 15% less than  $S_s$
- ii. The difference  $(S_s - S_r)$  should not be equal to  $\pm P$ ,  $\pm 2P$  or  $\pm 5P$  to avoid synchronous steps
- iii. The difference  $(S_s - S_r)$  should not be equal to  $\pm 3 P$  to avoid magnetic locking
- iv. The difference  $(S_s - S_r)$  should not be equal to  $\pm 1$ ,  $\pm 2$ ,  $\pm (p \pm 1)$  or  $\pm (p \pm 2)$  to avoid noise and vibrations

# DESIGN OF END RINGS

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- \* The distribution of current in the bars and end rings of a squirrel cage motor is complicated
- \* It can be shown that if flux distribution is sinusoidal then the bar current and end ring current will also be sinusoidal
- \* Max. value of end ring current

$$I_{e(\max)} = \frac{\text{Bars per Pole}}{2} \times \text{Current per Bar}$$
$$= \frac{S_r}{2p} \cdot I_{b(\max)}$$

- \* However, current is not maximum in all the bars under one pole at the same time but varies according to sine law
- \* Hence the max. value of the current in the end ring is the average of the current of half the bars under one pole

# DESIGN OF END RINGS

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- ★ Maximum value of end ring current,

$$\begin{aligned} I_{e(\max)} &= \frac{\text{Bars per pole}}{2} \times I_{b(\text{ave})} \\ &= \frac{S_r}{2p} \times \frac{2}{\pi} \times I_{b(\max)} \\ &= \frac{S_r}{2p} \times \frac{2}{\pi} \times \sqrt{2} \cdot I_b = \frac{\sqrt{2} \cdot I_b \cdot S_r}{\pi p} \end{aligned}$$

- ★ Current density of the end ring  $\delta_e$  - 4 to 7 A/mm<sup>2</sup>

$$A_e = I_e / \delta_e \text{ mm}^2$$

also  $A_e = \text{Depth of end ring} \times \text{Thickness of end rings} = d_e \times t_e$