

DESIGN OF ELECTRICAL MACHINES

Introduction

Introduction

▶ Engineering Design

- an **application** of Science & Technology and **Invention** to produce Machines
- to perform **specified tasks** with **optimum economy** and **efficiency**

Major Consideration to Evolve a Good Design

- Cost
- Durability
- Compliance with Performance Criteria

Electrical Machines

Static Machines - Transformers

Rotating Machines- Generators & Motors

- Conversion in any electrical M/C takes place through magnetic field.
- Magnetic Field produced by an EM which require core and winding.

IM : 20 to 30 Years - Low Initial Cost

SM & Trs : Designed with Reliability and Durability Low Initial Cost

Design Factors

Basic structure of Rotating Electrical Machines

- Magnetic Circuit
- Electric Circuit
- Dielectric Circuit
- Thermal Circuit
- Mechanical Parts

Magnetic Circuit

Provide path for

- magnetic flux and consist of Air gap
- Stator and Rotor Teeth and
- Stator and Rotor Core(yokes)

Electric Circuit

- Stator and Rotor Winding
- Winding of a Trs., Rotating M/c. conveys energy and is concerned with Production of emf and Development of mmf.

Dielectric Circuit

- To **isolate** one conductor from another conductor and also the windings from the core.
- Insulating Materials are Non –Metallic, Organic, inorganic, natural or Synthetic.

Thermal Circuit

Mode and Media **for dissipation of heat** produced inside the machine on account of losses.

Mechanical Parts

Frame, Bearings and Shaft

** A successful Design brings out an **economic compromise** for space occupied by iron, copper, Al., insulation and coolant.

Limitation in Design

- Saturation
- Temperature Rise
- Insulation
- Efficiency
- Mechanical Parts
- Commutation
- Power Factor
- Consumer Specifications
- Standard Specifications

Saturation

Electrical M/c use Ferro Magnetic materials - B_{max} – Increased Excitation resulting in higher cost for the field system.

Temperature Rise

- Cooling and ventilation –required to keep the temperature rise in safe limits.
- Coolant become excessive.

Insulation

- Able to withstand the electrical, mechanical and thermal stresses.
- Type of insulation – decided by maximum temperature.
- size of insulation - decided by maximum voltage stress and mechanical stress.

Efficiency

The capital cost of a M/C designed for high efficiency is high while its running cost is low.

Mechanical Parts

- Mechanical stresses at the bottom of rotor teeth do not exceed the maximum allowable limit – Turbo Alternator.
- Air gap length as small as possible to maintain high power factor- IM
- Bearings of rotating M/Cs are subjected to the action of rotor weight, external loads, Inertia forces.

Commutation

Commutation conditions limit the maximum output.

Power Factor

Poor PF results in larger values of current for the same power – larger conductor sizes have to be used.

Size and cost of IM reduced by using B_{max} which leads to saturation of iron parts and poor PF.

Consumer's Specification

Specification laid down in the consumer's order have to be met and the design evolved should be satisfies all the specifications and also the economic constraints imposed on the manufacture.

Standard Specification

These specifications are the biggest strain on the design because the manufacture as well as the consumer cannot get away from them without satisfying them.

Modern Machine Manufacturing Techniques

****Wide range of power output**

Small size Machines – M/cs having power o/p of 750watts.

Medium size Machines - power o/p of few KW to 250KW.

Large size Machines - power o/p of 250KW to 5000KW.

Larger size Machines - power o/p as high as hundreds of megawatt.

- ▶ Trend to build machines which are **smaller** in size. Using lesser materials without sacrificing their efficiency and capacity.

** **Modern M/c** – Magnetic materials having high permeability, low iron loss and high mechanical strength.

**improvement in the insulating materials

** Marked with the use of higher electro magnetic loadings for active parts and increased mechanical loadings

**Different and refined manufacturing techniques are used for individual machine parts.

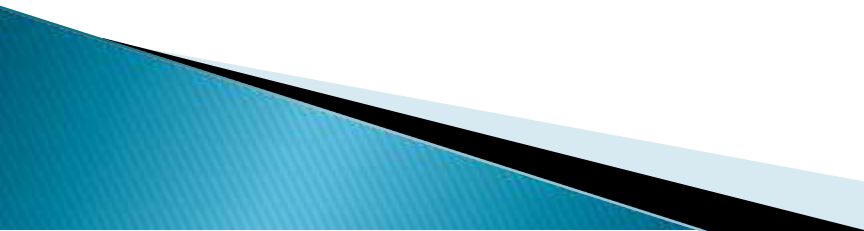
**M/cs are operates satisfactorily under the desired environmental conditions.

CLASSIFICATION OF M/Cs

▶ According to Size:

- Small Size : up to 750 Watts
- Medium Size : up to 250 KW
- Larger Size : 250 KW to 5000KW

▶ According to speed:

- Low speed : < 500 r.p.m.
 - Medium speed: 500 to 1000 r.p.m.
 - High speed / Turbo: > 1000 r.p.m.
- 

Manufacturers

- ▶ SIEMENS
 - ▶ ABB
 - ▶ KIRLOSKAR
 - ▶ GEC
 - ▶ BHEL
 - ▶ INDO TECH
 - ▶ GD Electricals
- 

Total Magnetic loading

Total flux around the armature periphery at the air gap.

$$= P\Phi$$

Total Electric loading

Total No.of armature conductors around the armature periphery.

$$= I_z Z$$

Specific Electric Loading (ac or q)

- ▶ Every section of armature is capable of carrying certain amount of **current**. Hence **ampere- turn per unit** section of armature periphery is an important parameter to estimate the intensity of electric loading

$ac = (\text{Total Armature ampere conductors}) / \text{Armature periphery at air gap}$

$$= (I_z Z) / \pi D$$

Choice of Specific Electric Loadings depends

- ▶ **Copper loss:** Higher the value of **ac**
 - **larger** will be the number of **armature of conductors** which results in **higher copper loss**.
 - This will result in higher temperature rise and reduction in efficiency.

Voltage: A higher value of **ac**

- can be used for **low voltage** machines
- since the **space required** for the insulation will be **smaller**.

- ▶ **Synchronous reactance:** High value of a_c leads to
 - higher value of leakage reactance and armature reaction and hence higher value of synchronous reactance.
 - Such machines will have
 - poor voltage regulation,
 - lower value of current under short circuit condition
 - low value of steady state stability limit and
 - small value of synchronizing power.
- ▶ **Stray load losses:** With increase of $q \Rightarrow$ stray load losses will increase.

Values of specific magnetic and specific electric loading can be selected from
Design Data Hand Book for salient and non salient pole machines

Specific Magnetic Loading

- ▶ Each unit area of armature surface is capable of receiving a certain magnetic flux. Hence Φ/A is an important parameter to estimate the intensity of magnetic loading.

$$\begin{aligned} B_{av} &= \text{Total flux around the air gap} / \text{Area of flux path at the air gap} \\ &= P\Phi / \pi DL \end{aligned}$$

Factors which influences the performance of the machine

- ▶ **Iron loss:** A high value of **flux density** in the **air gap leads** to higher value of **flux in the iron parts** of the machine which results in
 - increased iron losses and
 - reduced efficiency.
- ▶ **Voltage:** When the machine is designed for **higher voltage**
 - space occupied by the insulation becomes more
 - making the teeth smaller and hence
 - higher flux density in teeth and core.
- ▶ **Transient short circuit current:** A high value of gap density results in
 - decrease in leakage reactance and hence
 - increased value of armature current under short circuit conditions.

- ▶ **Stability:** The maximum power output of a machine under steady state condition is **indirectly proportional** to synchronous reactance.
 - If higher value of flux density is used it leads to smaller number of turns per phase in armature winding.
 - This results in reduced value of leakage reactance and hence increased value of power and hence increased steady state stability.
- ▶ **Parallel operation:** The parallel operation of synchronous generators depends on the synchronizing power.
 - Higher the synchronizing power higher will be the ability of the machine to operate in synchronism.
 - The synchronizing power is inversely proportional to the synchronous reactance and hence the machines designed with higher value air gap flux density will have better ability to operate in parallel with other machines

Electrical Engineering Materials



Electrical Engineering Materials

Material serving as electrical conductors can be divided into 2 groups

- High Conductivity Materials
- High Resistivity Materials

High Conductivity Materials


Used for making windings required in electrical Machines, apparatus Devices and Transmission & Distribution of Electrical Energy.

Least possible Resistivity

High Resistivity Materials

Used for making Resistances and Heating Devices

Insulating Materials

- ▶ To **avoid** any electrical activity between parts at different potentials, insulation is used
 - ▶ **Properties:**
 - High Dielectric strength
 - High resistivity
 - Good thermal conductivity
 - High degree of thermal stability
 - Low dielectric loss
 - Good mechanical properties
 - Ability to withstand moisture, chemical, heat etc.,
- 

Classification

Class	Temperature (° C) Limit
Y	90
A	105
E	120
B	130
F	155
H	180
C	> 180

Different Insulating materials

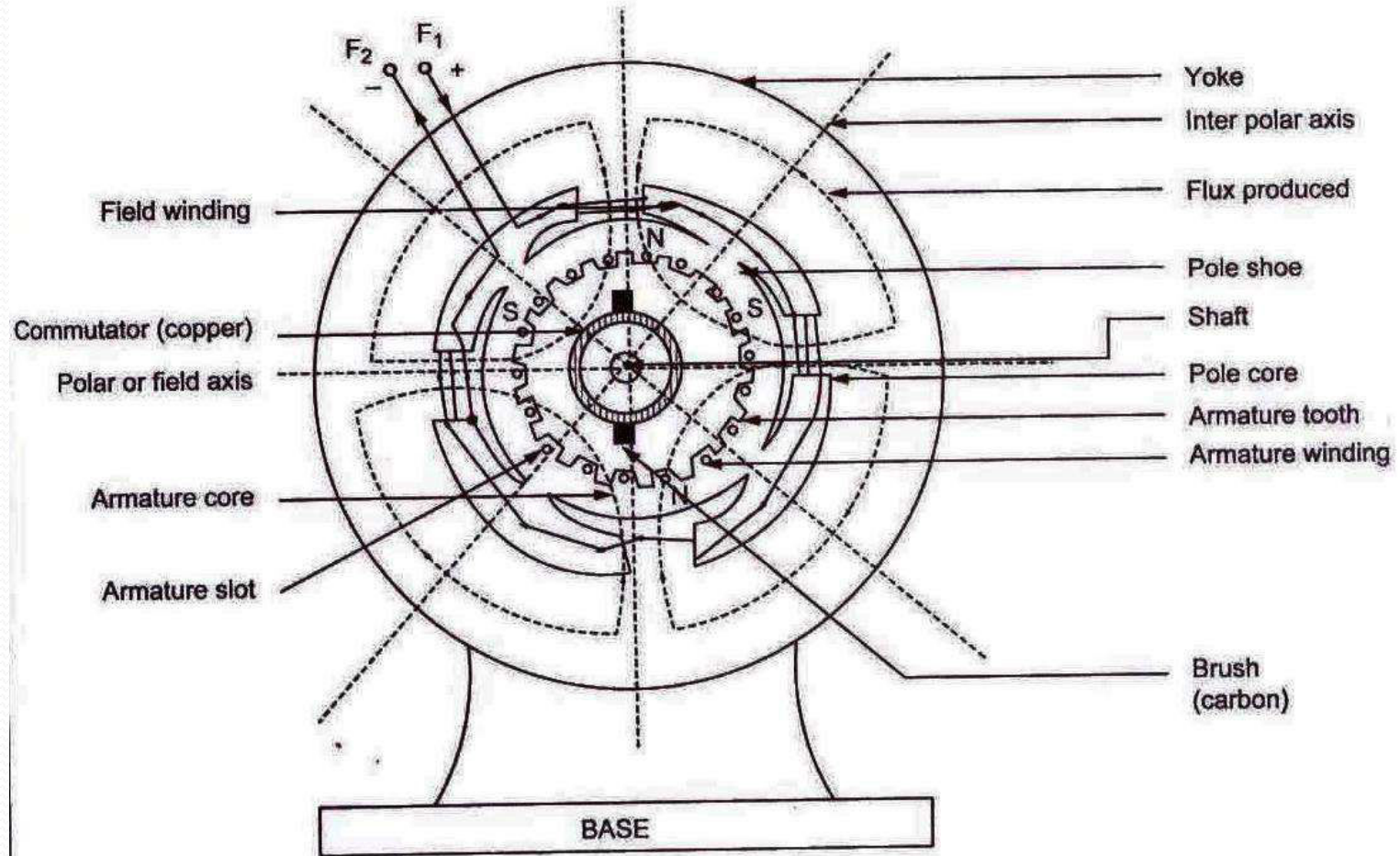
- ▶ Class Y : Cotton, Silk, Paper, Cellulose, Wood
- ▶ Class A : Cellulose esters, Insulating Oil, Laminated Wood, Varnished paper
- ▶ Class E : Synthetic resin enamels, Cotton & Paper laminates with formaldehyde bonding
- ▶ Class B : Mica, Glass fibre, Asbestos with bonding and laminates
- ▶ Class F : Materials of class B with suitable bonding of higher thermal stability
- ▶ Class H : Mica, Glass fibre and Asbestos with silicon resins.
- ▶ Class C : Ceramics, Quartz

THANK YOU



DC MACHINES

Parts of DC machine



Introduction

The aim in the design of dc machine is to obtain the complete dimensions of various parts like

- Main dimension of armature structure
- Design detail of armature winding
- Main dimension of field structure
- Design detail of field winding
- Design detail of commutator and brushes
- Design detail of the interpoles & its windings
- Performance characteristics

For design of dc machine required

- Detail specification of dc machine
- The limiting value of performance characteristics like iron losses, cu losses and efficiency
- Design equation based on which design procedure is to be initiated
- Information for proper choice of various design parameters
- Information regarding availability of material for various parts.

Specifications of dc machines

- Output : kW (for generators), kW or Hp (for motors)
- Voltage : V volt
- Speed : N rpm
- Rating : Continuous or Short time
- Temperature rise: $\theta^{\circ}\text{C}$ for an ambient temperature of 40°C
- Cooling : Natural or forced cooling
- Type : Generator or motor
- Voltage regulation
- Speed control
- Efficiency: must be as for as possible high
- Type of enclosure: based on the field of application – totally enclosed, screen protected, drip proof, flame proof, etc.,
- Size of the machine etc.,

Output Equation of DC Machines

Output Equation gives a **relation between** the machine rating and its armature dimensions in terms of armature **diameter, core length, speed, specific electric and specific magnetic loadings.**

E : emf induced or back emf

I_a : armature current

Φ : Average value of flux / pole

Z : Total number of armature conductors

N : Speed in rpm

P : Number of poles

A : number of armature paths or circuits

D : Diameter of the armature

L : Length of the armature core

Let

P_a = power developed by armature in kW

P_a = generated emf \times armature current $\times 10^{-3}$

$$P_a = E \times I_a \times 10^{-3} \text{-----(1)}$$

Generated emf in a dc machine, $E = \frac{\phi Z n p}{a}$

$$P_a = \frac{\phi Z n p}{a} \times I_a \times 10^{-3}$$

Let current in each conductor = $I_z = \frac{I_a}{a}$

$$P_a = (p\phi) \times (I_z Z) \times n \times 10^{-3}$$

Specific magnetic loading, $B_{av} = \frac{p\phi}{\pi DL}$

$$p\phi = B_{av} \pi DL$$

Specific electric loading, $ac = \frac{I_z Z}{\pi D}$

$$I_z Z = ac \pi D$$

Where

D – armature diameter

L – armature core length

Substitute

$$P_a = B_{av} \pi D L \times ac \pi D \times n \times 10^{-3}$$

$$= \pi^2 B_{av} ac D^2 L \times n \times 10^{-3}$$

$$P_a = C_o D^2 L \times n \text{ in kW}$$

Where

Output co-efficient, $C_o = \pi^2 B_{av} ac \times 10^{-3}$

Power developed by the armature

$$P_a = \frac{P}{\eta}$$

for generator

$$\{P_a = i/p - \text{losses}\}$$

$$P_a = P$$

for motor

$$\{P_a = o/p + \text{losses}\}$$

$$\{P = o/p\}$$

Let

K_f – form factor

B_{av} – average gap density

B_g (or) B_m – maximum gap density

Form factor ,
$$K_f = \frac{B_{av}}{B_g} = \frac{b}{\tau} = \psi$$

Where

b – pole arc

$$\tau = \frac{\pi D}{p} \quad \text{– Pole pitch}$$

ψ – Pole pitch

Main dimension

- a. Armature diameter (D)
- b. Armature core length (L)

- (i) Specific magnetic loading is related with D and L
- (ii) Specific electric loading is related with D
- (iii) The output coefficient depends on the value B_{av} and a_c

The choice of specific magnetic loading depends on :

- a. Teeth flux density
- b. Frequency of flux reversal
- c. size of the machine

Teeth flux density

Flux density in the air gap is high, it may increase a high flux density in the armature teeth beyond the limit. The value of flux density in the teeth at a minimum section should **not exceed 2.2 Wb/m²**.

The high value of flux density in the teeth

- (i) Causes more iron losses
- (ii) Requires higher mmf for passing the flux through the teeth. It can lead to increased field copper losses and higher cost of copper.

Frequency of flux reversal

$$f = (np/2)$$

Higher frequency of flux reversal results in increased iron losses in armature core and teeth. Therefore we should use a small value of flux density in the air gap for a machine having higher frequency.

Size of machine

If size of the machine increases, the width of the tooth also increases due to an increase in diameter of the armature. But this will not cause the saturation of machine when there is increased value of gap flux density.

Choice of specific electric loading (or) Ampere conductors per metre (ac)

- Temperature rise
- Speed
- Voltage
- Size of machine
- Armature reaction
- commutation

Temperature rise

- Heat dissipated in the machine increases when choosing a high value of 'ac' due to use of more armature conductors.
- A high value of 'ac' can be used for machines using insulating materials which can withstand a temperature rise.
- The choice of value for 'ac' depends upon type of enclosure and cooling techniques employed in the machine.

Speed

The ventilation of the machine is better when a machine rotates at high speed and greater losses can be dissipated. For a high speed machine, it is possible to use a high value of 'ac'.

Voltage

- The choice of 'ac' value depends on number of armature conductors which in turns depends on space availability for the provision of conductors.
- In high voltage machines, the thickness of insulation should be large, therefore there is less space for conductors results in low value of 'ac'

Size of machine

- In large size machine there is more space for accommodating the conductors. So it can be possible to use higher 'ac'.

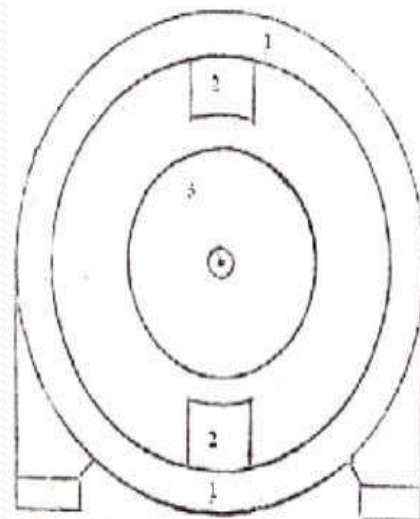
Armature Reaction

- For higher 'ac' armature reaction will be severe.
- In order to prevent this, the field should be made stronger. The mmf required for the field have to be increased to prevent decrease in flux.
- This increase the cost of conductors used

Commutation

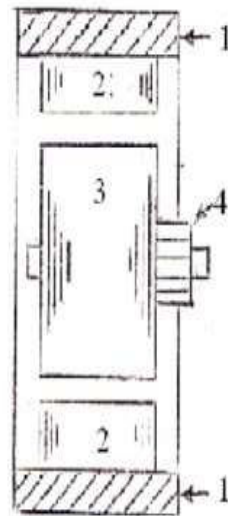
$$'ac' \propto (Z/D)$$

- For high value of 'ac', either increase the conductors or decrease the armature diameter.
- 'ac' \propto reactance voltage in coil \propto inductance in the coil
- High value of 'ac' result in increased reactance voltage which delay the commutation condition. ('ac' lies between 15000 to 50000)

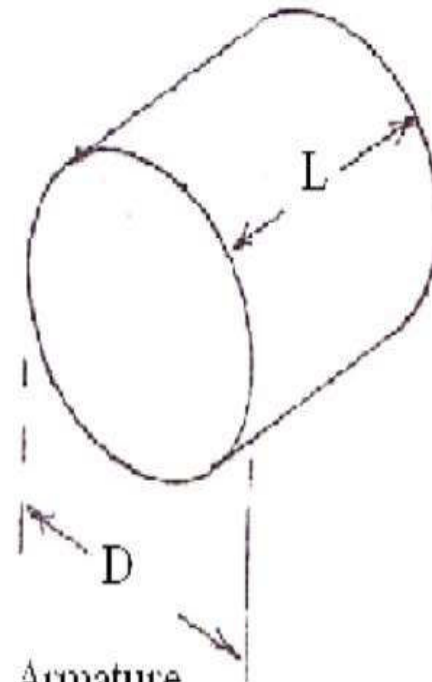


1. Yoke 2. Pole 3. Armature

DC Machine



1. Yoke 2. Pole
3. Armature
4. Commutator
Section of DC machine



Armature

Separation of D and L in DC machines

The factors which influence the relative value of D and L in dc machines are

- i. Machine proportions
- ii. Peripheral speed
- iii. Moment of inertia
- iv. Voltage between adjacent commutator segments

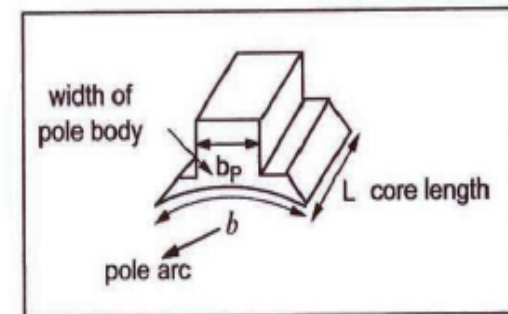
Machine proportions

- The dimensions of the machine are decided by the pole criterion
- The cross section of pole may be rectangular or square
- In a square section, width of the pole body is equal to length of the machine. But, the width of the pole body (b) is about 0.45 to 0.55 times of pole pitch.

$$L = b = (0.45 \text{ to } 0.55) \tau$$

- In rectangular pole construction, the length of the machine is equal to twice the width of pole body

$$L = b \text{ to } 2b \\ = (0.45 \text{ to } 1.1) \tau$$



- For square pole face construction, $L = b$ (or) $L/b = 1$

- For square pole length must be approximately equal to pole arc $L = b = \psi\tau$

The value of ψ is usually between 0.64 to 0.72

Assume value of $\psi = 0.67$

there fore $L/\tau = \psi = 0.64$ to 0.72

In practice L/τ is usually between **0.7 to 0.9** for square pole

$T =$ pole pitch, $\psi =$ pole arc/pole pitch

Peripheral speed

Peripheral speed of armature, $V_a = \pi D n \text{ m/s}$

Peripheral speed of armature is limiting factor to the value of diameter. Therefore, the Peripheral speed of armature should not exceed about 30 m/sec.

Moment of inertia

- Machines used for control systems, a small moment of inertia is desirable and it can be obtained by selecting low value of diameter for armature construction.
- If machines are designed for impact load applications, then selection of armature diameter should be large.

Voltage between adjacent commutator segments

The maximum core length of machine is decided by maximum allowable Voltage between adjacent commutator segments.

Maximum Voltage between adjacent commutator segments,

$$E_{cm} = 2B_{gm}LV_aT_c$$

Where

- B_{gm} - maximum gap density under load condition
- L - Core length of machine
- V_a - peripheral speed in m/sec
- T_c - number of turns/coil

The limiting values of

$$B_{gm} = 1.2 \text{ wb/m}^2$$

$$V_a = 30 \text{ m/sec}$$

$$E_{cm} = 30 \text{ v}$$



Thank You

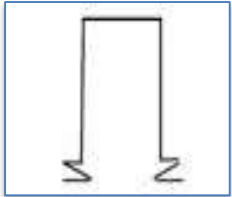
Design of Induction Motors

Design of Stator

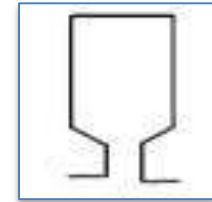
The Design consideration of Stator Involves in estimation of

- Stator Winding
- Stator Turns per Phase
- Length of Mean Turn
- Stator Conductors
- Shape & No of Stator Slots
- Area of Stator Slot
- Stator Teeth
- Depth of Stator Core

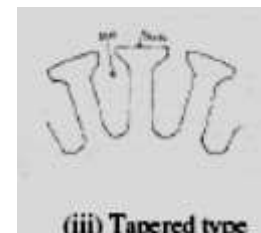
DESIGN OF STATOR

- Stator of an induction motor consists of stator core & stator slots.
- Stator slots: in general two types of stator slots are open slots & semi closed slots. The diagram shows a cross-section of an open stator slot. It is a rectangular shape with a wide top opening and narrow vertical sides. The bottom of the slot is open, with small horizontal lines indicating the bottom edges of the slot walls.
- **Open slots:** In this type , the **slot opening** will be **equal to** that of the **width** of the slots.
- In this slots **assembly and repair** of winding **are easy**. However such slots will lead to higher air gap contraction factor and hence **poor power factor**.
- Hence these types of slots are **rarely used in** 3 Φ induction motors.

Semi closed slots: In such type, slot opening is much smaller than the width of the slot. Hence in this type of slots assembly of windings is more difficult and takes more time compared to open slots and hence it is costlier. However the air gap characteristics are better compared to open type slots.



Tapered slots: In this type of slots also, opening will be much smaller than the slot width. However the slot width will at the bottom. be varying from top of the slot to bottom of the slot with minimum width



Stator Winding

- For **Small** Motors up to 5 HP **Single layer** Winding are used.
- For **large capacity** machines **Double layer** Winding (Lap or Wave) with diamond shaped coils is used.
- The three phases of winding can be connected in either **star** or **Delta** depending on the Starting Methods Employed.
- Squirrel cage – Star Delta Starter – Stators designed - Delta
 - Slip ring – Rotor resistance – Either star or Delta

Turns per phase

EMF equation of an induction motor is given by

$$E_{ph} = 4.44f\Phi T_{ph}k_w$$

Hence turns per phase $T_{ph} = E_{ph} / 4.44f\Phi k_w$

Generally the **induced emf** can be assumed to **be equal** to the **applied voltage** per phase

$$\text{Flux/pole, } = B_{av} \times \pi DL/P,$$

winding factor k_w may be assumed as **0.955** for full pitch distributed winding **unless otherwise specified**.

$$\text{Number conductors /phase, } Z_{ph} = 2 \times T_{ph},$$

$$\text{Total number of stator conductors } Z = 6T_{ph}$$

$$\text{conductors /slot } Z_s = Z/S_s \text{ or } 6 T_{ph}/S_s ,$$

where Z_s is an integer for single layer winding and even number for double layer winding.

Length of the mean Turn

- Length of the mean turn is calculated using an empirical formula $L_{mt} = 2L + 2.3 T + 0.24$ m
where L = the gross length of the stator & T = pole pitch in meter.
- **Resistance of stator winding:** Resistance of the stator winding per phase $r_s = (0.021 \times L_{mt} \times T_{ph}) / a_s$
where L_{mt} = length of mean turn of meter and a_s = area in mm².

copper losses in stator winding can be calculated as

- Total copper losses in stator winding = $3 (I_s)^2 r_s$

Stator Conductors

$$\text{kVA rating} \quad Q = 3 E_s I_s 10^{-3}$$

$$\text{Stator Current / Phase, } I_s = Q / 3 E_s \times 10^{-3}$$

$$\text{Area of Cross Section, } a_s = I_s / \check{\delta}_s$$

Where, $\check{\delta}_s$ – Current Density – 3 to 5 A/mm²

$$\text{Area of Cross Section, } a_s = \Pi d_s^2 / 4$$

Where, d_s – Diameter of Stator Conductor

Round conductors are generally used for **small diameter**.

For diameter **more than 2 or 3 mm** – **Bar or Strip**
conductors are used

Selection of number of stator slots

Number of stator slots must be **properly** selected at the design stage as such this number affects the

- weight
- cost and
- operating characteristics of the motor.

Though there are **no rules** for selecting the number of stator slots

-considering the advantages and disadvantages of selecting **higher number slots** comprise has to be set for selecting the number of slots

Choice of Stator Slots

- number of **slots/pole/phase** may be selected as **three** or **more** for **integral** slot winding
- **fractional** slot windings number of **slots/pole/phase** may be selected as **3.5**
- Slot Pitch for **open** type of Slots should be **15 to 25 mm**.
- Slot Pitch for **Semi enclosed** type of Slots **should be < 15 mm**.

- **Stator slot pitch, $Y_{ss} = \text{Gap Surface} / \text{Total No of Slots}$**

$$= \pi \cdot D / S_s$$

$$\text{So, } S_s = \pi \cdot D / Y_{ss}$$

- **Stator Slots $S_s = \text{Number of phases} \times \text{poles} \times \text{slots/pole/phase}$**

Guide lines to select a suitable number of slots

- the number of slots/pole/phase may be selected as **three or more for integral slot winding.**
- However for **fractional** slot windings number of slots/pole/phase may be selected as **3- 5.**
- So selected number of slots should satisfy the consideration of stator **slot pitch** at the air gap surface, which should be between **15 to 25 mm.**
- Stator slot pitch at the air gap surface $= Y_{ss} = \pi D / S_s$
where S_s is the number of stator slots

- Total number of stator winding conductors = $3 \times 2 \times T_s$ for 3ϕ

- No. of conductors per slot = $Z_{ss} = (3 \times 2 \times T_s) / S_s$

-

$$\text{area of each slot } a_s = \frac{\text{copper area /slot}}{\text{space factor } (s_f)}$$

- Copper area per slot = $(Z_{ss} \times a_s) / s_f$
- Space factor varies from 0.25 to 0.4
- The flux density in the teeth lies between 1.3 to 1.7 wb/m²
ratio of slot depth to width should be 3 to 6

Following are the advantages and disadvantages of selecting **Higher Number** of slots.

Advantages

- (i) Reduced leakage reactance.
- (ii) Reduced tooth pulsation losses.
- (iii) Higher over load capacity.

Disadvantages:

- (i) Increased cost
- (ii) Increased weight
- (iii) Increased magnetizing current
- (iv) Increased iron losses
- (v) Poor cooling
- (vi) Increased temperature rise
- (vii) Reduction in efficiency

Conductors per Slot

$$\begin{aligned}\text{Total No of Stator Conductors } Z_s &= \text{Phase} \times \text{conductors/Phase} \\ &= 3 \times 2 T_s = 6 T_s\end{aligned}$$

$$\begin{aligned}\text{Conductors per Slot, } Z_{ss} &= \text{Total No of } Z_s / \text{Total No of } S_s \\ &= 6 T_s / S_s\end{aligned}$$

Where, T_s – Stator Turns per Phase

S_s – Total Stator Slots

Z_{ss} – Must be Even for double
layer winding

Area of Stator Slot

Area of each slot = Copper Area per slot / Space Factor

$$= Z_{ss} \times a_s / S_f$$

Where, Z_{ss} – No of Conductors per slot

a_s – Area of each Conductor

S_f = Space factor

Space Factor – 0.25 to 0.4

Stator Teeth

- The Dimensions of slot determine the flux density in the teeth.
- Higher Flux Density – iron loss – Greater Magnetizing mmf.
- Mean Flux density in tooth $< 1.7 \text{ Wb/m}^2$

$$\begin{aligned}\text{Minimum teeth Area per pole} &= \text{flux per pole} / \text{flux density in the teeth} \\ &= \phi_m / 1.7\end{aligned}$$

$$\text{Teeth area per pole} = (S_s / p) \times L_i \times W_{ts} \text{ (Width of stator Tooth)}$$

$$\text{So, } \phi_m / 1.7 = (S_s / p) \times L_i \times W_{ts \text{ min}}$$

$$W_{ts \text{ min}} = \phi_m / 1.7 (S_s / p) \times L_i$$

S_s - no of slots /pole , L_i – net iron length , W_{ts} - min tooth width

Conductor cross section

Area of cross section of stator conductors

A_c = the **stator current per phase** and assumed value of **current density** for the stator windings.

Sectional area of the stator conductor $a_s = I_s / \delta_s$

where δ_s is the current density in stator windings

Stator current per phase $I_s = Q / (3V_{ph} \cos\Phi)$

A suitable value of current density has to be assumed considering the advantages and disadvantages.

Advantages of **higher** value of current density:

- (i) reduction in cross section
- (ii) reduction in weight
- (iii) reduction in cost

Disadvantages of **higher** value of current density

- (i) increase in resistance
- (ii) increase in cu loss
- (iii) increase in temperature rise
- (iv) reduction in efficiency

Depth of stator core

- the flux density in the stator core may be assumed varying between **1.2 to 1.4 Tesla**.
- The flux in the stator core is **half** the flux per pole.

Flux in the stator core section $\Phi_c = \frac{1}{2} \Phi$

Area of stator core $A_c = \Phi / 2B_{cs}$

Area of stator core $A_c = L_i \times d_{cs}$

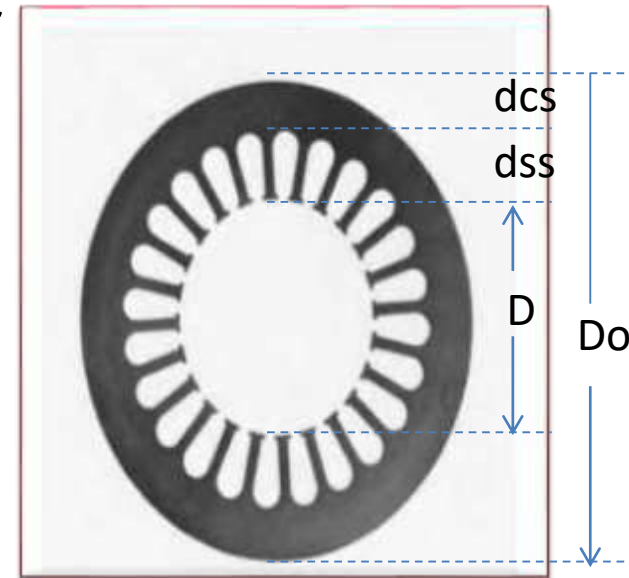
Hence, depth of the stator core $d_{cs} = A_c / L_i$

- outer diameter of the stator core

$$D_o = D + 2d_{ss} + 2d_{cs}$$

Where d_{ss} = is the depth of the stator slot.

D = stator diameter



Length of Air Gap

Advantages larger air gap length :

- Increased overload capacity
- Increased cooling
- Reduced unbalanced magnetic pull
- Reduced in tooth pulsation
- Reduced noise

Disadvantages of larger air gap length

- Increased Magnetising current
- Reduced power factor

For Small Induction Motor – $l_g = 0.2 + 2 \sqrt{DL}$ mm

$$L_g = 0.125 + 0.35D + L + 0.015 V_a \text{ mm}$$

For General Use - $l_g = 0.2 + D$ mm

For journal bearings - $l_g = 1.6 \sqrt{D} - 0.25$ mm

THANK YOU

DESIGN OF SQUIRREL CAGE AND SLIP RING ROTOR

- There are two types of rotor construction.
squirrel cage rotor & slip ring rotor.

Most of the induction motor are squirrel cage type.

- These are having the **advantage** of rugged and simple in construction and comparatively cheaper. However they have the **disadvantage** of lower starting torque.
- In this type, the rotor consists of bars of copper or aluminum accommodated in rotor slots.
- In case slip ring induction motors the rotor complex in construction and costlier with the advantage that they have the **better starting torque**.

Cond..

- This type of rotor consists of star connected distributed three phase windings.
- Between stator and rotor is the air gap which is a very critical part.
- The **performance parameters** of the motor like magnetizing current, power factor, over load capacity, cooling and noise are affected by length of the air gap.
- Hence length of the air gap is selected considering the advantages and disadvantages of larger air gap length.

Cond..

Advantages:

- Increased overload capacity
- Increased cooling
- Reduced unbalanced magnetic pull
- Reduced in tooth pulsation
- Reduced noise

Disadvantages

- Increased Magnetizing current
- Reduced power factor

Shape and Size of the Rotor slots

- Generally **semi-closed** slots or closed slots with very small or narrow openings are employed for the rotor slots.
- In case of **fully closed** slots the rotor bars are force fit into the slots from the sides of the rotor.
- The rotors with **closed slots** are giving better performance to the motor in the following way.

Cond..

- As the rotor is **closed** the rotor **surface is smooth** at the air gap and hence the motor draws lower magnetizing current.
- **reduced noise** as the air gap characteristics are better
- **increased leakage reactance** and
- **reduced** starting current.
- Over load capacity is **reduced**
- Undesirable and complex air gap characteristics. From the above it can be concluded that **semi-closed** slots are more suitable and hence are employed in rotors.

Cross sectional area of Rotor bar

- Sectional area of the rotor conductor can be calculated by rotor bar current and assumed value of current density for rotor bars.
- As cooling conditions are better for the rotor than the stator higher current density can be assumed.
- Higher current density will lead to reduced sectional area and hence increased resistance, rotor cu losses and reduced efficiency.
- With increased rotor resistance starting torque will increase.
- As a guideline the rotor bar current density can be assumed between 4 to 7 Amp/mm²
- Hence sectional area of the rotor bars , $A_b = I_b / \delta_b$ mm².

Equivalent Rotor Resistance

- Knowing the total copper losses in the rotor circuit and the equivalent rotor current equivalent rotor resistance can be calculated as follows.
- Equivalent rotor resistance

$$r'_r = \text{Total rotor copper loss} / 3 \times (I_r)^2$$

Design of wound Rotor

- This is another type of induction motor where in rotor also carries distributed star connected 3 phase winding.
- At one end of the rotor there are three slip rings mounted on the shaft. Three ends of the winding are connected to the slip rings.
- External resistances can be connected to these slip rings at starting, which will be inserted in series with the windings which will help in increasing the torque at starting.
- Such type of induction motors are employed where high starting torque is required.

Number of rotor slots and rotor Turns

- Numbers of rotor turns are decided based on the safety consideration of the personal working with the induction motors.
- The **voltage** between the slip rings on open circuit must be limited to safety values.
- In general the voltage between the slip rings for **low and medium** voltage machines must be limited to **400** volts.
- For motors with **higher voltage** ratings and large size motors this voltage must be limited to **1000** volts.

Cond..

$$\text{Voltage ratio } E_r / E_s = (K_{wr} \times T_r) / (K_{ws} \times T_s)$$

Hence rotor turns per phase

$$T_r = (E_r / E_s) (K_{ws} / K_{wr}) T_s$$

E_r = open circuit rotor voltage/phase

E_s = stator voltage /phase

K_{ws} = winding factor for stator

K_{wr} = winding factor for rotor

T_s = Number of stator turns/phase

Rotor Current

- Rotor current can be calculated by comparing the amp-cond on stator and rotor

$$I_r = (K_{ws} \times S_s \times Z'_s) \times I'_r / (K_{wr} \times S_r \times Z'_r)$$

K_{ws} - winding factor for the stator, S_s - number of stator slots,

Z'_s - number of conductors / stator slots,

K_{wr} - winding factor for the rotor,

S_r - number of rotor slots,

Z'_r - number of conductors / rotor slots and

I'_r - equivalent rotor current in terms of stator current

$I'_r = 0.85 I_s$ where I_s is stator current per phase

Area of Rotor Conductor

- Area of rotor conductor can be calculated based on the **assumed value** for the **current density** in rotor conductor and calculated **rotor current**.
- **Current density** rotor conductor can be assumed between 4 to 6 Amp/mm²

$$A_r = I_r / \delta_r \text{ mm}^2$$

$A_r < 5 \text{ mm}^2$ use circular conductor, else rectangular conductor,
for rectangular conductor width to thickness ratio = 2.5 to 4.

- Then the standard conductor size can be selected similar to that of stator conductor.

Size of Rotor slot

- Mostly Semi closed rectangular slots employed for the rotors.
- Based on conductor size, number conductors per slot and arrangement of conductors similar to that of stator, dimension of rotor slots can be estimated.
- Size of the slot must be such that the ratio of depth to width of slot must be between 3 and 4.

- Rotor bar current $I_b = 0.85 (6I_s T_s) / S_r$
- Length of rotor bar $l_b = L + \text{allowance for skewing}$
Rotor bar resistance = $0.021 \times l_b / A_b$
- Copper loss in rotor bars = $I_b^2 \times r_b \times \text{number of rotor bars}$
- area of the rotor bars $A_b = l_b / \delta_b \text{ mm}^2$
- **End Ring Current:**
- All the rotor bars are short circuited by connecting them to the end rings at both the end rings.
- Area of each end ring $A_e = I_e / \delta_e \text{ mm}^2$
- rotor turns per phase $T_r = (E_r / E_s) (K_{ws} / K_{wr}) T_s$
- $A_r = I_r / \delta_r \text{ mm}^2$

- Total copper loss:

Length of the mean Turn can be calculated from the empirical formula

$$l_{mt} = 2L + 2.3 \tau_p + 0.08 \text{ m}$$

- Resistance of rotor winding is given by

$$R_r = (0.021 \times l_{mt} \times T_r) / A_r$$

$$\text{Total copper loss} = 3 I_r^2 R_r \text{ Watts}$$

Depth of stator core below the slots

- Below rotor slots there is certain solid portion which is called depth of the core below slots.
- This depth is calculated based on the flux density and flux in the rotor core.
- Flux density in the rotor core can be assumed to be between 1.2 to 1.4 Tesla.
- Then depth of the core can be found as follows.

Cond..

- Area of stator core $A_{cr} = \Phi / 2B_{cr}$
- Area of stator core $A_{cr} = L_i \times d_{cr}$
- Hence, depth of the core $d_{cr} = A_{cr} / L_i$
- Inner diameter of the rotor can be calculated as follows
- Inner diameter of rotor = $D - 2l_g - 2h_{tr} - 2 d_{cr}$
- Flux in the rotor core section $\Phi_c = \frac{1}{2} \Phi$

PERFORMANCE CALCULATION FROM DESIGNED DATA

Based on the design data of the stator and rotor of an induction motor, performance of the machine has to be evaluated.

The parameters for performance evaluation are iron losses, no load current, no load power factor, leakage reactance etc.

Based on the values of these parameters design values of stator and rotor can be justified.

Iron losses

- Iron losses are occurring in all the iron parts due to the varying magnetic field of the machine.

Cond..

- Iron loss has two components, hysteresis and eddy current losses occurring in the iron parts depend upon the frequency of the applied voltage.
- The frequency of the induced voltage in rotor is equal to the **slip frequency** which is very low and hence the iron losses occurring in the rotor is negligibly small.
- Hence the iron losses occurring in the induction motor is mainly due to the losses in the stator alone.

Cond..

- Total iron losses in induction motor = Iron loss in stator core + iron losses in stator teeth.
- In addition friction and windage loss can be taken into account by assuming it as 1- 2 % of the output of the motor.
- Hence total no load losses = Total iron losses + Friction and windage loss.
- **No load current:** the no load current of an induction motor has two components magnetizing component, I_m and iron loss component, I_w .

Thus the no load current $I_0 = \sqrt{(I_m)^2 + (I_w)^2}$ amps

Magnetizing current

- Magnetizing current of an induction motor is **responsible** for producing the required amount of **flux** in the different parts of the machine.
- Hence this current can be calculated from all the magnetic circuit of the machine.
- The ampere turns for all the magnetic circuit such as stator core, stator teeth, air gap, rotor core and rotor teeth gives the total ampere turns required for the magnetic circuit.

Cond..

- Based on the total ampere turns of the magnetic circuit the magnetizing current can be calculated as

Magnetizing current $I_m = p AT_{30} / (1.17 k_w T_{ph})$

where p - no of pairs of poles, T_{ph} - Number of stator turns per phase

AT_{30} - Total ampere turns of the magnetic circuit at 30° from the centre of the pole,

. **Iron loss component of current:**

this component can be calculated from no load losses and applied voltage.

- Iron loss component of current

$$I_w = \text{Total no load losses} / (3 \times \text{phase voltage})$$

No load Power Factor

- No load power factor of an induction motor is very poor. As the load on the machine increases the power factor improves.
- No load power factor can be calculated knowing the components of no load current.

No load power factor $\cos\Phi_0 = I_w / I_0$

THANK YOU

Design of Induction Motors

Introduction

- Induction motors are the **ac motors** which are employed as the **prime movers** in most of the industries.
- widely used in **industrial applications** from small workshops to large industries.
- These motors are employed in **applications** such as **centrifugal pumps, conveyers, compressors crushers, and drilling machines etc.**

Constructional Details

- Similar to DC machines an induction motor consists of a stationary member called **stator** and a rotating member called **rotor**. However the induction motor **differs from a dc machine** in the following aspects.
 1. Laminated stator
 2. Absence of commutator
 3. Uniform and small air gap
 4. Practically almost constant speed

The AC induction motor comprises two electromagnetic parts

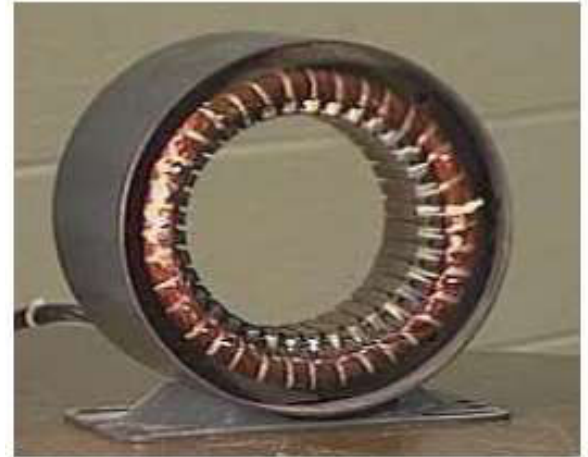
- **Stationary** part called the **stator**
- **Rotating** part called the **rotor**

The stator and the rotor are each made up of

- An **electric circuit**, usually made of insulated copper or aluminum winding, to carry **current**
- A **magnetic circuit**, usually made from laminated silicon steel, to carry **magnetic flux**

Stator - Construction

- The stator is the outer stationary part of the motor
- outer cylindrical frame - **yoke** which is made either of **welded sheet steel**, **cast iron** or **cast aluminum alloy**
- The magnetic path - **comprises a set of slotted steel laminations** called **stator core** pressed into the cylindrical space inside the outer frame.
 - *It is **laminated** to **reduce eddy currents**, **reducing losses and heating***



Smooth Yoke



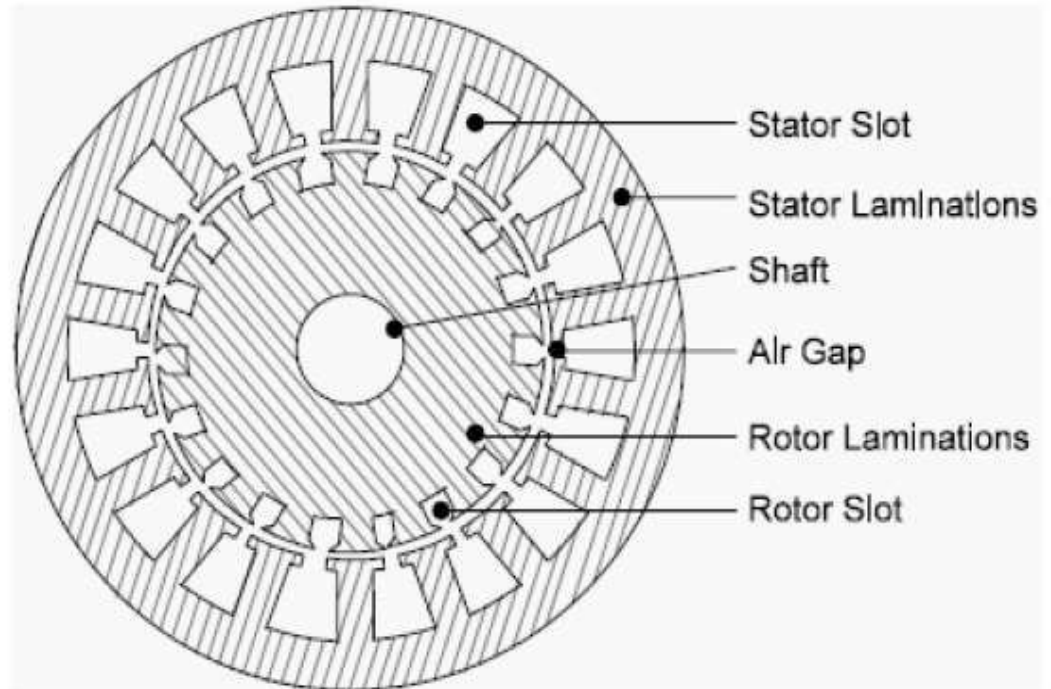
Ribbed Yoke

Stator - Construction

- A set of insulated electrical windings, which are placed inside the slots of the laminated Stator.
- For a 3-phase motor, 3 sets of windings are required, one for each phase connected in either star or delta..



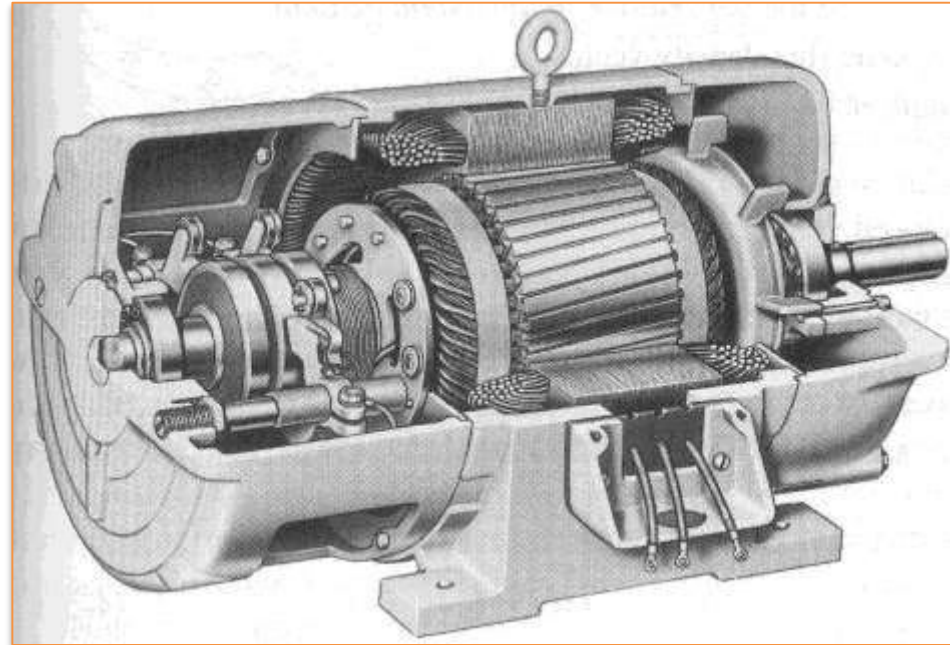
Stator Laminations



cross sectional view of an induction motor

Rotor - Construction

- Rotor is the **rotating part** of the induction motor
- of a **set of slotted silicon steel** laminations pressed together to form of a cylindrical magnetic circuit and the electrical circuit
- The electrical circuit of the rotor is of
 - *Squirrel cage rotor*
 - *Wound rotor (Slip Ring Rotor)*

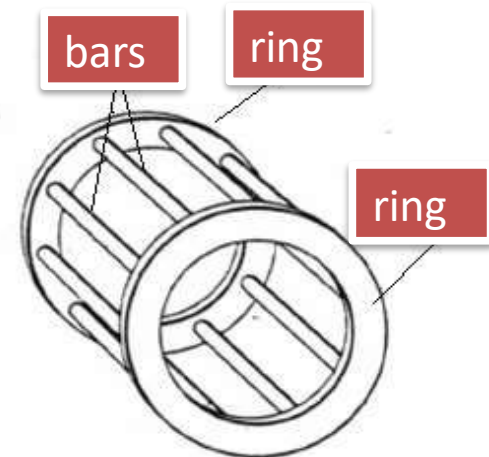
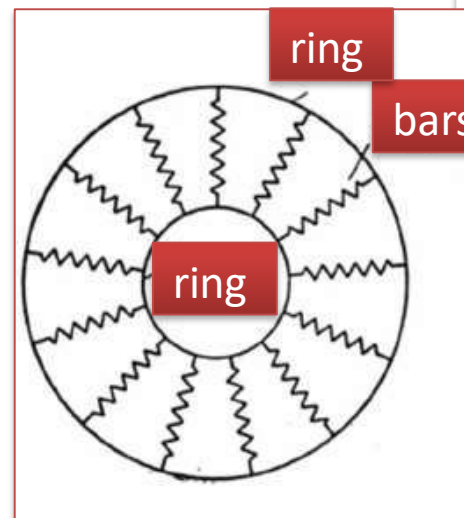


Squirrel Cage Rotor

- set of **copper or aluminum bars** installed into the **slots**, which are connected to an **end-ring** at each end of the rotor
- windings resembles a 'squirrel cage'

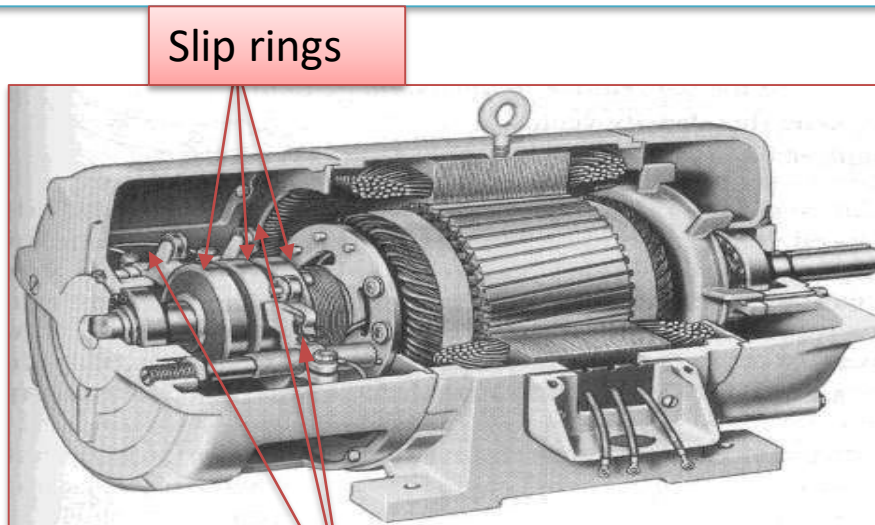


- Even though the aluminum rotor bars are in **direct contact with the steel laminations**, practically **all the rotor current flows through the aluminum bars** and not in the lamination



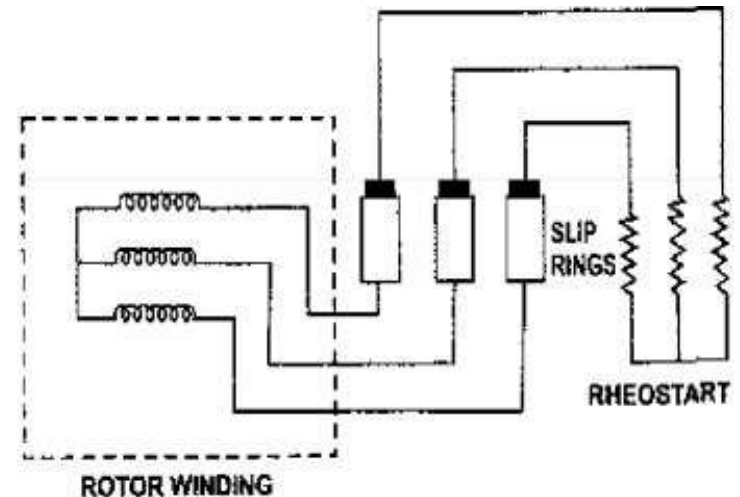
Wound Rotor

- consists of **three sets of insulated windings** with connections brought out to **three slip rings** mounted on one end of the shaft
- The external connections to the rotor are made through brushes onto the slip rings



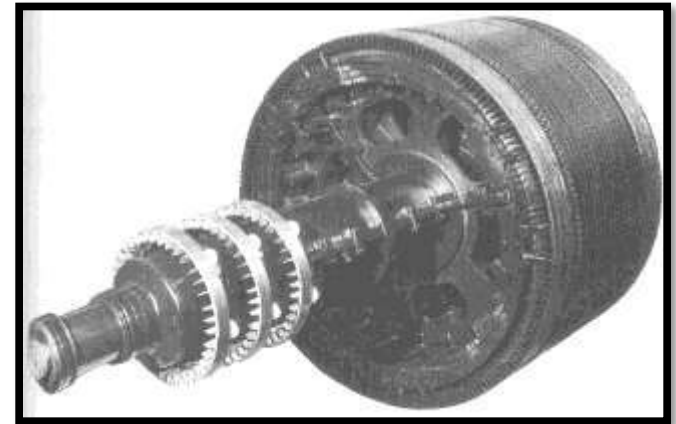
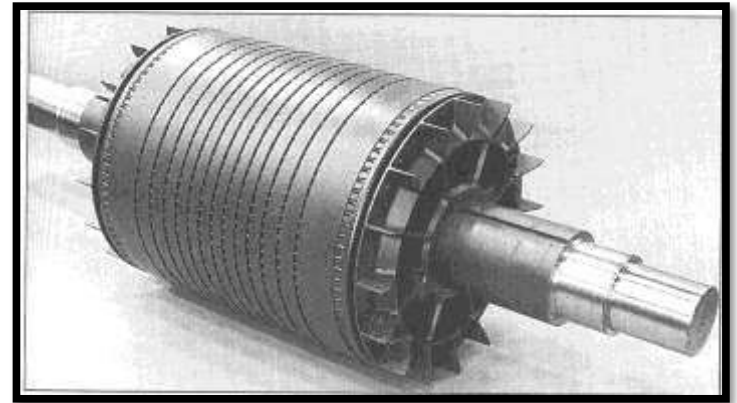
Slip rings

Brushes



Some more parts

- **Two end- flanges** to support the two bearings, one at the driving-end and the other at the non driving-end.
- **Two sets of bearings** to support the rotating shaft
- **Steel shaft** for transmitting the mechanical power to the load
- **Cooling fan** located at the non driving end
- **Terminal box** on top of the yoke or on side to receive the external electrical connections



Introduction to Design

The main purpose of designing an induction motor is to obtain the complete physical dimensions of all the parts of the machine as mentioned below to satisfy the customer specifications. The following design details are required.

1. The main dimensions of the stator.
2. Details of stator windings.
3. Design details of rotor and its windings
4. Performance characteristics. Like iron & cu loss, magnetizing current, no load current, power factor, short circuit current, efficiency etc

In order to get the above design details the designer needs the following

- Detailed specification of IM
- Limiting value of performance parameter iron & cu loss, magnetizing current ,no load current, power factor, short circuit current, efficiency etc
- Design equations based on which design procedure is to be initiated
- Information for proper choice of various design parameters
- Information regarding availability of materials for various parts

Specification of 3 phase IM

- rated output power
- rated voltage
- number of phases
- speed
- frequency
- connection of stator winding
- type of rotor winding
- Power factor
- efficiency
- Class of insulation
- shaft extension details etc.

Output Equation

- output equation is the mathematical expression which gives the relation between the various physical and electrical parameters of the electrical machine.

In an induction motor the output equation can be obtained as follows

Consider an 'm' phase machine, with usual notations

V_{ph} = phase voltage ; I_{ph} = phase current

Z_{ph} = no of conductors/phase

T_{ph} = no of turns/phase

N_s = Synchronous speed in rpm

n_s = synchronous speed in rps

p = no of poles, q = Specific electric loading Φ = air gap

flux/pole; B_{av} = Average flux density k_w = winding factor

η = efficiency $\cos\Phi$ = power factor

D = Diameter of the stator, L = Gross core length

C_o = Output coefficient

$$\text{Output } Q \text{ in kW} = \text{Input} \times \text{efficiency kW} \text{ -----(1)}$$

$$\text{Input to motor } Q = m V_{ph} I_{ph} \cos \Phi \times 10^{-3} \text{ kW}$$

For a 3 Φ machine $m = 3$

$$\text{Input to motor} = 3 V_{ph} I_{ph} \cos \Phi \times 10^{-3} \text{ -----(2)}$$

$$\text{Assuming } V_{ph} = E_{ph}$$

$$\begin{aligned} V_{ph} = E_{ph} &= 4.44 f \Phi T_{ph} K_w \\ &= 2.22 f \Phi Z_{ph} K_w \text{ -----(3)} \end{aligned}$$

$$\text{ie, } T_{ph} = Z_{ph} / 2$$

$$f = P N_s / 120 = P n_s / 2, \text{ -----(4)}$$

$$P\Phi = B_{av}\pi DL \quad , \quad \Phi = B_{av}\pi DL / P \quad \text{-----}(5)$$

Substitute eu (4) & (5) in euq (3)

$$V_{ph} = 2.22 \times (Pn_s/2) \times (B_{av}\pi DL / P) Z_{ph} K_w$$

$$V_{ph} = 1.11 \times n_s \times B_{av}\pi DL Z_{ph} K_w \quad \text{-----}(6)$$

Sub equ (6) in (2)

$$\text{Input} = 3 \times (1.11\pi DB_{av}Ln_s Z_{ph} K_w) I_{ph} \cos\Phi \times 10^{-3}$$

For IM the specific loading is

$$3I_{ph} Z_{ph} / \pi D = ac$$

$$\text{Input} = 3 Z_{ph} I_{ph} \times (1.11\pi DB_{av}Ln_s K_w) \cos\Phi \times 10^{-3}$$

$$\text{Input} = 1.11\pi \pi Dac D B_{av}Ln_s K_w \cos\Phi \times 10^{-3}$$

$$\text{Input} = 11 B_{av} ac D^2 L n_s K_w \cos\Phi \times 10^{-3} \text{ kW} \text{---(7)}$$

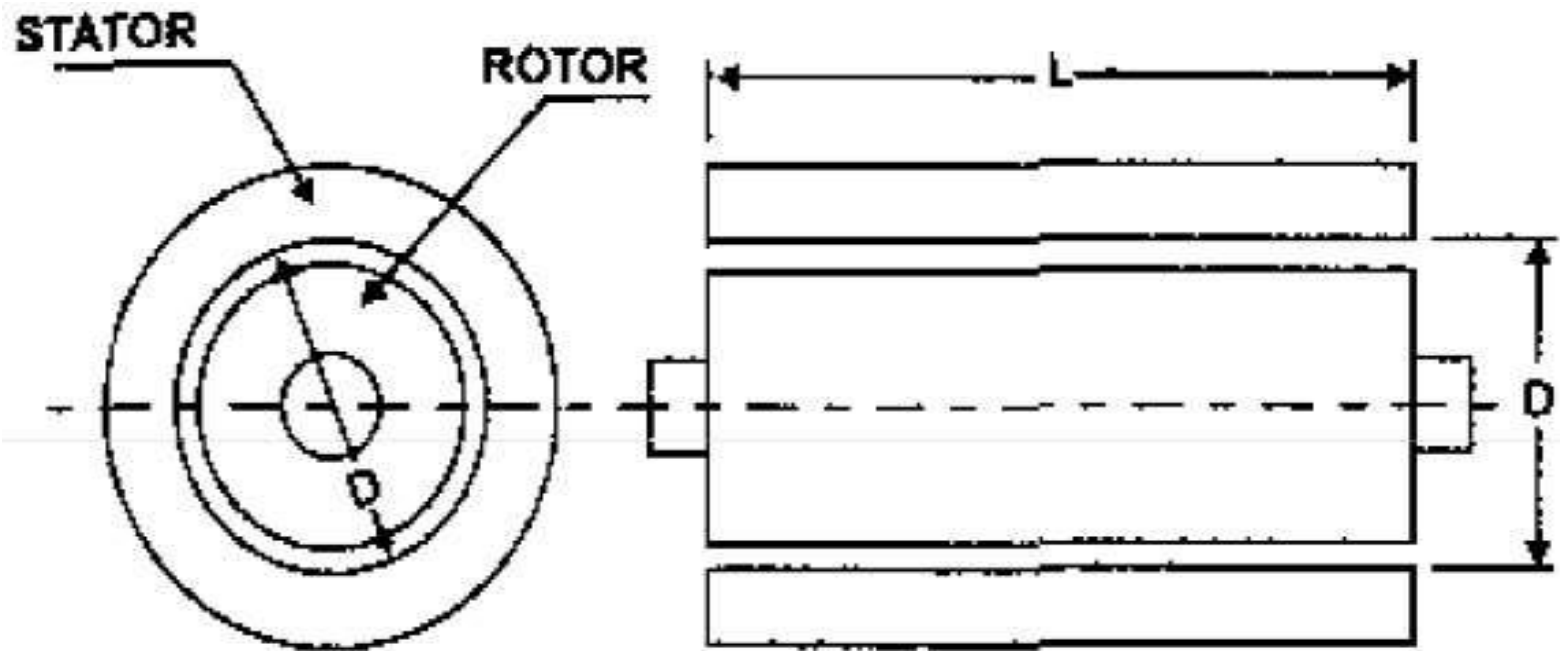
Sub (7) in (1)

$$\text{Output to motor } Q = 11 B_{av} ac K_w \eta \cos\Phi D^2 L n_s \times 10^{-3} \text{ kW}$$

$$\text{Output } Q = C_o D^2 L n_s \text{ kW}$$

$$\text{where } C_o = (11 B_{av} ac K_w \eta \cos\Phi \times 10^{-3})$$

Main dimensions D and L



Separation of D and L

- The output equation gives the relation between D^2L product and **output of the machine**.
- To separate D and L for this product a relation has to be assumed or established.
- Following are the various design considerations based on which a suitable ratio between gross **length** and **pole pitch** (L/τ) can be assumed.
 - i. To obtain **minimum over all cost** 1.5 to 2.0
 - ii. To obtain **good efficiency** 1.4 to 1.6
 - iii. To obtain **good over all design** 1.0 to 1.1
 - iv. To obtain **good power factor** 1.0 to 1.3

- As power factor plays a very important role the performance of induction motors it is **advisable** to **design an induction motor** for **best power factor** unless specified.
- Hence **to obtain** the **best power factor** the following relation will be usually assumed for separation of D and L.

Pole pitch/ Core length = **0.18/pole pitch** or

$$(\pi D/p) / L = 0.18 / (\pi D/p)$$

i.e **$T = \sqrt{0.18L}$** where D and L are in meter.

Peripheral Speed

For the normal design of induction motors the calculated diameter of the motor should be such that the peripheral speed must be **below 30 m/s**.

In case of **pecially designed** rotor the peripheral speed can be **60 m/s**.

Ventilating Ducts : **Provided when core length exceeds 100 – 125 mm. The width of Duct – 8 to 10 mm**

Choice of Specific loadings

- **Specific Magnetic loading or Air gap flux density**

Iron losses largely **depend** upon **air gap flux density**

Limitations :

- Flux density in **teeth** < 1.8 Tesla
- Flux density in **core** 1.3 – 1.5 Tesla

Advantages of **Higher value of B_{av}**

- Size of the machine reduced
- Cost of the machine decreases
- Overload capacity increases
- For 50 Hz machine, **0.35 – 0.6 Tesla**. The suitable values of B_{av} can be selected from design data hand book.

Specific Electric loading (q or ac)

- Total armature ampere conductor over the periphery.

Advantages of Higher value of q

- Reduced size
- Reduced cost

Disadvantages of Higher value of q

- Higher amount of copper
- More copper losses
- Increased temperature rise
- Lower overload capacity

Normal range **10000 ac/m – 45000 ac/m**. The suitable values of q can be selected from design data hand book.

Choice of power factor and efficiency

- power factor and efficiency under full load conditions will **increase with increase in rating** of the machine
- Percentage **magnetizing current** and **losses will be lower** for a **larger machine** than that of a smaller machine
- the **power factor** and **efficiency** will be **higher for a high speed machine** than the **same rated low speed** machine because of better cooling conditions
- Squirrel cage – **Efficiency** – 0.72 to 0.91 & **P.F** – 0.66 to 0.9
- Slip ring - **Efficiency** – 0.84 to 0.91 & **P.F** – 0.7 to 0.92

THANK YOU

Design of Synchronous Machine



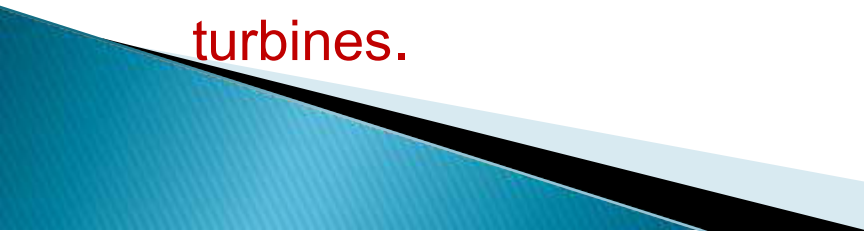
TYPES OF SYNCHRONOUS MACHINES

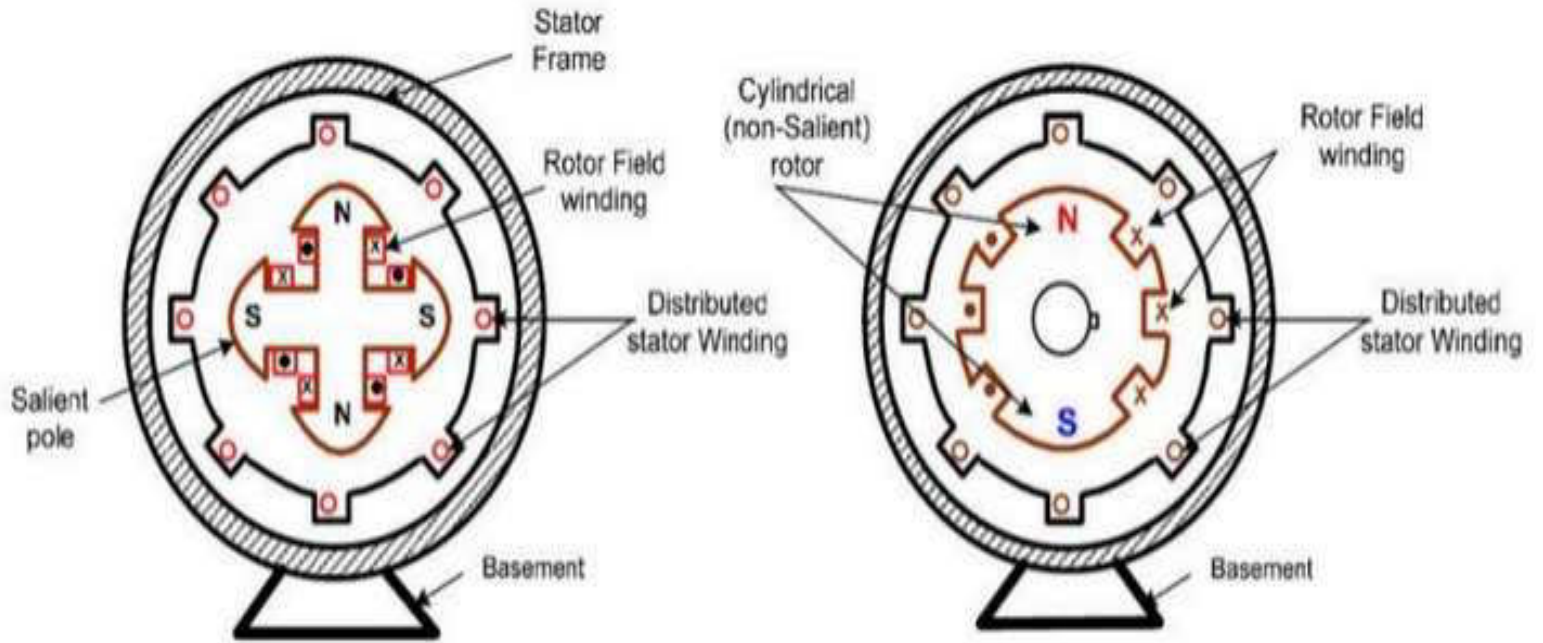
▶ Salient pole Machines

These types of machines have **salient pole** or **projecting poles** with **concentrated** field windings. This type of construction is for the machines which are driven by **hydraulic turbines** or **Diesel engines**.

▶ Non-salient pole or cylindrical rotor or Round rotor Machines:

These machines are having **cylindrical smooth** rotor construction with **distributed** field winding in slots. This type of rotor construction is employed for the machine driven by **steam turbines**.





Salient-Pole

Non-Salient-Pole

OUTPUT EQUATION

V_{ph} = phase voltage

I_{ph} = phase current

E_{ph} = induced emf per phase

Z_{ph} = no of conductors/phase in stator

T_{ph} = no of turns/phase

N_s = Synchronous speed in rpm

n_s = synchronous speed in rps

p = no of poles, q = Specific electric loading

Φ = air gap flux/pole;

B_{av} = Average flux density

k_w = winding factor

Output of the 3 phase synchronous generator is given by

Output of the machine $Q = 3V_{ph}I_{ph} \times 10^{-3} \text{ KVA}$

Assuming Induced emf $E_{ph} = V_{ph}$

Output of the machine $Q = 3E_{ph}I_{ph} \times 10^{-3} \text{ KVA}$

Induced emf $E_{ph} = 4.44 f \Phi T_{ph} K_w$
 $= 2.22 f \Phi Z_{ph} K_w$

Frequency of generated emf $f = PN_s/120 = Pn_s/2,$

Air gap flux per pole $\Phi = B_{av} \pi DL/p,$

Specific electric loading $ac = 3I_{ph}Z_{ph}/\pi D$

Output of the machine

$$Q = 3 \times (2.22 \times Pn_s/2 \times B_{av} \pi DL/p \times Z_{ph} \times K_w) I_{ph} \times 10^{-3} \text{ kVA}$$

$$\text{Output } Q = (1.11 \times B_{av} \pi DL \times n_s \times K_w) (3 \times I_{ph} Z_{ph}) \times 10^{-3} \text{ kVA}$$

Substituting the expressions for Specific electric loadings

$$\text{Output } Q = (1.11 \times B_{av} \pi D L \times n_s \times K_w) (\pi D a c) \times 10^{-3} \text{ kVA}$$

$$Q = (1.11 \pi^2 D^2 L B_{av} a c K_w n_s \times 10^{-3}) \text{ kVA}$$

$$Q = (1.11 \pi^2 B_{av} a c K_w \times 10^{-3}) D^2 L n_s \text{ kVA}$$

Therefore

$$\text{Output } Q = C_o D^2 L n_s \text{ kVA}$$

$$\text{or } D^2 L = Q / C_o n_s \text{ m}^3$$

$$\text{where } C_o = (11 B_{av} a c K_w \times 10^{-3})$$

Output equation

- ▶ The output equation of an AC machine is given by

$$Q = C_o D^2 L n_s$$

- ▶ Where, $C_o = 11 B_{av} ac K_{ws} \times 10^{-3}$

Q=kVA output for alternator and kVA input for synchronous motor

D=Diameter of stator core, m

L=length of the stator, m

n_s =synchronous speed, rps

B_{av} =specific magnetic loading, Wb/m²

ac =specific electric loading, amp.cond./m

K_{ws} =stator winding factor

Design of salient pole machines

- ▶ When round poles are used the ratio of pole arc to pole pitch b_s/τ is between 0.6 to 0.7.

- ▶ For round poles with square pole shoes,

Length of pole(L) = Width of pole shoe (b_s)

The ratio, $L/\tau = 0.6$ to 0.7

$L =$ Length of pole = Length of stator core

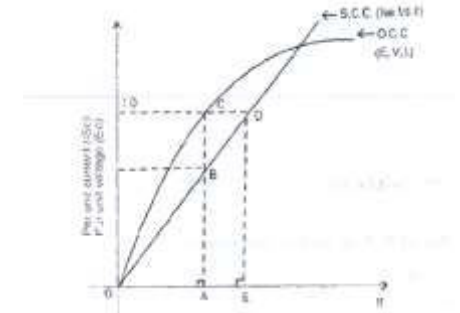
- ▶ For rectangular poles, pole arc/pole pitch varies between 1 to 5.

(i.e) $L/\tau = 1$ to 5

Short circuit ratio (SCR)

$$\text{SCR} = \frac{\text{field current for OC volt}}{\text{field current for SC current}}$$

$$\text{SCR} = \frac{OF_0}{OF_s}$$



- ▶ OF_0 = per unit field current required to develop rated voltage on open circuit
- ▶ OF_s = per unit field current required to develop rated current on short circuit
- ▶ Direct axis reactance, $X_d = \frac{\text{pu volt}}{\text{pu SC current}}$

$$\text{SCR} = \frac{1}{X_d}$$

Length of air gap

- ▶ For salient pole machines of normal construction and having open type slots,

$$\frac{\text{Length of air gap}}{\text{Pole point}} = \frac{l_g}{\tau} = 0.01 \text{ to } 0.015$$

l_g = Length of air gap at the centre of poles

$$\frac{\text{Length of air gap}}{\text{Pole point}} = \frac{l_g}{\tau} = 0.02$$

- ▶ For synchronous motors designed with maximum output equal to 1.5 times rated output,

Estimation of Air-gap using SCR

- ▶ The air gap can also be estimated from short circuit ratio.

$$\text{mmf required for air gap} = 800,000 B_g K_g l_g$$

- ▶ Also mmf required for air-gap is approximately equal to 80% of no-load field mmf.

- ▶ Let, AT_{fo} = Field mmf no-load

$$\text{mmf required for air gap} = 0.8 AT_{fo}$$

- ▶ On equating the two equations for mmf we get,

$$800,000 B_g K_g l_g = 0.8 AT_{fo}$$

$$l_g = \frac{0.8 AT_{fo}}{800,000 B_g K_g} = \frac{0.8 AT_{fo}}{B_g K_g \times 10^6}$$

- ▶ We know that,

$$B_g = \frac{B_{av}}{K_f}$$

- ▶ $AT_{fo} = AT_a \times SCR$

$$AT_a = 2.7 \frac{I_p T_{ph} K_{ws}}{p}$$

Where, AT_a = Armature mmf per pole

I_p = current per phase

T_{ph} = turns per phase

K_{ws} = winding factor of stator

K_f = Form factor

On substituting the expression for AT_{fo} and B_g in the equation

for l_g we get,

$$l_g = \frac{AT_a \times SCR \times K_f}{B_{av} \times K_g \times 10^6}$$

Armature design

Number of armature slots

- ▶ The usual values of stator slot pitch y_{ss} are given below.

$y_{ss} \leq 25$ mm for low voltage machines

$y_{ss} \leq 40$ mm for 6kV or low voltage machines

$y_{ss} \leq 60$ mm for machines upto 15 kV

- ▶ In salient pole machines, the number of stator slots per pole per phase is usually between 2 to 4.

Turns per phase

- ▶ The flux per pole, $\phi = B_{av} \tau L$
- ▶ If number of parallel paths per phase = 1, then,
- ▶ Turns per phase,
$$T_{ph} = \frac{E_{ph}}{4.44 \phi f K_{ws}}$$
- ▶ If number of parallel paths per phase = a, then,
- ▶ Turns per phase,
$$T_{ph} = \frac{E_{ph} \times a}{4.44 \phi f K_{ws}}$$

Armature conductors

▶ Current per phase, $I_{ph} = \frac{kVA}{3E_{ph} \times 10^{-3}}$

▶ If number of parallel path per phase=1, then,

Current through a conductor, $I_z = I_{ph}$

▶ If number of parallel path per phase=a, then,

Current through a conductor, $I_z = I_{ph} / a$

▶ The area of cross-section of armature conductor can be estimated by assuming a suitable current density.

▶ The range of current density, $\delta_a = 3$ to 5 A/mm^2

Area of cross-section of armature conductor, $a_a = I_z / \delta_a$

Design of turbo alternators

- ▶ In turbo-alternators the diameter is limited by the maximum peripheral speed, V_a

$$\text{Peripheral speed, } V_a = \pi D n_s$$

$$\text{Diameter, } D = V_a / (\pi n_s)$$

- ▶ The output equation of ac machine can be modified by using the above relation,

$$\text{The kVA rating (or) Output kVA, } Q = C_o D^2 L n_s$$

$$\text{Where, } C_o = 11 B_{av} a c K_{ws} \times 10^{-3}$$

- ▶ Substitute, $D = V_a / (\pi n_s)$ and the expression for C_o in the equation for Q

$$Q = 11 B_{av} a c K_{ws} \times 10^{-3} \left(\frac{V_a}{\pi n_s} \right)^2 L n_s$$

$$Q = 1.11 B_{av} a c K_{ws} \frac{V_a^2}{n_s} L \times 10^{-3}$$

- ▶ The value of specific loading for conventionally cooled alternators are

$$B_{av} = 0.54 \text{ to } 0.65 \text{ Wb/m}^2$$

$$ac = 50000 \text{ to } 75000 \text{ amp.cond./m}$$

- ▶ The specific loadings used in large water cooled alternators are

$$B_{av} = 0.54 \text{ to } 0.65 \text{ Wb/m}^2$$

$$ac = 180000 \text{ to } 200000 \text{ amp.cond./m}$$

Length of air gap

- ▶ The length of armature can be estimated from the ratio $l_g / \tau = 0.02$ to 0.025.

$$\text{mmf required for air gap} = 800,000 B_g K_g l_g$$

- ▶ Also, mmf for air-gap = 80% of no-load field mmf (AT_{fo})

$$\text{Here, } AT_{fo} = AT_a \times SCR ; \quad AT_a = \mathbf{ac} (\tau/2);$$

- ▶ $SCR = 0.5$ to 0.7 for turbo-alternators and $B_g = B_{av} / K_f$
- ▶ On equating the two equations for mmf we get,

$$800,000 B_g K_g l_g = 0.8 AT_{fo}$$

$$800,000 B_g K_g l_g = 0.8 \times AT_a \times SCR$$

$$800,000 B_g K_g l_g = 0.8 \times SCR \times \mathbf{ac} (\tau/2)$$

$$I_g = \frac{0.8 \times \text{SCR} \times \text{ac} \left(\frac{\tau}{2}\right)}{800000 K_g B_g} = \frac{0.5 \times \text{SCR} \times \text{ac} \tau}{K_g B_g \times 10^6}$$

- ▶ Substitute, $B_g = B_{av} / K_f$ in above equation

$$I_g = \frac{0.5 \times \text{SCR} \times \text{ac} \tau \times 10^{-6}}{K_g B_{av} / K_f} = \frac{0.5 \times \text{SCR} \times \text{ac} \tau \times K_f \times 10^{-6}}{K_g B_{av}}$$

THANK YOU

