UNIT - I

ELECTRICAL MACHINE DESIGN – SEE1304

SEE1304 – ELECTRICAL MACHINE DESIGN

Unit 1 – General Concept of Machine Design

What is mean by design

- Design means furnishing data for the manufacturer of the machine or apparatus to suit a given specification using available material economically

Major Considerations to evolve a good design

- Cost
- Durability
- Compliance with performance criteria as laid down in specifications.

Limitations in Design

- Apart from availability of suitable materials, facilities available for manufacture of required for transportation, the following considerations impose limitations in design.
  - ✓ Saturation
  - ✓ Temperature rise
  - ✓ Insulation
  - ✓ Efficiency
  - ✓ Mechanical parts
  - ✓ Commutation
  - ✓ Power Factor
  - ✓ Consumers specifications
  - ✓ Standard specification

STANDARD SPECIFICATIONS :

- The standard specifications are the specifications issued by the standard organization of a country.
- The standard specifications serve as guideline for the manufacturers to produce quality products at economical prices.

The standard specifications for electrical machines include,

- ✓ Ratings,
- ✓ Types of enclosure
- ✓ Dimensions of conductors
- ✓ Name plate details
- ✓ Performance specifications
- ✓ Permissible temperature rise
- ✓ Permissible loss
- ✓ Efficiency, etc.

Name plate of a rotating machines :

- As per ISI specifications
  - ✓ KW or KVA rating of the machine
  - ✓ Rated working voltage
  - ✓ Operating speed
  - ✓ Full load current
  - ✓ Class of insulation
  - ✓ Frame size
  - ✓ ISI specification number
  - ✓ Manufacturers name
  - ✓ Serial number of the product

Example for Indian Standard Specifications for transformer

- IS 1180 – 1989 : Specifications for out door 3 phase distribution transformer up 100 KVA
- IS 2026 – 1972 : Specifications for Power Transformers

Example for Indian Standard Specifications for Induction Motor

- IS 325 – 1966 : Specifications for 3 phase Induction motor
- IS 996 – 1979: Specifications for 1 phase AC and Universal motor

BASIC MATERIALS USED IN THE CONSTRUCTION OF MACHINES

The various material used can be classified under three heads,

- Conducting material
- Magnetic material
- Insulating material

Properties require of these materials :

- **Electrical Properties** : Conductivity, Electrical resistivity, dielectric constant and dielectric strength.
- **Mechanical Properties** : Strength, Hardness, Toughness, Hardenability, Brittleness, Ductility.
- **Thermal Properties** :Thermal conductivity and thermal expansion.
- **Chemical Properties** : Resistance to correction and oxidation.
- **Optical Properties** : Refraction, Polarization, Diffraction, Dispersion. Absorption, Transmittance.

CONDUCTING MATERIALS

These materials are used for manufacturing all types of windings required in electrical machines, apparatus and devices, as well as for transmission and distribution of electric energy. These materials should have the least possible resistivity

Properties requirements of High Conductivity Materials

- Highest possible conductivity (Least resistivity)
- Least possible temperature coefficient of resistance
- Adequate mechanical strength, in particular, high tensile strength and elongation characterizing to a certain degree of the flexibility
- Rollability and draw ability which is important in the manufacture of wires of small intricate sections.
- Good weldability and solderability which ensure high reliability and low electrical resistance of the joints.
- Adequate resistance to corrosion.

Example : Copper, Aluminimum, Iron and steel, Copper silver alloy, Alloys of copper – Bronze, Beryllium copper, Brass, etc.

MAGNETIC MATERIALS

They are Iron, Cobalt, Nickel, and Gadolinium. The magnetic properties of these materials are due to the spinning and orbital motion of Electrons around the Nucleus. When the spin motion is in one direction a large magnetic field is produced, while opposing spin reduces it.

Properties requirements of magnetic materials

- Highest possible permeability
- Should have very high resistivity
- Should have low Hysteresis loss

Classification of Magnetic Materials

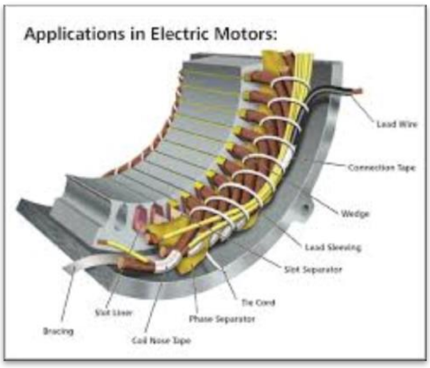
- Diamagnetic materials
- Para magnetic materials
- Ferro magnetic materials
- Anti Ferro magnetic materials
- Ferric magnetic materials

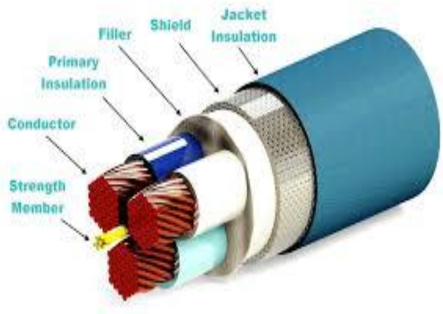
INSULATING MATERIALS

The material which does not allow the electricity to pass through them is known as an electrical insulating material.

The charge of the insulating material does not move freely, or in other words, it provides the high resistive path to the electric current through which it is nearly impossible for the electric current to conduct through it.

It is used in the conductor for preventing the flow of electric current from the conductor to earth





Properties requirements of Insulating materials

- The material must have high insulation resistance for preventing the flow of leakage current from the conductor to earth
- They must have high dielectric strength.
- They must have high mechanical strength
- They must have good heat conductivity
- They should with stand alternating heat cycle
- They must have high melting point
- They should not vaporize easily
- The electrical and chemical property of the material should not be affected by the temperature

Classification of Insulating materials

I. Solid Type Insulating Materials

- Fibrous Materials – They are derive from animal origin or from cellulose (plants)
  eg. Paper, Wood, Card board, Cotton, Jute, etc.
- Plastic Materials – In is an organic material and they are may be either natural or synthesis resins.
  Eg. PTFE (Poly Tetra Fluoro Ethylene)
- Rubber Materials – They may be natural, synthetic, hard rubber or silicon rubber
- Mineral Materials – Mica, Glass, Marbles, etc
- Ceramic Materials – Clay, Quartz, Porcelain, etc
- Glass Materials – Soda line glass, high silica glass, lead glass

II. Liquid Insulating Materials

Mostly mineral oils are used. They should have the following properties

- non inflammable
- non slugging
- Should have high permittivity
- Good cooling properties

Example : Transformer oil, mineral oil, Vegetable Oils, Wax, Silicone Oils, etc.

III. Gaseous Insulating materials

Air, Hydrogen, Nitrogen, Inert gases like Argon (Ar), Neon (Ne), Helium (He) and Sulfur hexafluoride (SF_6) etc.

Classification of Insulating materials based on temperature rise

CLASS	MAX TEMP RISE IN °C	APPLICATION	NATURE OF COMBINATION OF MATERIALS
γ	90	Electrical Apparatus	Cotton, Silk, Paper, Wood, Natural Rubber, etc.
A	105	Mainly used in electric machine	Impregnated cotton, silk, paper with suitable
E	120	Electric machine	Same as above but should be able to withstand temperature up to 120°C
B	130	Commutator, winding of slots, capacitor	Mica, Glass, Fiber, etc with suitable bonding materials
F	155	Same as above with higher capacity	Same as above but should be withstand temperature up to 155 °C.
H	180	Traction motor, Transformers	Silicon, combination of mica glass fiber, etc with suitable bonding materials.
C	ABOVE 180	Large rating alternators	Mica, Glass, Quartz and other materials with can with stand temperature above 180°C

MAGNETIC CIRCUITS

- The magnetic circuit is the path of magnetic flux. The mmf of the circuit creates flux in the path by overcoming the reluctance of the path.
- The magnetic circuit is analogous to an electric circuit. In electric circuit the emf circulated current against resistance when a closed path is provided. Similarly, in a magnetic circuit the mmf created flux in a closed path against reluctance of the part.

mmf

A coil wound on an iron core with N turns and carrying a current of I Amperes, then mmf is given by the product of number of turns and current.

mmf = NI (Ampere Turns)

Relation between Flux, mmf & Reluctance

Flux = mmf / Reluctance

$\boxed{\phi = \frac{AT}{S}}$ or $\boxed{\phi = AT \times \wedge}$ where $\wedge$ = Permeance

The reluctance of the magnetic material can be estimated fusing the following equation

Reluctance, $\boxed{S = \frac{length}{area} \times \frac{1}{Permeability} = \frac{l}{A\mu}}$

where, μ = Permeability of the magnetic material

$\mu = \mu_r \mu_0$

μ_r = Relative permeability

$\mu_0 = 4\pi \times 10^{-7}$ H/m = Absolute permeability of free space.

The strength of the magnetic field is measure by the term magnetizing force, H. It is the mmf required to establish flux in a unit length of magnetic path.

magnetizing force, H = mmf per unit length = flux x reluctance per unit length

$$H = \phi \frac{1}{l}\frac{l}{A\mu} = \frac{\phi}{A\mu} = \frac{B}{\mu} \qquad where, B = \frac{\phi}{A}$$

For the magnetic length of ,l, and carrying a uniform flux, the total mmf AT is

AT = H x l = at x l

In a series magnetic circuit, the total reluctance is the sum of reluctances of individual parts.

Total Reluctance $S = S_1 + S_2 + S_3 + \ldots$

Where $S_1, S_2, S_3, \ldots$ are reluctances of individual parts.

Total mmf, $AT = \phi S$

$= \phi (S_1 + S_2 + S_3 + \ldots)$

$= AT_1 + AT_2 + AT_3 + \ldots\ldots$

$= at_1 l_1 + at_2 l_2 + at_3 l_3 + \ldots\ldots$

$= \phi$ at l

The above equation represent the circuital law for magnetic circuits, where at_1, at_2, at_3 are the mmf per meter for the individual part and l_1, l_2, l_3 are lengths of parts connected in series.

In Parallel circuits, the same mmf is applied to each of the parallel paths and the total flux divides between the paths in inverse proportion to their reluctances.

In parallel circuits,

Total flux, $\phi = \phi_1 + \phi_2 + \phi_3 + \ldots$

$$\frac{\phi}{At} = \frac{\phi_1}{At} + \frac{\phi_2}{At} + \frac{\phi_3}{At} + \ldots..$$

$$\frac{1}{S} = \frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} + \ldots..$$

$$\wedge = \wedge_1 + \wedge_2 + \wedge_3 + \ldots..$$

Where, S = Total reluctance of magnetic circuit.

S_1, S_2, S_3 ,… are reluctances of individual parts

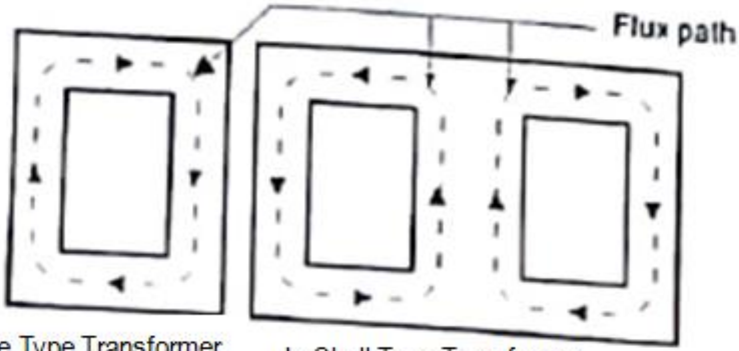
$\wedge$- Total permeance of magnetic circuit.

$\wedge_1$, $\wedge_2$, $\wedge_3$ - permeance of individual parts

Comparison between Electric Circuit & Magnetic Circuit

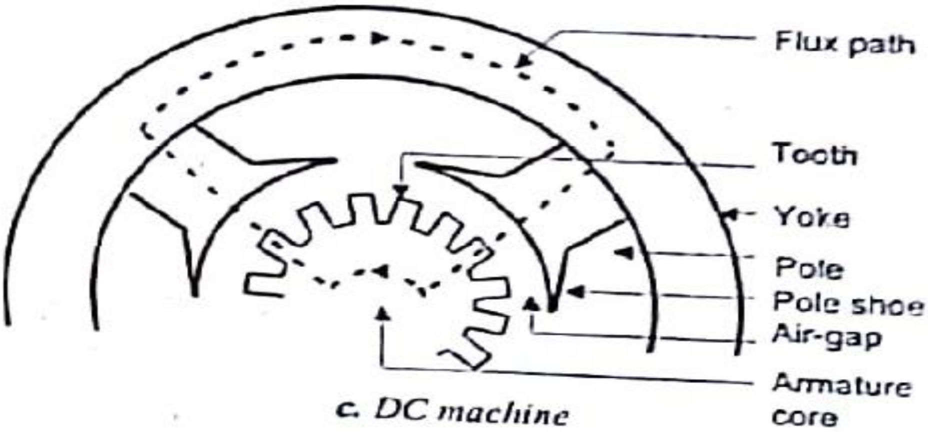
Electrical Circuit	Magnetic Circuit
The emf circulates current in closed path	The mmf creates flux in a closed path
Flow of current is opposed by resistance of the circuit	The creation of flux is opposed by reluctance of the circuit
The path of current is called electric circuit	The path of flux is called magnetic circuit.
Resistance, R = ρl / A	Reluctance S = $l/\mu A$
Current = emf / Resistance	Flux = mmf / Reluctance
Current Density δ = Current / Unit Area	Flux Density, B = Flux / Area of cross section

MAGNETIC CIRCUITS – FLUX PATH IN ELECTRIAL MACHINES

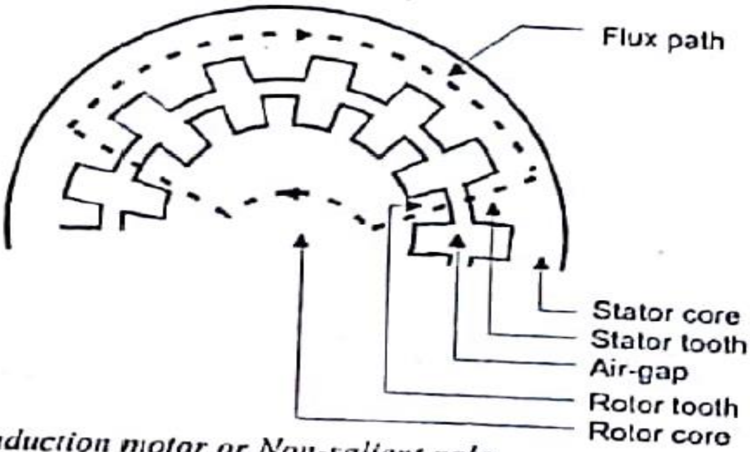


a. Core Type Transformer

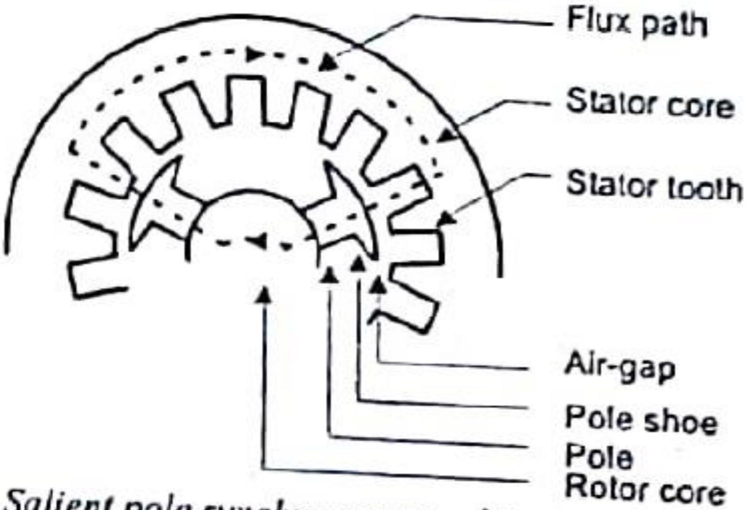
b. Shell Type Transformer



c. DC machine



d. Induction motor or Non-salient pole synchronous machine



e. Salient pole synchronous machine

RELUCTANCE OF AIR GIR IN MACHINES

1. With Smooth Armature :

- The rotating machines will have a small air-gap between armature and pole surface.
- Smooth armature surfaces are possible only if the armature has closed slots.

L = Length of core

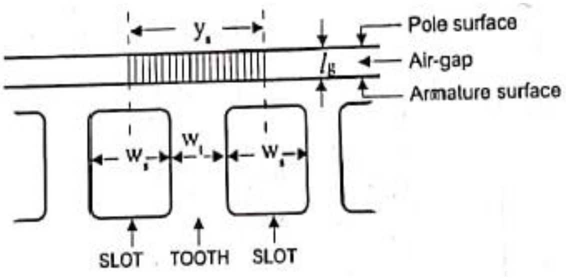
l_g = air gap length

y_s = slot pitch

W_s = width of slot

W_t = width of teeth

$y_s = W_t + W_s$



Consider the armature with closed slots, the flux is uniformly spread over the entire slot pitch and goes straight across the air gap

The reluctance, S of a magnetic path is given by $= l / \mu A$

Where, l = Length of magnetic path

μ = Permeability of the medium

A = Area of cross section of the magnetic path.

Consider the area of cross section of the magnetic path over one slot of the armature. It is given by the product of length of armature and slot pitch.

Hence the reluctance of air gap can be given as, $\boxed{S_g = \frac{l_g}{\mu_0 L y_S}}$

Where S_g = reluctance of air gap

l_g = length of air gap

μ_o = permeability of air

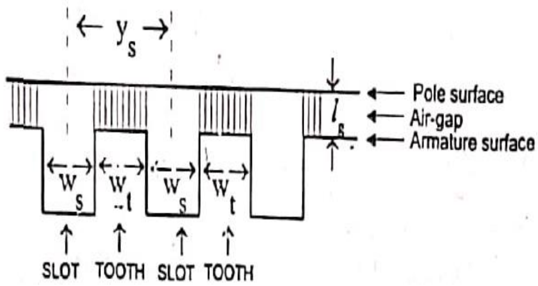
$L\,y_s$ = area of cross section of air gap over one slot.

2. With Open Armature :

- In armature with open and semi enclosed slots, the flux will flow through the teeth of the armature.
- Hence the effective area of flux path is decreased, which results in increased reluctance in air gap.

a. Reluctance of air gap neglecting fringing effect :

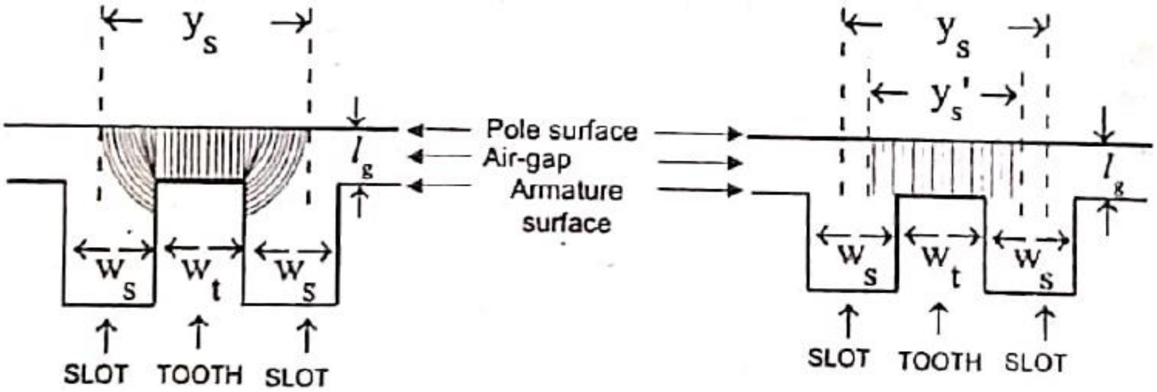
- In open type slots, consider the flux is only confined to the width of teeth.
- Area of cross section of air gap through which the flux passes is L (y_s-w_s) or L w_t.
- Hence the reluctance of air gap in machines with open armature slots



$$\boxed{S_g = \frac{l_g}{\mu_0 L (y_S - W_S)}}$$

Note : This is applicable only if the fringing of the flux is neglected.

b. Reluctance of air gap including the effect of fringing :



- In the case of armature with open type slots, the flux would fringe around the teeth and this fringing would increase the area of cross section of flux path.
- Consider the open type slots of armature, the fringing of flux around the teeth increasing the area of cross section of flux path by δW_s.
- Assume the air gap flux is uniformly distributed over the whole slot pitch except for a fraction of slot width.
- i.e. flux distributed over one slot pitch is given by $W_t + \delta W_s$.
- Effective slot pitch, $y_s' = W_t + \delta W_s$
- By adding and subtracting W_s,

$$y_s' = W_t + \delta W_s + W_s - W_s$$

$$y_s' = y_s + \delta W_s - W_s$$

$$y_s' = y_s + W_s (\delta - 1)$$

$$y_s' = y_s - (1 - \delta) W_s$$

$$\boxed{y_S' = y_S - K_{cd} w_s}$$

Where K_{cs} = Carter's gap co-efficient for slots.

Hence the reluctance of air gap in machines with open armature slots

$$\boxed{S_g = \frac{l_g}{\mu_0 L y_S'}} \quad \text{or} \quad \boxed{S_g = \frac{l_g}{\mu_0 L (y_S - K_{CS} W_S)}}$$

GAP CONTRACTION FACTOR FOR SLOTS K_{gs}

The gap contraction factor for slots is defined as the ratio of reluctance of air gap in machine with open armature slot to reluctance of air gap machine with smooth armature.

$$K_{gs} = \frac{\text{Reluctance of air gap in machine with open armature slot}}{\text{Reluctance of air gap machine with smooth armature.}}$$

$$K_{gs} = \frac{\dfrac{l_g}{\mu_0 L (y_S - K_{CS} W_S)}}{\dfrac{l_g}{\mu_0 L y_S}} = \frac{l_g}{\mu_0 L (y_S - K_{CS} W_S)} \times \frac{\mu_0 L y_S}{l_g} = \frac{y_S}{y_S - K_{CS} W_S}$$

$$\boxed{K_{gs} = \frac{y_S}{y_S'}}$$

CARTERS GAP COEFFICIENT FOR SLOTS K_{CS}

The Carter's gap coefficient for slots K_{cs} depends on the ratio of slot opening to gap length

$$K_{CS} = \frac{1}{1+5\frac{l_g}{W_0}}$$

Where W_0 = Slot opening.

($W_0 = W_s$ in open type slot).

EFFECT OF VENTILATING DUCTS IN RELUCTANCE OF AIR GAP

When the length of the armature is higher than the diameter or when the length is greater than 0.1 m, radial ventilating ducts are provided for better cooling of the armature core.

The radial ventilating ducts are small gaps of width Wd in between the stacks of armature core.

The core is normally divided into stacks of 40 – 80 mm thick, with ventilating ducts of width 10 mm in between two stacks

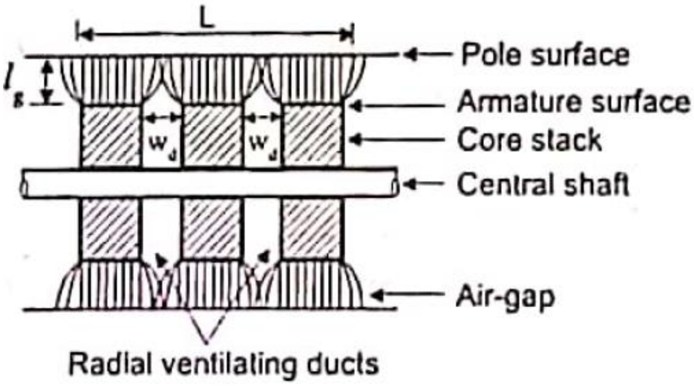
The provision of radial ventilating ducts results in contraction of flux in the axial length of the machine is reduced and this results in an increase in the reluctance of air gap.

Effective axial Length $L' = L - K_{cd} n_d w_d$

Where, K_{cd} = Carter's co-efficient for ducts

n_d = number of ducts

W_d = width of ducts



The reluctance of air gap in machines with smooth armature slots and with ventilating duct

$$S_g = \frac{l_g}{\mu_0 L' y_S}$$

The reluctance of air gap in machines with open armature slots and with ventilating duct

$$S_g = \frac{l_g}{\mu_0 L' y_S'}$$

CARTERS GAP COEFFICIENT FOR DUCTS K_{cd}

The Carter's gap coefficient for ducts K_{cd} depends on the ratio of width of duct to gap length

$$K_{Cd} = \frac{1}{1+5\frac{l_g}{W_d}}$$

Where W_d = Width of duct

GAP CONTRACTION FACTOR FOR DUCT K_{gd}

The gap contraction factor for ducts is defined as the ratio of reluctance of air gap in machine with radial ducts to reluctance of air gap machine without armature radial ducts.

$$K_{gd} = \frac{\text{Reluctance of air gap in machine with radial ducts}}{\text{Reluctance of air gap machine without radial ducts}}$$

$$K_{gd} = \frac{\dfrac{l_g}{\mu_0 L' y_S}}{\dfrac{l_g}{\mu_0 L y_S}} = \frac{l_g}{\mu_0 L' y_S} \times \frac{\mu_0 L y_S}{l_g} \qquad \boxed{K_{gd} = \frac{L}{L'}}$$

TOTAL GAP CONTRACTION FACTOR K_g

The gap contraction factor Kg is defined as the ratio of reluctance of air gap in machine with slotted armature and radial ducts to reluctance of air gap machine with smooth armature and without armature ducts.

$$K_g = \frac{\text{Reluctance of air gap in machine with slotted armature and radial duct}}{\text{Reluctance of air gap machine with smooth armature and without ducts}}$$

The gap contraction factor

$$K_g = \frac{\dfrac{l_g}{\mu_0 L' y_S'}}{\dfrac{l_g}{\mu_0 L y_S}} = \frac{l_g}{\mu_0 L' y_S'} \times \frac{\mu_0 L y_S}{l_g} = \frac{L}{L'} \frac{y_S}{y_S'}$$

$$\boxed{K_g = K_{gs} K_{gd}}$$

The gap contraction factor is the product of gap contraction factor for slots and ducts.

TOTAL GAP CONTRACTION FACTOR FOR INDUCTION MOTOR

In Induction motor both the rotor and stator has slots.

Therefore the gap contraction factor should be computed for both the stator and the rotor.

$$\boxed{K_{gs} = K_{gss} K_{gsr}}$$

Where, K_{gs} = Total gap contraction factor for slots

K_{gss} = Gap contraction factor for stator slots

K_{gsr} = Gap contraction factor for rotor slots

In Induction motor, the total gap contraction factor is given by the product of gap contraction factor for stator and rotor.

mmf FOR AIR GAP

Non magnetic materials have a constant value of permeability and so the B-H curve for them is a straight line passing through the origin.

mmf per meter path in non magnetic material $at_g = \dfrac{B}{\mu_0} = \dfrac{B}{4\pi \times 10^{-7}} = 800{,}000B$ AT/ m

Where, B = Flux density in the non magnetic material

μ_0 = Permeability of non magnetic material

mmf per meter for air gap $at_g = \dfrac{B_{av}}{\mu} = \dfrac{B_{av}}{4\pi \times 10^{-7}} = 800{,}000B_{av}$

Where, B_{av} = Average Flux density in the air gap

$\mu = \mu_0 = 4\pi \times 10^{-3}$ H/m - Permeability of air gap

If l_g is the length of air gap, then

mmf per meter for air gap of length l_g in machines with smooth armature is given by,

$$\boxed{AT_g = 800{,}000B_{av}l_g}$$

mmf of air gap in machines with open armature slot and radial ventilating ducts

The reluctance of air gap in machines with open armature slots is higher than with smooth armatures.

The mmf required for air gap in machines with open armature slot is Kg times the mmf required for air gap in machines with smooth armature.

mmf required for air gap in machines with open armature slot and ducts

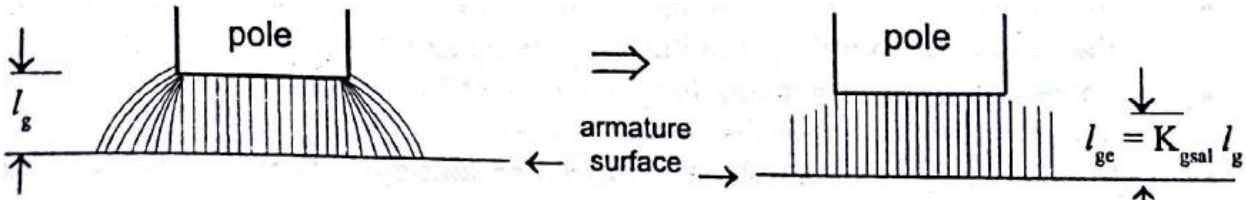
$$AT_g = K_g \times 800{,}000B_{av}l_g$$

$$\boxed{AT_g = 800{,}000B_{av}K_g l_g}$$

Effect of Saliency on the mmf for air gap

In the case of salience pole machines, the length of air gap is not constant over the whole pole pitch.

To find the mmf in this case, we c of an consider the length of air gap as an effective gap given by $K_{gsal}\,l_g$, where K_{gsal} is the gap contraction factor for salient poles.



mmf required for air gap in salient pole machines $\boxed{AT_g = 800{,}000B_g K_g l_g}$

Where, $K_g = K_{gs}K_{gd}K_{gsal}$

K_g is the total gap contraction factor for including the effect of saliency

Field Form Factor K_f

Field form factor, K_f = $\dfrac{\text{Average gap density over the pole pitch}}{\text{Maximum flux density in the air gap}}$

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

$$\boxed{K_f = \psi = \frac{Pole.arc}{Pole.ptich}}$$

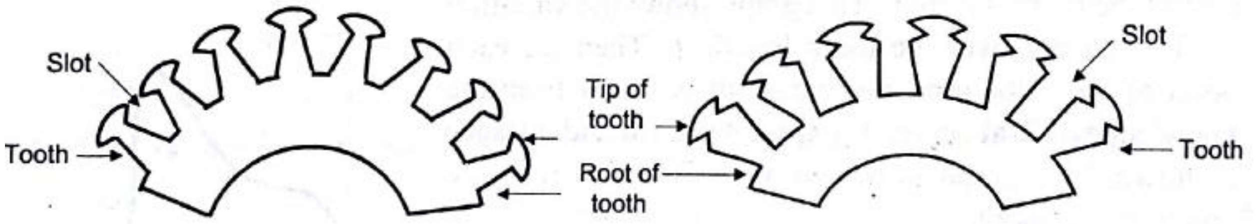
$$\boxed{B_g = \frac{B_{av}}{K_f} = \frac{B_{av}}{\psi}}$$

mmf FOR TEETH

The mmf required for teeth depends on area of cross section of the tooth and flux passing through it.

The area of cross section depends on dimensions of teeth.

Dimension intern depends on the type of slot.



Different dimension of teeth

Different method for calculation of mmf required for teeth

- Graphical Method
- Three Ordinate method (Simpson's rule)
- $B_{t1/3}$ method

Graphical Method

- Flux density at various sections of the teeth are determined
- The flux density at any section of teeth, $\boxed{B_t = \dfrac{\phi}{n_t A_t}}$

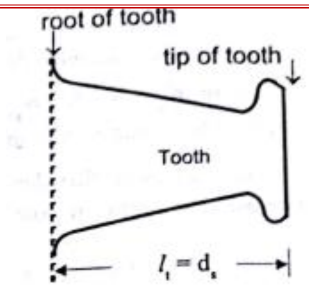
Where B_t = Flux density of the teeth corresponding to A_t

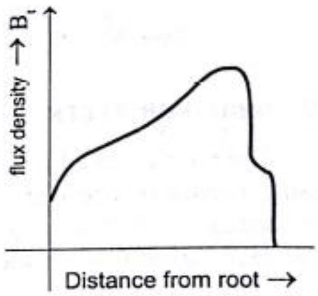
ϕ = Flux per pole

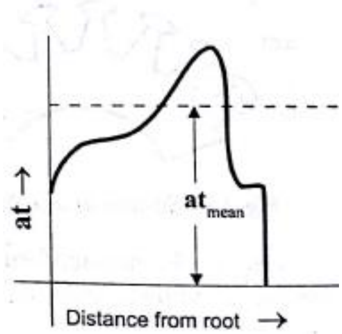
n_t = number of teeth under a pole

A_t = Area of cross section of teeth at the desired section

- A graph drawn between flux density and the distance from the root of the teeth.
- This graph shows the variation of flux density over the length of the teeth l_t.
- Then each point of the teeth mmf / m, at is found from BH curve.
- A graph drawn between mmf / m (at) and distance from the root of the teeth.
- This graph shows the variation of at over the length of the teeth.
- The mean ordinate of this graph gives the equivalent at for the whole teeth.







$$at_{mean} = \text{mean ordinate} = \int at\ .dl$$

$$At_t = at_{mean} \text{ x } l_t = at_{mean} \text{ x } d_s$$

Where l_t = length of teeth

d_s = depth of slot ($l_t = d_s$)

AT_t = total mmf for the teeth.

Three Ordinate Method (Simpson's Rule)

- This method can be applied to teeth of very sinple form and of a small taper.
- It is based on the assumption that the curve relating mmf per meter, at with flux density is a parabola.
- Flux density and mmf / m, at are chosen at root, centre and tip of the teeth.
- The flux density at any section of teeth, $\boxed{B_t = \frac{\phi}{n_t A_t}}$

Where B_t = Flux density of the teeth corresponding to A_t

ϕ = Flux per pole

n_t = number of teeth under a pole

A_t = Area of cross section of teeth at the desired section

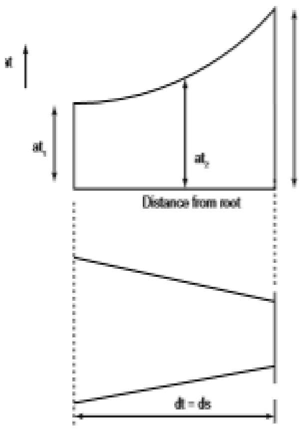
Let at_1 = at for the root of teeth

at_2 = at for the centre of the teeth

at_3 = at for the tip of the teeth

$$\boxed{at_{tmean} = \frac{at_1 + at_2 + at_3}{6}}$$

$$At_t = at_{mean} \text{ x } l_t = at_{mean} \text{ x } d_s$$



Where l_t = length of teeth

d_s = depth of slot ($l_t = d_s$)

AT_t = total mmf for the teeth.

$B_{t1/3}$ Method

- This method is applied to teeth of small tapper.
- It is smple method
- Assumption made : mmf / m, at is obtained for the flux density at a section 1/3 of teeth hight from the narrow ned is at_{mean}.
- Calculate flux density at 1/3 height from narrow end using $\boxed{B_t = \frac{\phi}{n_t A_t}}$

Where B_t = Flux density of the teeth corresponding to A_t

ϕ = Flux per pole

n_t = number of teeth under a pole

A_t = Area of cross section of teeth at the desired section

- From the B H curve find at for this value of flux density.
- This at is denoted as $at_{1/3}$

Total mmf for teeth, $At_t = at_{1/3} \times l_t = at_{1/3} \times d_s$

Where l_t = length of teeth

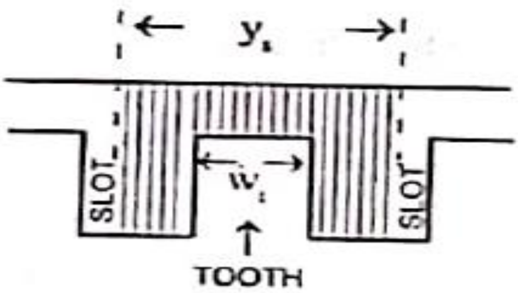
d_s = depth of slot ($l_t = d_s$)

AT_t = total mmf for the teeth.

REAL AND APPARENT FLUX DENSITIES

The apparent flux density is defined as,

$$B_{app} = \frac{\text{Total flux in a slot pitch}}{\text{Teeth area}}$$



The real flux density is defined as,

$$B_{real} = \frac{\text{Actual flux in a teeth}}{\text{Teeth area}}$$

In an actual machine, there are two parallel paths for the flux over one slot pitch. They are iron path of teeth and air & conductor path of slot

Let, ϕ_i = Flux passing through iron (teeth) over a slot pitch

ϕ_a = Flux passing through air (slot) over a slot pitch

y_s = slot pitch

L = Length of slot

L_i = Net iron length

A_a = Area of air path of slot

A_i = Area of iron path of teeth

W_t = Width of teeth

μ_0 = Permeability of air

$\mu_0 = 4\pi \times 10^{-3}$ H/m

ϕ_s = Flux over one slot pitch

$$\phi_S = \phi_i + \phi_a$$

Divide A_i both LHS and RHS

$$\frac{\phi_S}{A_i} = \frac{\phi_i}{A_i} + \frac{\phi_a}{A_i}$$

By definition of real and apparent flux densities,

$$B_{app} = B_{reeal} + \frac{\phi_a}{A_a}\frac{A_a}{A_i}$$

$$B_{app} = B_{reeal} + B_a K \qquad \ldots \ (1)$$

$$where.K = \frac{A_a}{A_i}$$

B_a = Flux density in air

$= \mu_o H$

$= \mu_o at_{real}$ . . . (2)

$\mu_o at_{real}$ = mmf per meter across the teeth for the teeth density B_{real}

A_i = Teeth width x net iron length

$$A_i = W_t L_i \qquad where.L_i = K_i(L - n_d W_d)$$

A_a = Total area - Teeth area

$$A_a = Ly_s - L_i W_t$$

$$\frac{A_a}{A_i} = \frac{Ly_s - L_i W_t}{L_i W_t}$$

$$\frac{A_a}{A_i} = \frac{Ly_s}{L_i W_t} - 1$$

$$\frac{A_a}{A_i} = K_S - 1 \qquad \ldots \ (3)$$

$$where.K_S = \frac{Ly_s}{L_i W_t}$$

Substitute eqn (2) & (3) in (1)

$$\boxed{B_{app} = B_{real} + \mu_0 at_{real}(K_S - 1)} \quad \text{OR} \quad \boxed{B_{real} = B_{app} - \mu_0 at_{real}(K_S - 1)}$$

MAGNETIC AND ELECTRIC LOADINGS

Work done = Force x distance

Consider a conductor of length L, carrying current Iz amperes, if the conductor is moved in a uniform magnetic field of flux density B_{av} wb/m^2, in x distance, then work done is given by,

$$\begin{aligned} workdone &= BIL \times x \\ &= B_{av} I_Z L \times x \\ &= B_{av} L x \times I_Z \\ &= \phi \times I_Z \end{aligned}$$

If ϕ is the flux per pole and there are P number of poles, Z is the total number of armature conductors, then work done is given by,

$$\boxed{workdone = P\phi \times I_Z Z}$$

$P\phi$ = Total magnetic loading

$I_z Z$ = total Electric loading.

The work done in one complete revaluation is given by the product of total magnetic loading and total electric loading

Total Magnetic Loading ($P\phi$)

The total magnetic loading is defined as the total flux available at the armature periphery at the air gap.

Total Electric Loading ($I_Z Z$)

The total electric loading is defined as the total number of ampere conductors around the armature periphery.

Specific Magnetic Loading (B_{av})

The Specific Magnetic Loading is defined as the average value of flux density available at the area of armature surface

$$B_{av} = \frac{\text{Flux per pole}}{\text{Area under a pole}} = \frac{\text{Flux per pole}}{\text{Pole pitch x Length of Armature}}$$

$$B_{av} = \frac{\phi}{\frac{\pi D}{P} \times L} \qquad Polepitch.\tau = \frac{\pi D}{P}$$

$$\boxed{B_{av} = \frac{P\phi}{\pi D L}}$$

Specific Electric Loading (ac)

Specific electric Loading is defined as the average value of armature conductors per meter available at the armature periphery.

$$ac = \frac{\text{Total armature ampere conductors}}{\text{Armature periphery at the air gap}}$$

$$\boxed{ac = \frac{I_Z Z}{\pi D}}$$

Choice of Specific Magnetic Loading (B_{av})

It is determined by

- maximum flux density in the iron parts of the machine (B_m)
- magnetizing current (I_m)
- core loss

(i) Maximum flux density in the iron parts of the machine (B_m)

It must be below a certain limiting value.

ϕ flows through teeth, so maximum flux exist in teeth of armature

$B_m = \dfrac{\phi}{A}$, If A is constant, then $B_m \propto \phi$

$B_{av} = \dfrac{P\phi}{\pi DL}$ P, π. D, L are constant, $B_{av} \propto \phi$

$\therefore$ $B_m \propto B_{av}$

$\therefore$ Choice of B_{av} should be such that B_m should not be exceeded.

Maximum value of Bm is between 1.7 to 2.2. wb/m^2.

(ii) Magnetizing current (I_m)

mmf = NI, if N is constant then mmf $\propto$ I

$\phi = \dfrac{NI}{S}$ if S is constant, then $\phi \propto$ mmf

$\phi \propto B_{av}$ $I_m \propto$ mmf $\propto B_{av}$

If B_{av} increased, mmf increases and so I_m increases.
When I_m is increased in an AC machine the power factor Cosϕ decreases,

P = VI Cosϕ

Reduction of power factoe reduces the efficiency.

(iii) Core loss

Core loss = Hysteresis loss + Eddy current loss.

$= W_h + W_e$

$$W_h = \eta B_{max}^{1.6} fV \qquad W_h \propto B_{max}^{1.6}$$

$$W_e = KB_{max}^{2} f^3 V^2 t^2 \qquad W_e \propto B_{max}^{2}$$

So if value of B_{av} is increases, B_{max} also increases.

If B_{max} increases, then W_h, W_e increases thus increasing core loss.

Similarly, if frequency f increases, then losses increases.

So, for high speed & high frequency AC machine B_{av} must be reduced in order to have low iron loss.

Choice of Specific Electric Loading (ac)

It depends on

- Permissible temperature rise
- Voltage raging of the machine
- size of the machine
- current density.

(i) Permissible temperature rise

- ac value is determined by temperature rise and cooling coefficient,
- High value of ac is used in machine will have high temperature rise.
- Temperature is determined by insulating material used.
- Machine with high quality insulating materials, can with stand high temperature rise and high value of ac can be used.
- High value of ac is used for machines with low cooling coefficient and so high value of ac is used.

(ii) Voltage raging of the machine

- In high voltage machine the thickness of insulation is very high
- So there will be less space for winding due to larger insulation thickness.
- Less winding, so less current and so small value of ac is chosen.

(iii) Size of the machine

- In large size machine, the depth of slot is high.
- So there is a large space for the winding, so high current can flow.
- Hence high value of ac can be used.

(iv) Current density

- For machine lower current density, higher value of ac is used.

UNIT - II

ELECTRICAL MACHINE DESIGN – SEE1304

Unit 2 – DC MACHINES

OUT PUT EQUATION OF DC MACHINE

It is the equation connecting the main dimensions with the specific magnetic and electric loadings.

If Q is the power developed in the dc machine in KW, then

$$Q = EI_a \times 10^{-3}$$

Substituting Emf equation,

$$Q = \frac{\phi NZ}{60}\frac{p}{A} I_a \times 10^{-3}$$

$$Q = \phi nZ \frac{p}{A} I_a \times 10^{-3}$$ Where, $n = \frac{N}{60} in.rps$

$$Q = P\phi nZ \frac{I_a}{A} \times 10^{-3}$$

$$Q = P\phi nZI_Z \times 10^{-3}$$ Where, $I_Z = \frac{I_a}{A}$ current through the conductor

$$Q = (P\phi) \times (I_Z Z) \times n \times 10^{-3}$$ --- (1)

We know that, Specific magnetic loading is

$$\boxed{B_{av} = \frac{P\phi}{\pi DL}}$$

$$P\phi = B_{av}\pi DL$$ ---- (2)

Specific electric loading is $\boxed{ac = \dfrac{I_Z Z}{\pi D}}$

$$I_Z Z = ac\pi D \quad \text{--- (3)}$$

Substitute (2) and (3), in equation (1),

$$Q = (B_{av}\pi DL)\times(ac\pi D)\times n\times 10^{-3}$$

$$Q = \pi^2 B_{av} acD^2 Ln\times 10^{-3}$$

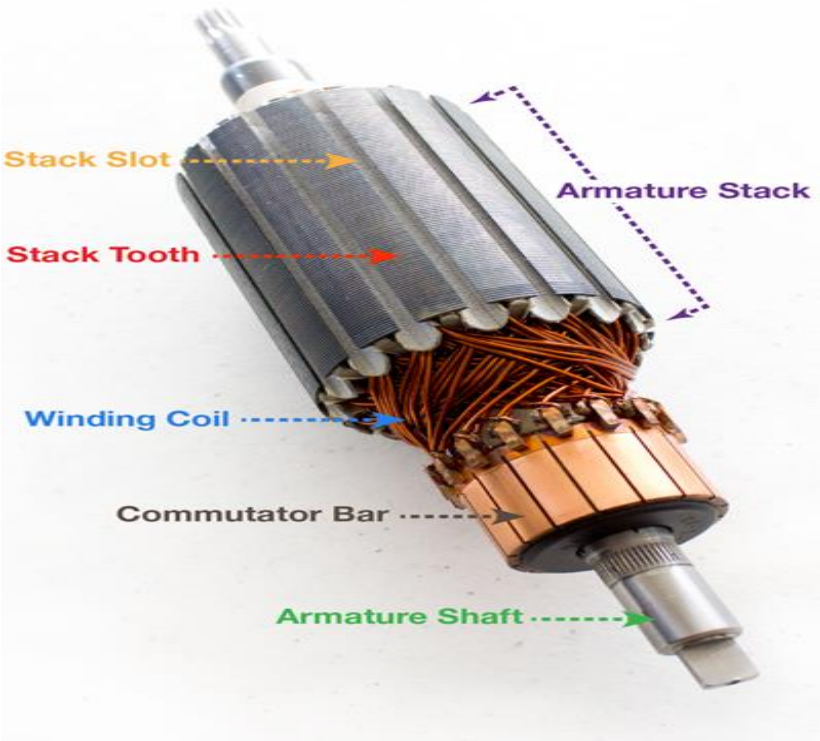
$\boxed{Q = C_0 D^2 Ln}$ is called output equation of DC machines.

$\boxed{where.C_0 = \pi^2 B_{av} ac\times 10^{-3}}$ is called output coefficient of DC machines

Separation of D & L for DC Machines

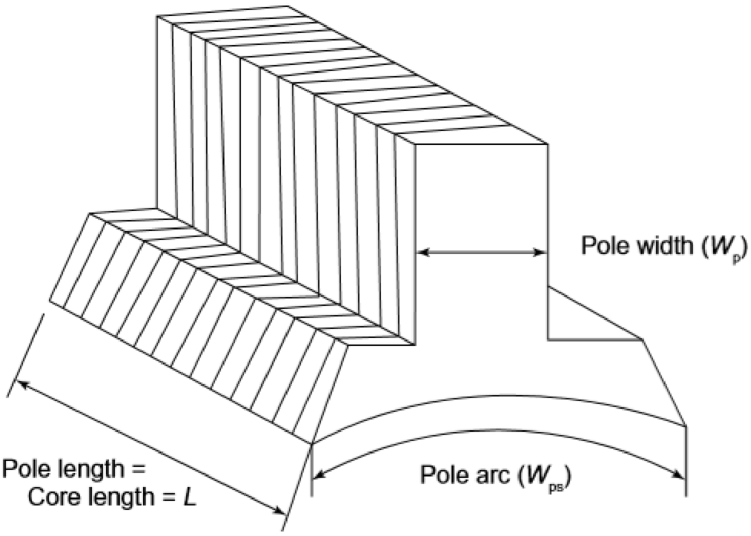
It depends on

- Pole Proportions
- Peripheral speed
- Moment of inertia
- Voltage between adjacent segments



Pole Proportions

The material used for field winding is minimum if the pole is circular cross section.
But if the cross section is circular, it should be solid without any laminations.
So, if the length of filed turn has to be minimum, pole should have a square cross session.



Square pole criteria :

i.e. Pole arc = length of core

b = L

The ratio, $\frac{L}{\tau}$ = **0.64 to 0.72**

In Practical we use a pole of rectangular cross session with laminations.

The ratio $\frac{L}{\tau}$ = **0.7 to 0.9**

Peripheral Speed (V_a):

It should not exceed about 30 m/s in DC machines.

$V_a \leq 30$ m/s

$V_a = \pi Dn$

Where D = Diameter of the armature, n = N/60, speed in rps.

Moment of Inertia :

Machines used in control systems, small moment of Inertia is desirable.
For this the diameter should be made as small as possible.

Voltage between adjacent segments :

The maximum core length is decided by the maximum voltage that can be allowed between adjacent segment. It is given by,

$$E_{cm} = 2\, B_{gm}\, L\, V_a\, t_c.$$

Where, B_{gm} = Maximum air gap flux density under loaded condition

L = Length of armature

V_a = Peripheral speed and T_c = Turns per coil

Factors affecting size of rotating machines

The factors affecting size of rotation machines are

- Speed (n)
- Output coefficient (C_o)

i. Speed :

The output equation of DC machine is $Q = C_0 D^2 L n$

$Q \propto n$ { provided D^2L is constant

Also, $n \alpha \dfrac{Q}{D^2 L}$ { D^2L is proportional to volume of active parts

Hence for same volume, with increase in speed the output will increase,

for given output, high speed machines will have less volume and less cost.

For reducing cost, highest possible speed may be selected. The maximum speed limited by mechanical stress of the rotating parts.

ii. Output Coefficient :

The output equation of DC machine is $Q = C_0 D^2 L n$

$Q \propto C_0$ { provided D^2L is constant

Also, $C_0 \alpha \dfrac{Q}{D^2 L}$ { D^2L is proportional to volume of active parts

Hence for same volume, with increase in output coefficient the output will increase, for given output, output coefficient will have less volume and less cost.

For reducing cost, highest possible value of output coefficient may be selected.

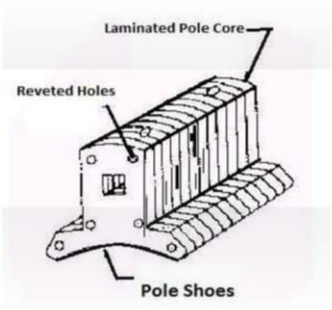
The output coefficient depends on Specific magnetic loading (B_{av}) and Specific electric loading (ac).

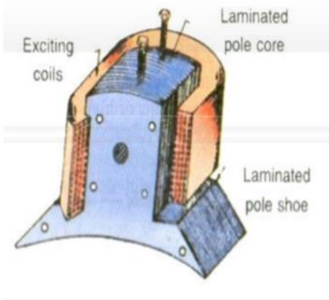
Where as B_{av} in tern depends on B_m, Magnetizing current & Core loss where as Specific electric loading intern depends on Temp rise, insulation, size of the machine & voltage rating.

Choice of number of poles

The selection of number of poles depends on,

- Frequency
- Weight of iron parts
- Weight of copper
- Length of commutator
- Labor charges
- Flash over and
- Distortion of field form





Advantages of large number of poles

Large number of poles results in reduction of,

- Weight of armature core and yoke
- Cost of armature and field conductor
- Overall length and diameter of machine
- Length of commutator
- Distortion of filed form under load conditions

Disadvantages of large number of poles

Large number of poles results in increase in,

- Frequency of flux reversal
- Labor charges
- Flash over between brush arms

Guiding factors for selection of number of poles

i. Frequency should lie between 25 to 50 Hz.

ii. Current / Parallel path is limited to 200 A. $\frac{I_a}{P} \leq 200A$

or

Current / Brush arm is limited to 400 A $\frac{2I_a}{P} \leq 400A$

iii. mmf should not be too large.

Power in KW	Mmf / Pole in AT
Upto 100 KW	less than 5,000
100 – 500	5,000 – 7,500
500 - ,1500	7,500 – 10,000
Above 1,500	Up to 12,500

If there are more than one choice for number of poles, which satisfies the above three condition, then choose the large value of poles.

This results in reduction in iron and copper.

Estimation of Power P_a :

The output equation P_a (in kW) $= C_o D^2 L n$ relates the power developed by the armature of a DC machine to its main dimensions D and L. But for DC generators and motors, the power output, P, is alone specified as the main specifications. Now, let us relate P_a with P for motors and generators.

- **For motor**
  Power developed by armature,

$$P_a = \text{output power } (P) + \text{rotational losses}$$

  where rotational losses include friction, windage and iron losses.
- **For generator**
  Power developed by armature,

$$P_a = \text{input power} - \text{rotational losses}$$

$$= \frac{\text{Output power } (P)}{\text{Efficiency } (\eta)} - \text{rotational losses}$$

For large machines, the rotational losses are very small. Thus, the difference between P_a and P is very small. So, the rotational losses could be neglected. Hence,

$P_a = P$ for motors

$P_a = \frac{P}{\eta}$ for generators.

Armature Design

- Armature of a DC machine consists of core and winding.
- Armature core is cylindrical in shape with slots on the outer periphery of the armature.
- Circular laminations with 5 mm thickness
- Windings are placed on the slots in the armature core.

Design of Armature includs

- **Design of main dimensions**
- **Number of Armature slots (S_a)**
- **Slot dimensions (width and duct)**
- **Depth of core (d_c)**

Number of Armature Slots (S_a)

Factors to be consider

- Slot width (or slot pitch)
- Cooling of armature conductors
- Flux pulsations (change of air gap flux due to slot loading)
- Commutation
- Cost

Guiding factors for number of armature slots

- Slot pitch :

  Slot pitch should lie between 25 mm to 35 mm
- To avoid dummy coils

  Lap Winding : Number of slots should be a multiple of pole pair.

  Wave Winding: Number of slots should not be a multiple of pole pair.
- To avoid flux pulsation loss

  Lap Winding : Slots / Pole should be an integer plus ½.

  Wave Winding : Slots / Pole arc should be an integer plus ½.
- Commutation

  The number of slots / pole should be at least 9
- Slot loading

  should not exceeding 1500 ampere conductors.

Slot Dimensions

Factors to be consider.

- Flux density in tooth
- Flux pulsations
- Eddy current loss in conductors
- Reactance voltage
- Mechanical difficulties

Depth of armature core (d_c)

$$D = D_i + 2d_c + 2d_s$$

$$d_c = \frac{1}{2}\left(D - D_i - 2d_s\right)$$

UNIT - III

ELECTRICAL MACHINE DESIGN – SEE1304

Unit 3 – TRANSFORMERS

Output Equation of Single Phase Transformer :

The equation which relates the rated KVA output of a transformer to the area of core and window is called output equation.

In transformers the output KVA depends on flux density and ampere turns.

Induced emf in a transformer E = 4.44 f ϕ_m T volts

Emf per turn, $E_t = \frac{E}{T} = 4.44\, f\phi_m$

The window in single phase transformer contains one primary and one secondary winding.

The window space factor Kw is the ratio of conductor area in window to the total area of window.

$$K_w = \frac{\text{Conductor area in window}}{\text{Total area of window}} = \frac{A_c}{A_w}$$

Conductor area in window, Ac = $K_W A_W$ ---- (1)

The current density δ is same in both the windings.

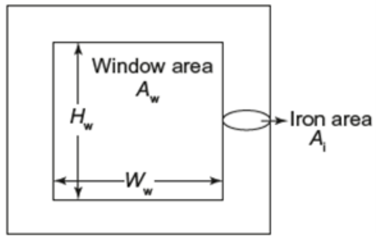
$\therefore$ Current density, $\delta = \frac{I_P}{a_P} = \frac{I_S}{a_S}$

Area of cross section of primary conductor, $a_P = \frac{I_P}{\delta}$

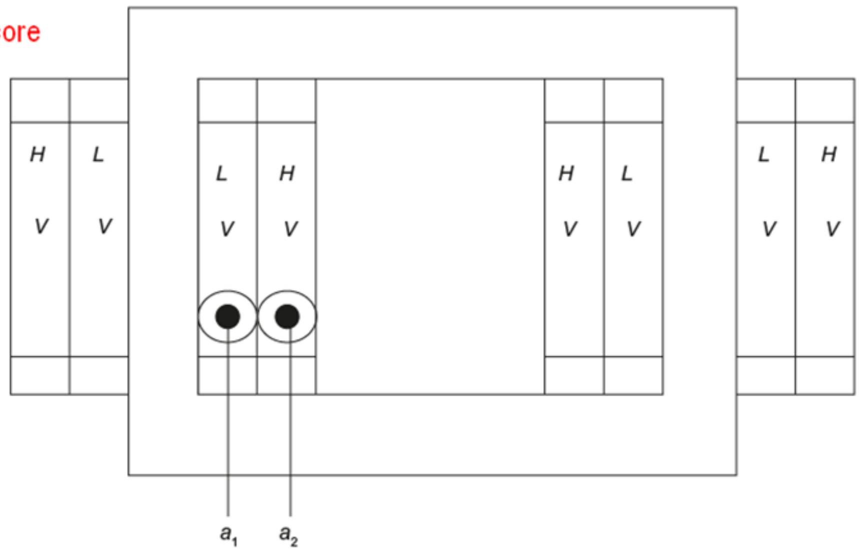
Area of cross section of secondary conductor, $a_S = \frac{I_S}{\delta}$

If we neglect magnetizing mmf then, primary ampere turns is equal to secondary ampere turns,

$\therefore$ Ampere turns, $AT = I_P T_P = I_S T_S$ --- (2)



Cross section of single phase core type transformer



Winding arrangement of single phase core type transformer

Total copper area in window A_c	=	Copper area in Primary winding		+	Copper area in secondary winding		
	=	(Number of turns in primary	x	Area of cress section of primary conductor)	+	(Number of turns in secondary	x Area of cress section of secondary conductor)

$$= (T_P \times a_p) + (T_s \times a_s)$$

$$A_C = T_P \frac{I_P}{\delta} + T_S \frac{I_S}{\delta}$$

$$A_C = \frac{1}{\delta}(T_P I_P + T_S I_S)$$

$$A_C = \frac{1}{\delta}(AT + AT)$$

$$A_C = \frac{2AT}{\delta} \qquad \text{---- (3)}$$

From equation. (1) and (3), $A_W K_W = \frac{2AT}{\delta}$

$$AT = \frac{1}{2} A_W K_W \delta$$

KVA rating of single phase transformer is, $Q = V_P I_P \times 10^{-3}$

$$Q = E_P I_P \times 10^{-3} \qquad \{V_P = E_P$$

Multiple and divided by E_p,

$$Q = \frac{E_P}{T_P} T_P I_P \times 10^{-3}$$

$$Q = E_t AT \times 10^{-3} \qquad \{E_t = \frac{E_P}{T_P}$$

$$Q = 4.44 f\phi_m \frac{A_W K_W \delta}{2} \times 10^{-3}$$

$$Q = 2.22 f\phi_m A_W K_W \delta \times 10^{-3} \qquad \{B_m = \frac{\phi_m}{A_i}$$

$$\boxed{Q = 2.22 f B_m A_i A_W K_W \delta \times 10^{-3}}$$

is called output equation of single phase transformer

Output Equation of Three Phase Transformer :

The equation which relates the rated KVA output of a transformer to the area of core and window is called output equation.

In transformers the output KVA depends on flux density and ampere turns.

Induced emf in a transformer $E = 4.44 f \phi_m T$ volts

Emf per turn, $E_t = \frac{E}{T} = 4.44 f\phi_m$

The window in three phase transformer contains two primary and two secondary winding.

The window space factor Kw is the ratio of conductor area in window to the total area of window.

$$K_w = \frac{\text{Conductor area in window}}{\text{Total area of window}} = \frac{A_c}{A_w}$$

Conductor area in window, $A_c = K_W A_W$ ---- (1)

The current density δ is same in both the windings.

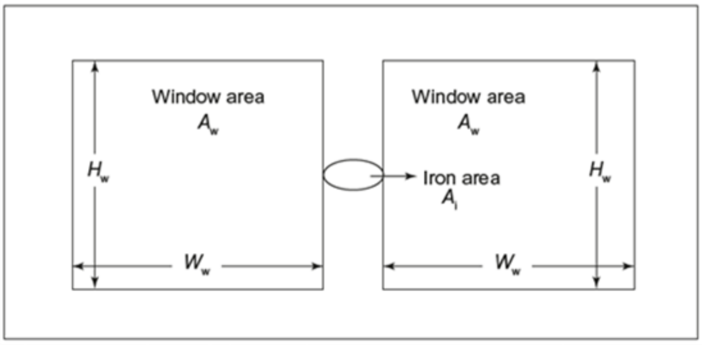
$\therefore$ Current density, $\delta = \dfrac{I_P}{a_P} = \dfrac{I_S}{a_S}$

Area of cross section of primary conductor, $a_P = \dfrac{I_P}{\delta}$

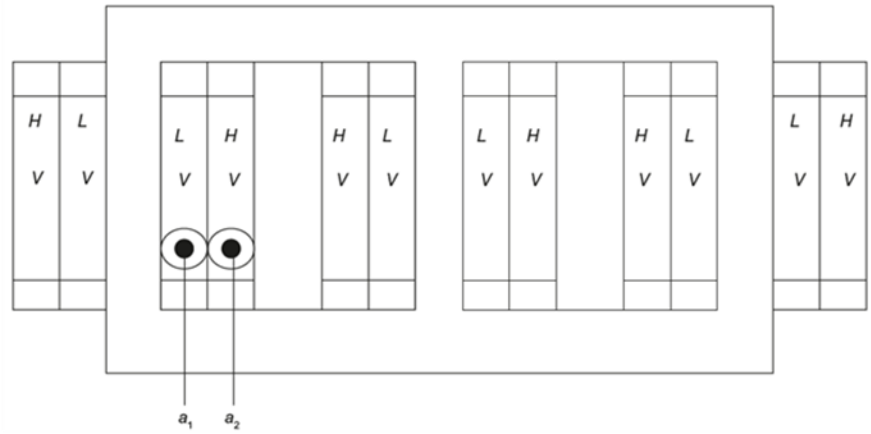
Area of cross section of secondary conductor, $a_S = \dfrac{I_S}{\delta}$

If we neglect magnetizing mmf then, primary ampere turns is equal to secondary ampere turns,

$\therefore$ Ampere turns, $AT = I_P T_P = I_S T_S$ --- (2)



Cross section of three phase core type transformer



Winding arrangement of three phase core type transformer

Total copper area in window A_c	=	2 x Copper area in Primary winding			+	2 x Copper area in secondary winding		
	=	(2 x Number of turns in primary	x	Area of cross section of primary conductor)	+	(2 x Number of turns in secondary	x	Area of cross section of secondary conductor)

= (2 x T_P x a_p) + (2 x T_s x a_s)

$$A_C = 2T_P \frac{I_P}{\delta} + 2T_S \frac{I_S}{\delta}$$

$$A_C = \frac{2}{\delta}\left(T_P I_P + T_S I_S\right)$$

$$A_C = \frac{2}{\delta}\left(AT + AT\right)$$

$$A_C = \frac{4AT}{\delta} \qquad \text{---- (3)}$$

From equation. (1) and (3), $A_W K_W = \frac{4AT}{\delta}$

$$AT = \frac{1}{4} A_W K_W \delta$$

KVA rating of single phase transformer is, $Q = 3V_P I_P \times 10^{-3}$

$$Q = 3E_P I_P \times 10^{-3} \qquad \{V_P = E_P$$

Multiple and divided by E_p,

$$Q = 3\frac{E_P}{T_P} T_P I_P \times 10^{-3}$$

$$Q = 3E_t AT \times 10^{-3} \qquad \{E_t = \frac{E_P}{T_P}$$

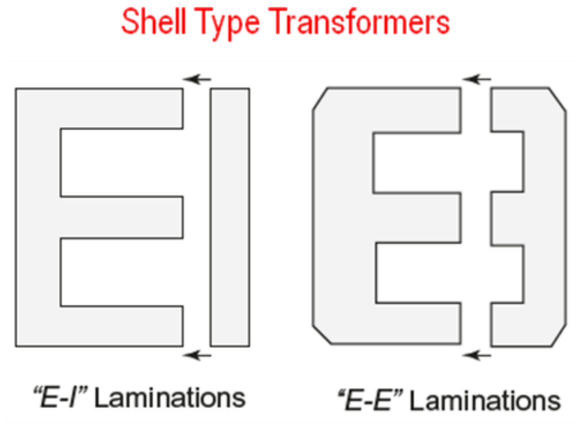
$$Q = 3 \times 4.44 f\phi_m \frac{A_W K_W \delta}{4} \times 10^{-3}$$

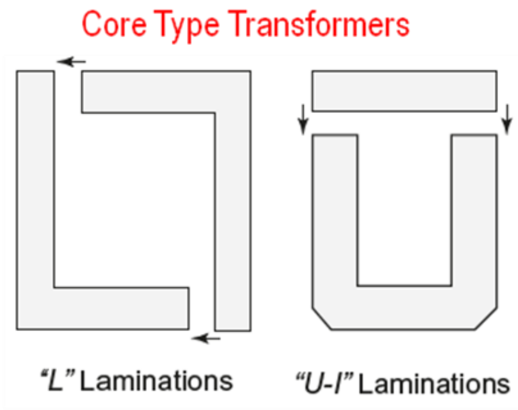
$$Q = 3.33 f\phi_m A_W K_W \delta \times 10^{-3} \qquad \{B_m = \frac{\phi_m}{A_i}$$

$$\boxed{Q = 3.33 f B_m A_i A_W K_W \delta \times 10^{-3}}$$

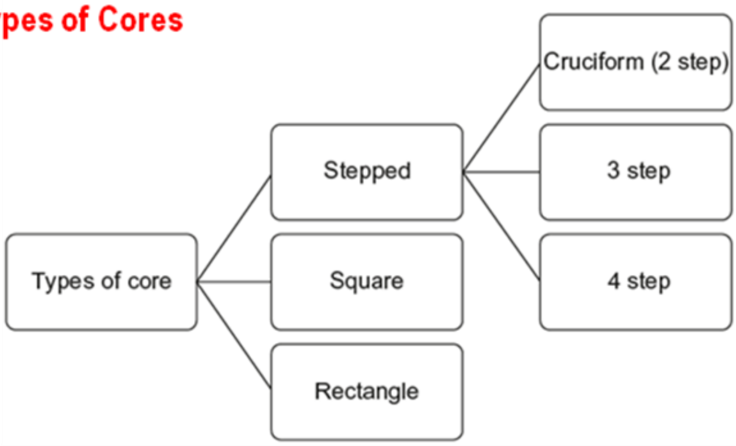
is called output equation of three phase transformer

Design of Cores





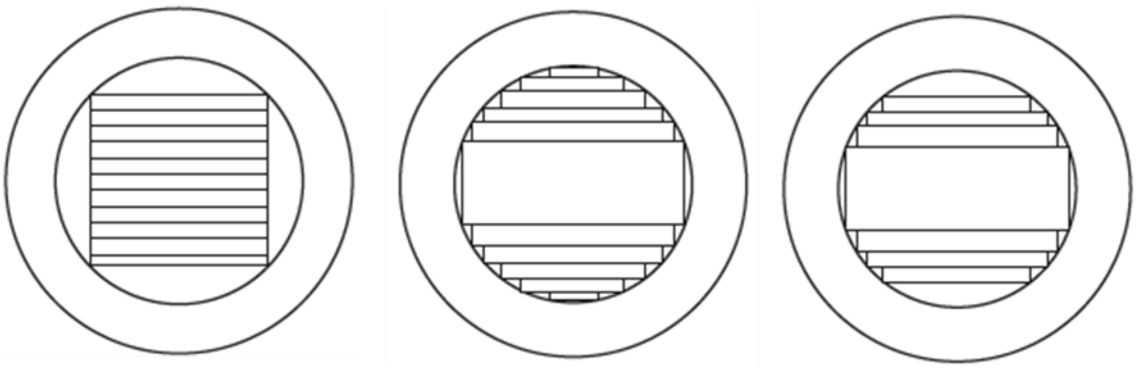
Types of Cores



For core type transformers, the cross section may rectangular, square or stepped.

When circular coils are used for distribution and power transformer. The square and stepped cores are used.

For shell type transformer, the cross section may be rectangular. Coils are also rectangular in shape.



Cross section of Square, four stepped and Multi stepped core

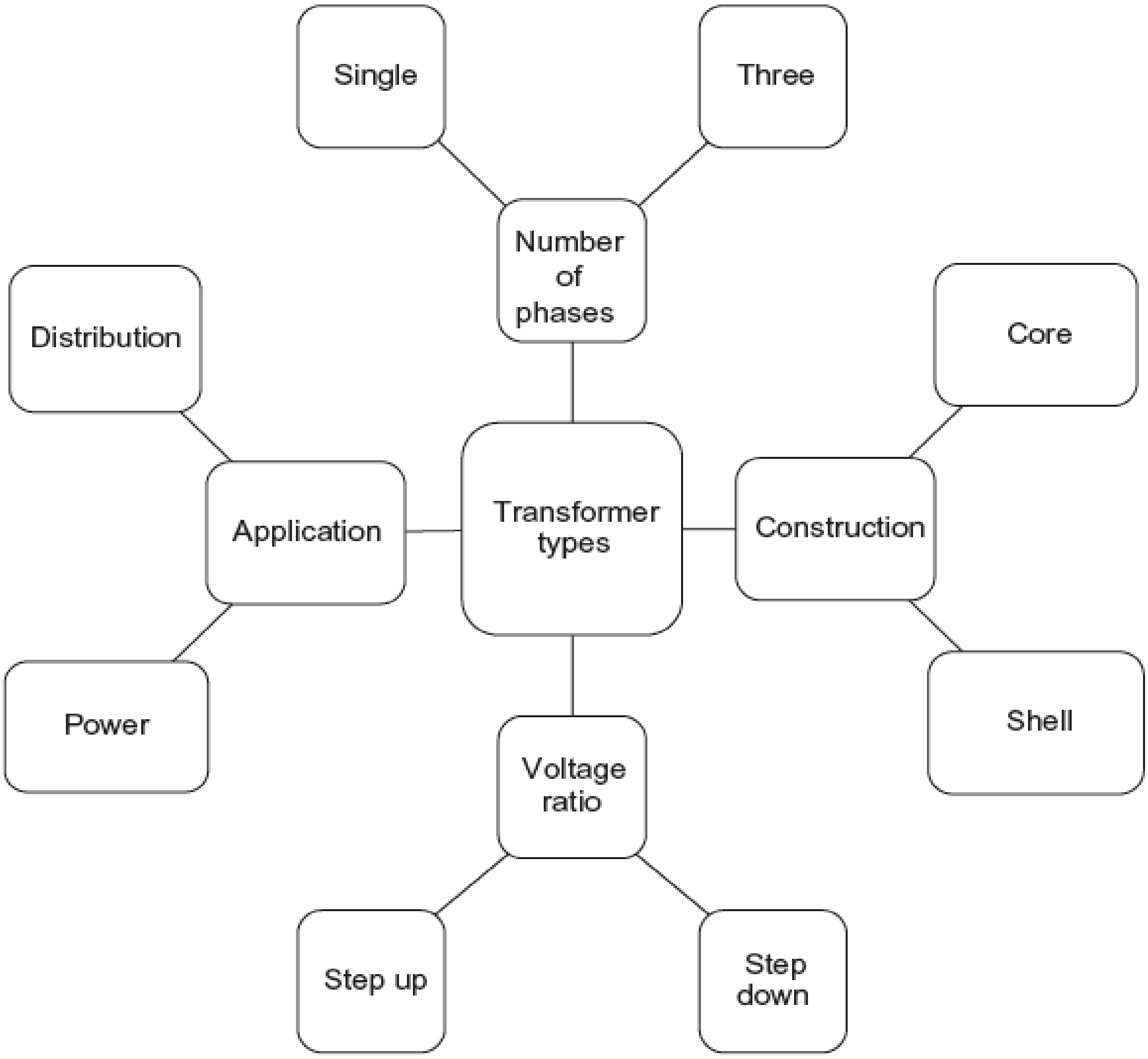
Merits and Demerits of stepped cores

In square cores, the diameter of the circumscribing circle is larger than the diameter of stepped cores of same area of cross section.

Stepped cores are used the length of mean turn of winding is reduced. Results in reduction of cost of copper and hence copper loss.

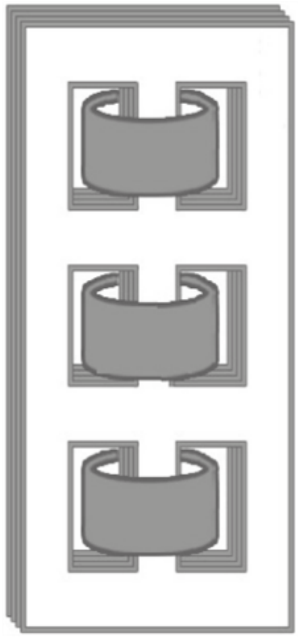
However with large number of steps, a large number of different sizes of laminations have to used. This results in higher labor charges for assembling different types of laminations.

Classification of Transformer :

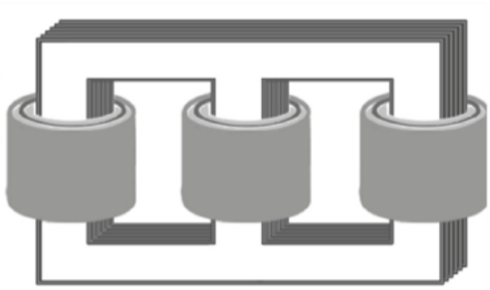


Single phase core type transformer

Single phase shell type transformer



Three phase shell type transformer

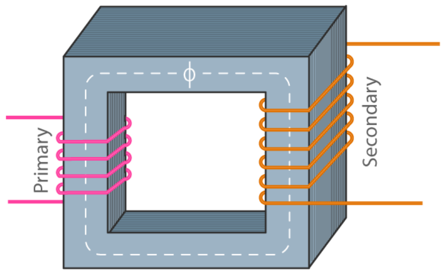


Three phase core type transformer

Optimum Design

The design involves,

- Total volume
- Total weight
- Total cost
- Total losses.



The ratio, ϕ_m / AT is high value,

If ϕ_m is large, it requires

large cross section,
results in higher volume,
increased weight,
increased cost of iron ,
higher iron loss.

If decreased in AT,

Number of turns reduced,
results in volume reduced,
weight reduced,
cost of copper reduced,
copper loss reduced.

Method of cooling

- Air Natural (AN)
- Air Blast (AB)
- Oil Natural (ON)
- Oil Natural Air Forced (ONAF)
- Oil Natural Water Forced (ONWF)
- Oil Forced (OF)
- Oil Forced Air Natural (OFAF)
- Oil Forced Air Forced (OFAF)
- Oil Forced Water Forced (OFWF)

Types of Winding

- Cylindrical winding
- Helical winding
- Double helical winding
- Multi layer helical winding
- Cross over winding
- Disc & continuous disc winding

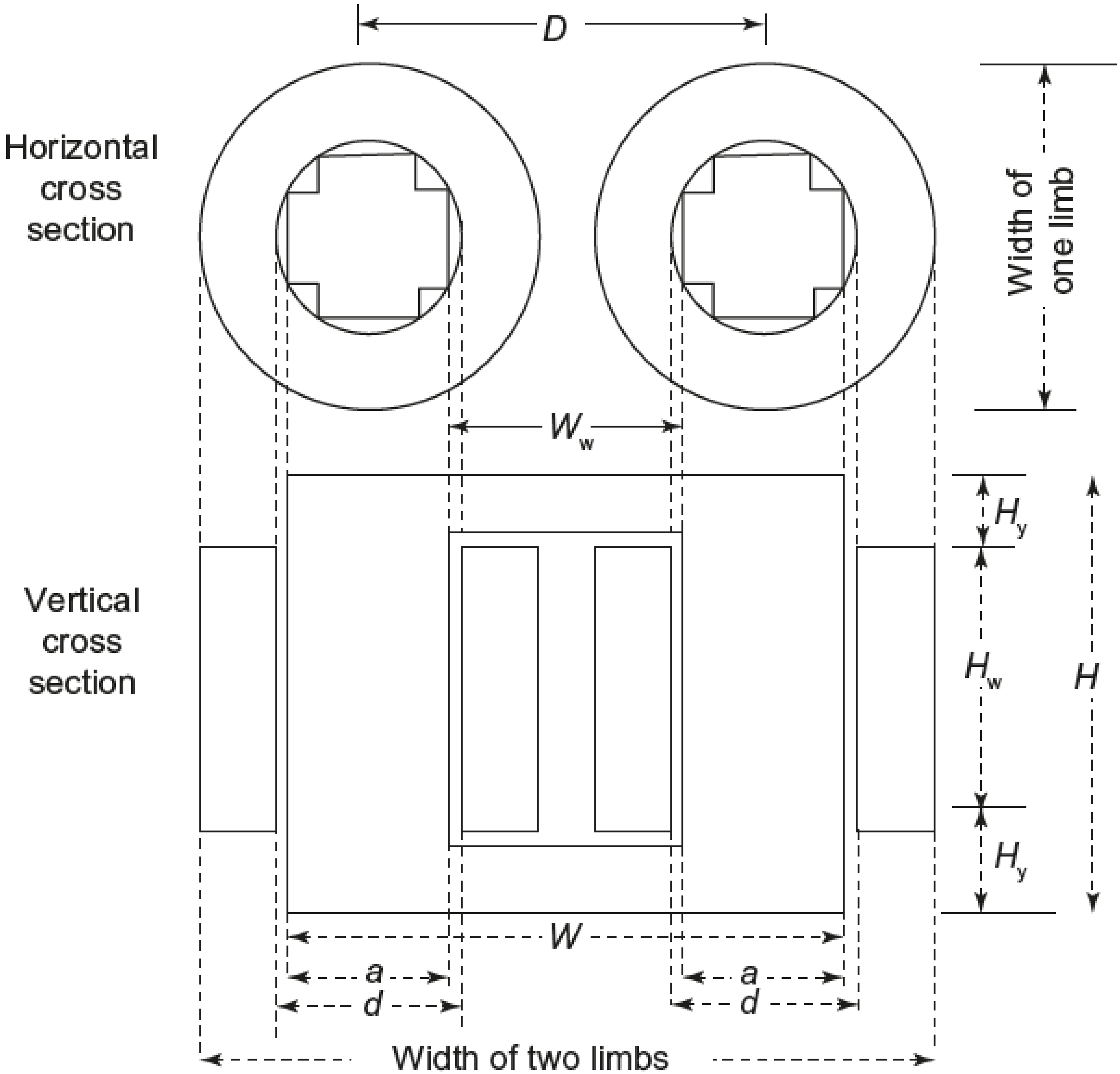
Factors to be consider to choose type of winding for a core type transformer

- Current density
- Short circuit ratio
- Temp rise
- Surge voltage
- Impedance
- Transport facilities



Overall Dimensions of Transformer

Single phase Core type Transformer



H - Overall height
W – Overall width
D – Distance between core centers
d – diameter of circumscribing circle
W_W – Width of the window
H_W – Height of window
H_Y – Height of Yoke
D_Y – Depth of yoke

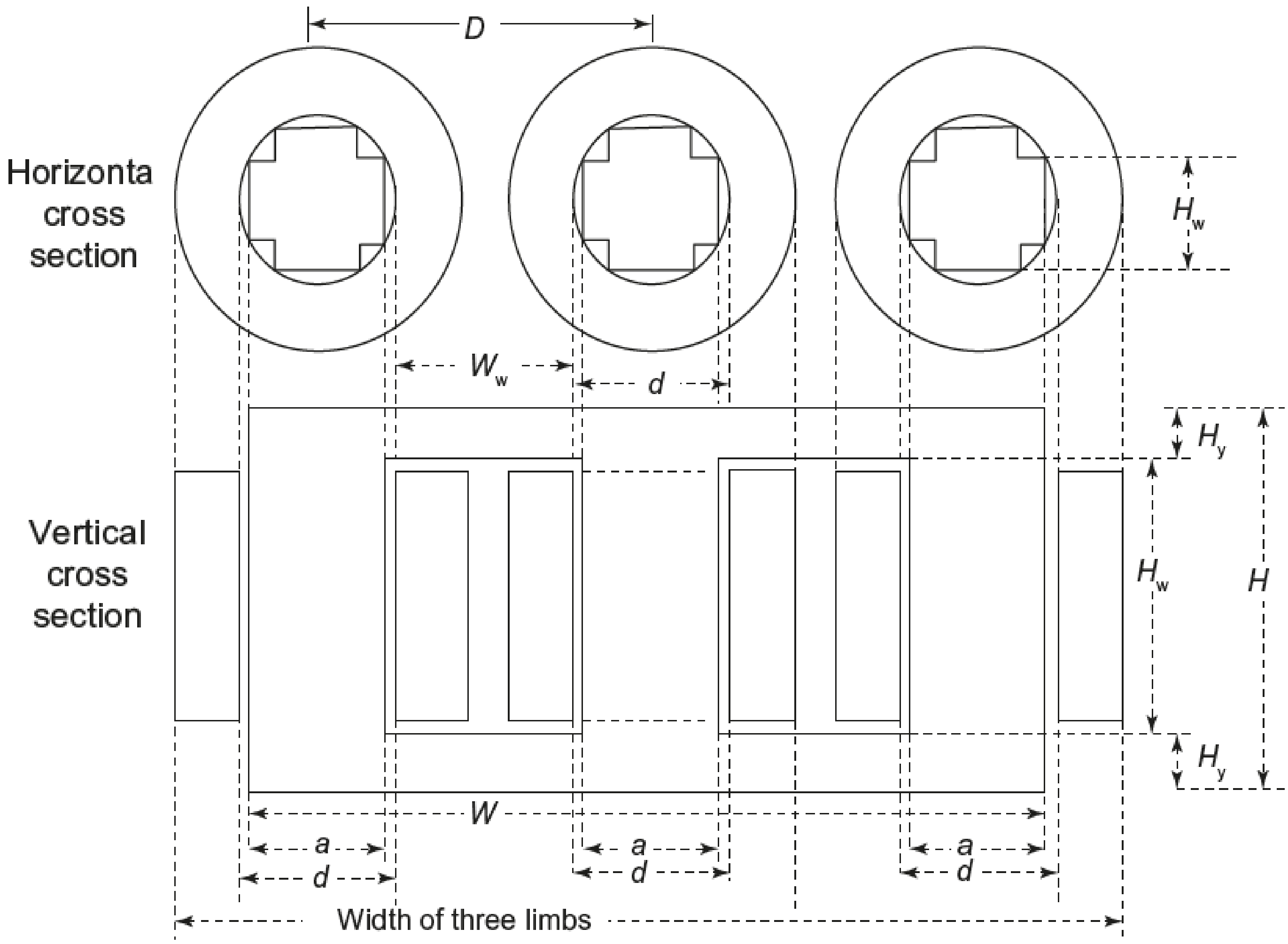
$$H = H_w + 2\,H_y$$

$$D = W_w + d$$

$$W = D + a$$

$$D_y = a$$

Three phase Core type Transformer



H - Overall height

W – Overall width

D – Distance between core centers

d – diameter of circumscribing circle

W_W – Width of the window

H_W – Height of window

H_Y – Height of Yoke

D_Y – Depth of yoke

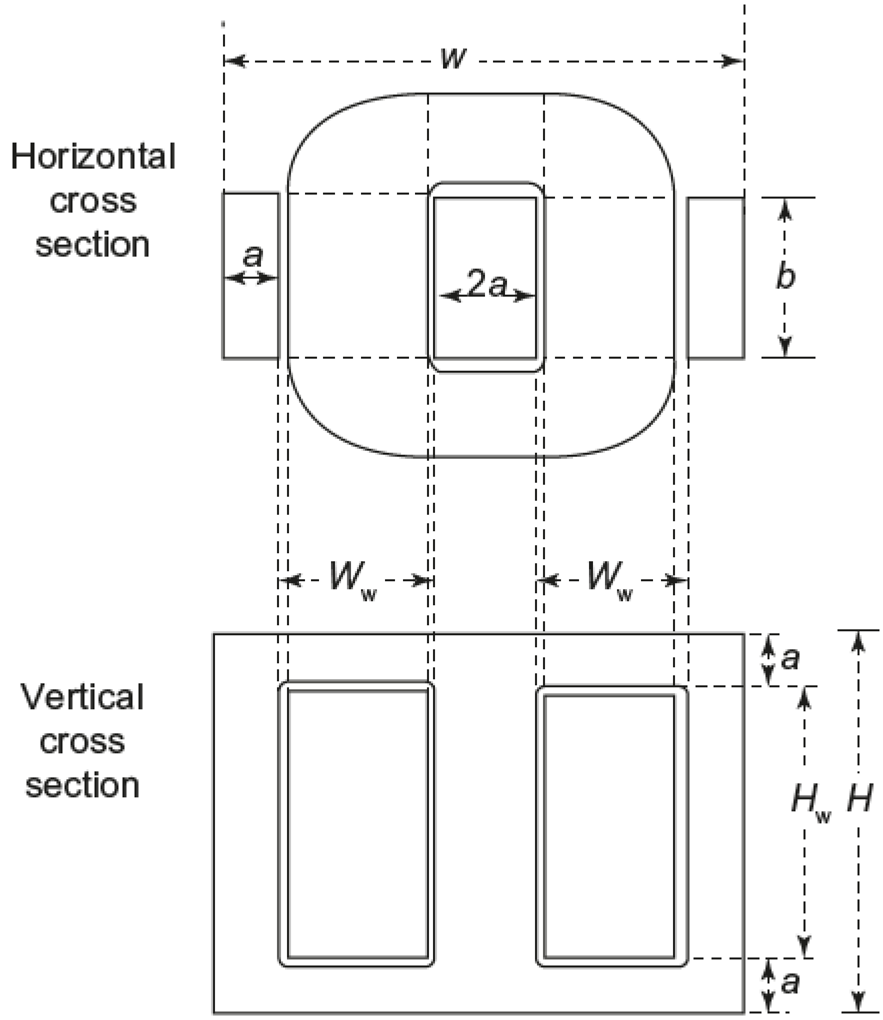
$H = H_w + 2\,H_y$

$D = W_w + d$

$W = 2D + a$

$D_y = a$

Single phase Shell type Transformer



H - Overall height

W – Overall width

D – Distance between core centers

d – diameter of circumscribing circle

W_W – Width of the window

H_W – Height of window

H_Y – Height of Yoke

D_Y – Depth of yoke

$H = H_w + 2\,H_y$

$W = 2\,W_w + 4a$

$D_y = b$

$H_y = a$

Design of Transformer Tank and Tubes

Transformers are provided with cooling tubes to increase the heat dissipating area.

The tubes are mounted on the vertical sides of the transformer tank.

Let, Dissipating surface of tank = S_t

Dissipating surface of tube = xS_t

Total area of tank walls and tubes = $S_t + xS_t = (1+x)S_t$

Loss dissipated by surface of the Tank by radiations and convection = $(6 + 6.5)\ S_t$

= $12.5\ S_t$

Loss dissipated by tubes by convection = $6.5 \times \frac{135}{100} xS_t = 8.8xS_t$

Total loss dissipated by tank walls and tubes $= (12.5 + 8.8x)S_t$ W/°C

Loss dissipated per unit area of dissipating surface = $\dfrac{\text{Total loss dissipated}}{\text{Total area}}$

$$= \frac{S_t(12.5+8.8x)}{S_t(1+x)} = \frac{(12.5+8.8x)}{(1+x)} \quad \text{W / m}^2\text{ -°C}$$

Temperature rise in transformer with cooling tubes = $\dfrac{\text{Total loss}}{\text{Loss Dissipated}}$

$$\theta = \frac{P_i + P_C}{S_t(12.5+8.8x)}$$

$$(12.5+8.8x) = \frac{P_i + P_C}{\theta \times S_t}$$

$$x = \left(\frac{P_i + P_C}{\theta \times S_t} - 12.5\right)\frac{1}{8.8}$$

Total area of cooling tubes = $xS_t = \left(\frac{P_i + P_C}{\theta \times S_t} - 12.5\right)\frac{1}{8.8} \times S_t$

$$= \frac{1}{8.8}\left(\frac{P_i + P_C}{\theta} - 12.5S_t\right)$$

Surface area of each tube = $\pi\, d_t\, l_t$

Where d_t = diameter of tube

l_t = length of tube

$$\text{Total number of tubes } n_t = \frac{\text{Total area of tube}}{\text{Area of each tube}}$$

$$n_t = \frac{1}{8.8\pi d_t l_t}\left(\frac{P_i + P_C}{\theta} - 12.5S_t\right)$$

UNIT - IV

ELECTRICAL MACHINE DESIGN – SEE1304

Unit 4 – INDUCTION MOTORS

OUT PUT EQUATION OF AC MACHINES

The equation of induced emf, frequency, current through each conductor and total number of ampere conductors of an ac machine gives the output equation of ac machines.

KVA rating of AC machine,

Q = No of phase x Voltage per phase x Current per phase x 10^{-3}.

$$Q = m \times V_{ph} I_{ph} \times 10^{-3}$$

$$Q = m \times E_{ph} I_{ph} \times 10^{-3} \qquad \{V_{Ph} = E_{Ph}$$

$$Q = 3 \times 4.44 f \phi_m T_{ph} K_w \times I_{ph} \times 10^{-3} \qquad \{E_{ph} = 4.44 f \phi_m T_{ph} K_w$$

Current through each conductor $I_Z = I_{ph}$

We know that synchronous speed, $N_S = \dfrac{120 f}{p}$

$$\therefore f = \frac{pN_S}{120} = \frac{pn_S}{2}$$

From the above steps,

$$Q = 3 \times 4.44 \left(\frac{pn_S}{2} \right) \phi_m T_{ph} K_w \times I_Z \times 10^{-3}$$

$$Q = 6.66 (P\phi) n_S T_{ph} K_w \times I_Z \times 10^{-3}$$

$$Q = 6 \times 1.11 (P\phi) n_S T_{ph} K_w \times I_Z \times 10^{-3}$$

Total number of conductors Z = Number of phase x 2 x turns per phase

$Z = 3 \times 2 \times T_{ph}$

$Z = 6\, T_{ph}$

From the above, $Q = 1.11(P\phi)n_S Z K_w \times I_Z \times 10^{-3}$

$$Q = 1.11(P\phi)\times(I_Z Z)\times n_S K_W \times 10^{-3}$$

We know that, Specific magnetic loading is $\boxed{B_{av} = \frac{P\phi}{\pi DL}}$

$$\therefore P\phi = B_{av}\pi DL \qquad \ldots (1)$$

Specific electric loading is $\boxed{ac = \frac{I_Z Z}{\pi D}}$

$$\therefore I_Z Z = ac\pi D \qquad \ldots (2)$$

From (1) and (2),

$$Q = 1.11(B_{av}\pi DL)\times(ac\pi D)\times n_S K_W \times 10^{-3}$$

$$Q = 11 B_{av} ac K_W D^2 L n_S \times 10^{-3}$$

$\boxed{Q = C_0 D^2 L n_S}$ is called output equation of AC machines.

$\boxed{where. C_0 = 11 B_{av} ac K_W \times 10^{-3}}$ is called output coefficient of AC machines.

For Induction Motor KVA input $\boxed{Q = C_0 D^2 L n_S}$

Induction Motor KVA input , $Q = \frac{kW}{\mu\cos\phi} = \frac{HP\times 746}{\mu\cos\phi}$

Main Dimensions

The operating characteristics of an induction motor are mainly influenced by ration L / τ

ration L / τ for various design factors are,

for minimum cost, L / τ = 1.5 to 2

for good power factor, L / τ = 1.0 to 1.25

for good efficiency, L / τ = 1.5

for good overall design, L / τ = 1

for best power factor, $\tau = \sqrt{0.18L}$

Peripheral speed

For normal design, the diameter should be chosen, that the peripheral speed does not exceed about 30 m/s.

Ventilating duct

The stator is provided with ventilating ducts if the length of core exceed 100 to 125 mm. The width of ventilating duct is 10 mm.

Selection of Stator Slots (S_s)

***Step* 1**: Slot pitch : Stator slot pitch varies from 15 mm to 25 mm.

Stator slots, $S_S = \dfrac{\pi D}{Y_{SS}}$

Step 2 : Stator slots should be a multiple of "q"

Where q is slots per pole per phase

q = 2, 3, 4 ….

S_s = number of phase x poles x q

S_s = m x P x q

***Step* 3** : Select the choice of stator slots which are common between the values obtained in step 1 and step 2.

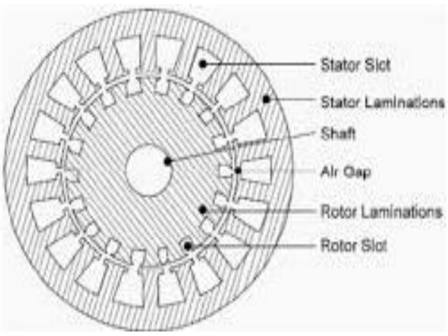
Step 4 : Slot loading = I_z x Z_{ss}

I_z = current through stator conductor, Z_{ss} – conductor per slot

Length of Air gap

The length of air gap in induction motor is decided by

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

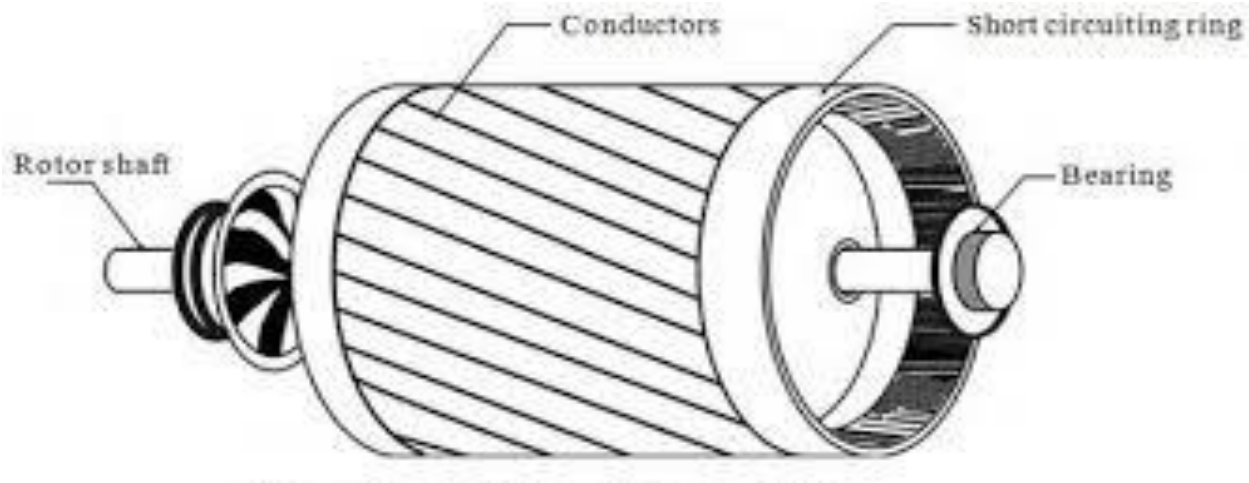


For small machines, length o f air gap $\boxed{l_g = 0.2 + 2\sqrt{DL}}$ in mm

or

$\boxed{l_g = 0.2 + D}$ in mm

Design of Squirrel Cage Rotor



Rotor of Squirrel Cage Induction Motor

Rotor bar current $I_b = \frac{6 I_S T_S}{S_r} K_{ws} Cos\phi$

$$\boxed{I_b = 0.85 \frac{6 I_S T_S}{S_r}}$$ in Ampere

Where I_s = Stator current per phase
T_s = Stator turns per phase
S_r = number of rotor slots

Area of cross section of each rotor bar, $\boxed{a_b = \frac{I_b}{\delta_b}}$ in mm^2

Where I_b = Rotor bar current
δ_b = Current density in rotor bars

End ring current, $\boxed{I_e = \frac{s_r I_b}{\pi p}}$ in Ampere

Where S_r = number of rotor slots
I_b = Rotor bar current
p = number of poles

Area of cross section of end ring, $\boxed{a_e = \frac{I_e}{\delta_e}}$ in mm^2

Where I_e = Rotor end ring current
δ_e = Current density in rotor end ring

Current density
Stator conductors δ = 3 to 5 A/mm^2
Rotor bars δ = 4 to 7 A/mm^2

Rules for selection of rotor slots (for squirrel cage I M)

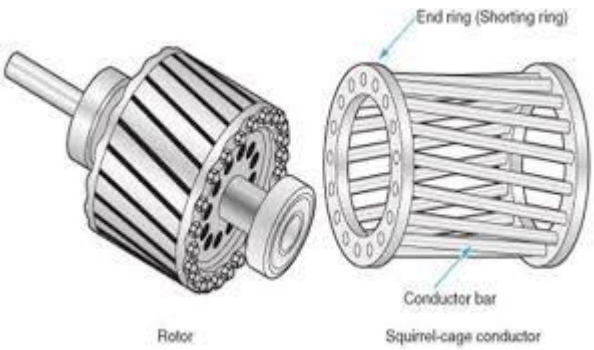
- The number of stator slots should never be equal to rotor slots.
- The difference ($S_s \sim S_r$) should not be equal to $\pm$ P, $\pm$ 2 P or $\pm$ 5 P

  - to avoid synchronous cusps
- The difference ($S_s \sim S_r$) should not be equal to $\pm$ 3 P

  - to avoid magnetic locking
- The difference ($S_s \sim S_r$) should not be equal to ± 1, ± 2, $\pm (P \pm 1)$, $\pm (P \pm 2)$

  - to avoid noise and vibrations

($S_s \sim S_r$) should not be equal to
0, $\pm$ P, $\pm$ 2 P, $\pm$ 3 P, $\pm$ 5 P, ± 1, ± 2, $\pm (P \pm 1)$, $\pm (P \pm 2)$



Squirrel Cage Rotor

Design of Wound Rotor
(Slip Ring Rotor)

Wound Rotor

The wound rotor has the facility of adding external resistance to rotor circuit in order to improve the torque developed by the motor.

The motor consists of laminated core with semi enclosed slots and carries a three phase winding.

Number of Rotor Turns

The rotor is equivalent to secondary of transformer and the voltage between slip rings is maximum when the rotor is at rest.

For Induction motor the turns ratio is given by, $\frac{E_r}{E_s} = \frac{K_{wr} T_r}{K_{ws} T_s}$

Rotor turns per phase, $\boxed{T_r = \frac{K_{ws} T_s}{K_{wr}} \times \frac{E_r}{E_s}}$

The rotor ampere turns is assumed as 85 % of stator ampere turns.

Rotor ampere turns = 0.85 stator ampere turns

$$T_r I_r = 0.85 I_s T_s$$

$\therefore$ Rotor current $\boxed{I_r = \frac{0.85 I_s T_s}{T_r}}$

The current density for rotor conductors is assumed as same as that of stator conductors.

Current density In rotor conductors δ = 3 to 5 A/mm²

Area of cross section of rotor conductor $\boxed{a_r = \frac{I_r}{\delta_r}}$ in mm²

UNIT - V

ELECTRICAL MACHINE DESIGN – SEE1304

Unit 5 – SYNCHRONOUS MACHINES

OUT PUT EQUATION OF AC MACHINES

The equation of induced emf, frequency, current through each conductor and total number of ampere conductors of an ac machine gives the output equation of ac machines.

KVA rating of AC machine,

Q = No of phase x Voltage per phase x Current per phase x 10^{-3}.

$$Q = m \times V_{ph} I_{ph} \times 10^{-3}$$

$$Q = m \times E_{ph} I_{ph} \times 10^{-3} \qquad \{V_{Ph} = E_{Ph}$$

$$Q = 3 \times 4.44 f \phi_m T_{ph} K_w \times I_{ph} \times 10^{-3} \qquad \{E_{ph} = 4.44 f \phi_m T_{ph} K_w$$

Current through each conductor $I_Z = I_{ph}$

We know that synchronous speed, $N_S = \dfrac{120 f}{p}$

$$\therefore f = \frac{pN_S}{120} = \frac{pn_S}{2}$$

From the above steps,

$$Q = 3 \times 4.44 \left(\frac{pn_S}{2} \right) \phi_m T_{ph} K_w \times I_Z \times 10^{-3}$$

$$Q = 6.66 (P\phi) n_S T_{ph} K_w \times I_Z \times 10^{-3}$$

$$Q = 6 \times 1.11 (P\phi) n_S T_{ph} K_w \times I_Z \times 10^{-3}$$

Total number of conductors Z = Number of phase x 2 x turns per phase

$Z = 3 \times 2 \times T_{ph}$

$Z = 6\, T_{ph}$

From the above, $Q = 1.11(P\phi)n_S Z K_w \times I_Z \times 10^{-3}$

$$Q = 1.11(P\phi) \times (I_Z Z) \times n_S K_W \times 10^{-3}$$

We know that, Specific magnetic loading is $\boxed{B_{av} = \frac{P\phi}{\pi DL}}$

$$\therefore P\phi = B_{av}\pi DL \qquad \ldots (1)$$

Specific electric loading is $\boxed{ac = \frac{I_Z Z}{\pi D}}$

$$\therefore I_Z Z = ac\pi D \qquad \ldots (2)$$

From (1) and (2),

$$Q = 1.11(B_{av}\pi DL) \times (ac\pi D) \times n_S K_W \times 10^{-3}$$

$$Q = 11 B_{av} ac K_W D^2 L n_S \times 10^{-3}$$

$\boxed{Q = C_0 D^2 L n_S}$ is called output equation of AC machines.

$\boxed{where. C_0 = 11 B_{av} ac K_W \times 10^{-3}}$ is called output coefficient of AC machines.

For Synchronous Machines, KVA output $\boxed{Q = C_0 D^2 L n_S}$

Output equation in terms of peripheral speed $\boxed{Q = 1.11 B_{av} ac K_W \times 10^{-3} \frac{V_a^2 L}{n_S}}$

Where, Q = KVA output for alternator
D = Diameter of stator bore in m
L = Length of stator core in m
n_s = Synchronous speed in rps
B_{av} = Specific magnetic loading
ac = Specific electric loading in Amp. Cond. / m
K_{ws} = Stator winding factor
V_a = Peripheral speed in m/s

Main Dimensions

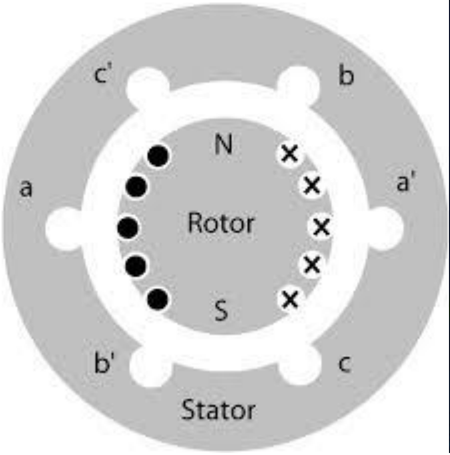
The main dimensions of salient pole machines are D and L.

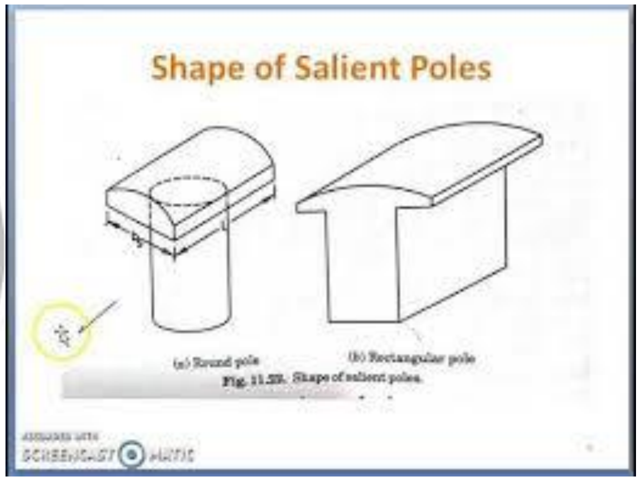
The choice of D and L depends on the type of pole and the permissible peripheral speed.

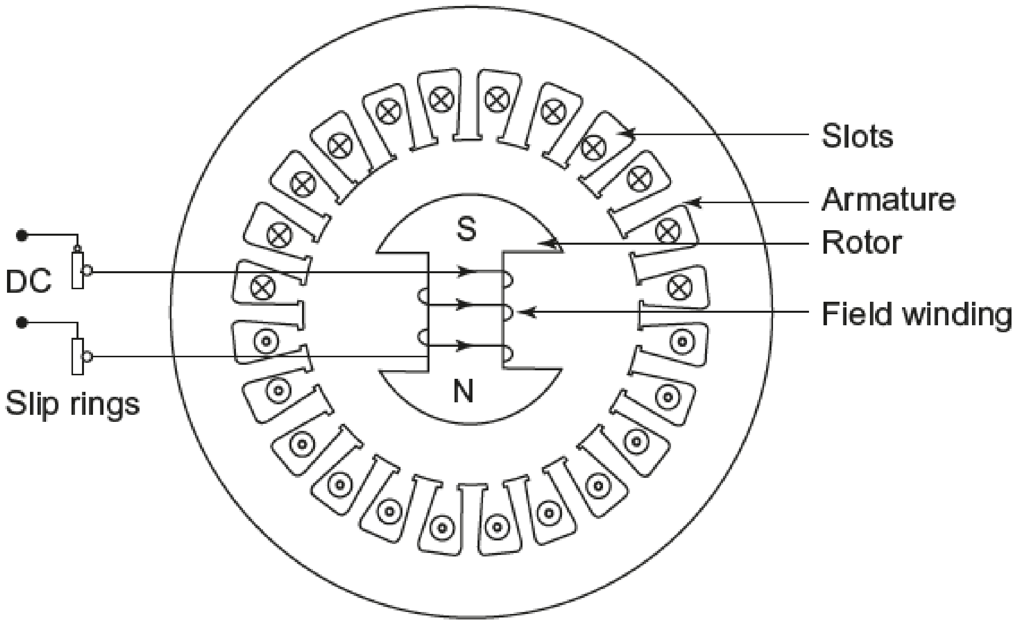
Two types of poles used are (i) Rectangular poles (ii) Round poles.

Round Poles : $L / \tau = 0.6$ to 0.7

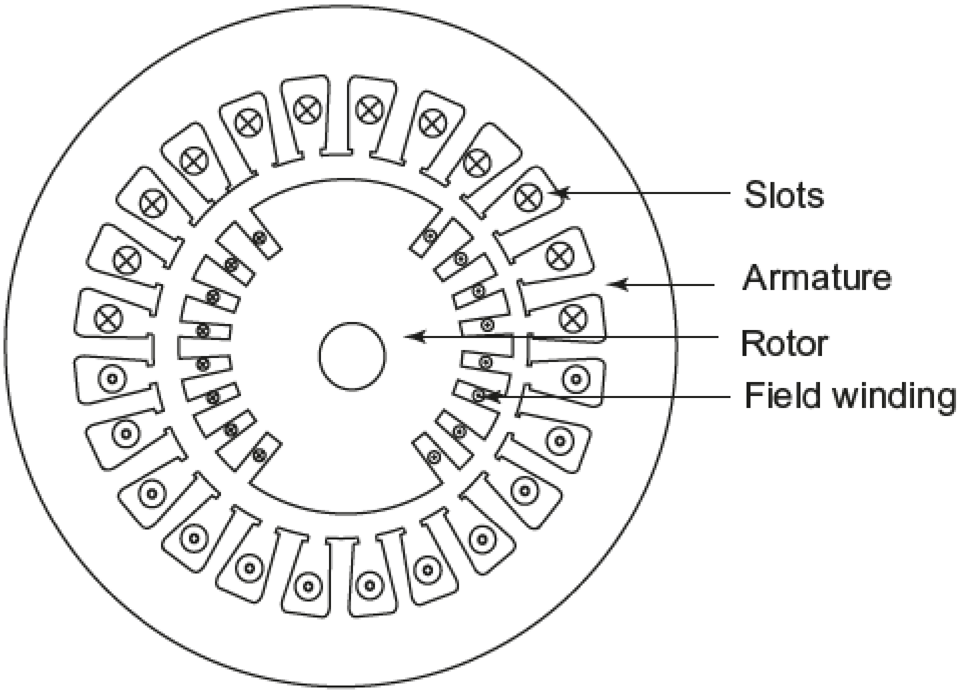
Rectangular Poles : $L / \tau = 1$ to 5







Salient pole synchronous machine



Cylindrical Rotor synchronous machine

Run away speed

The run-away speed is defined as the speed which the prime mover would have, if it is suddenly unloaded when working at its rated load.

Steam Turbine : 1.1 time the rated speed
Turbo Alternators : 1.25 time the rated speed
Pelton Wheel Turbine : 1.8 time the rated speed
Francis Turbine : 2 to 2.2 time the rated speed
Kaplan Turbine : 2.5 to 2.8 time the rated speed

Peripheral speed

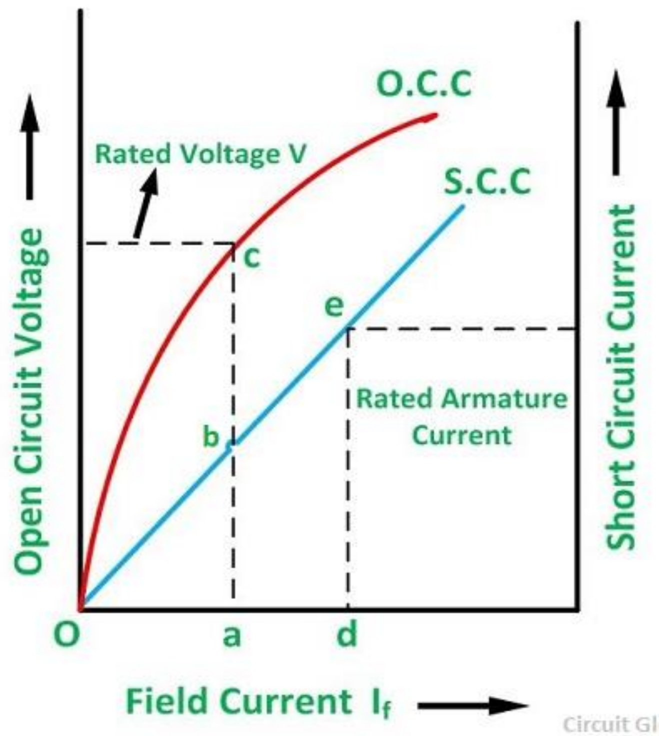
For bolted pole construction : 50 m / s

For dove tailed and T head construction : 80 m / s

Short Circuit Ratio (SCR)

The short circuit ratio is defined as the ratio of field current required to produce rated voltage on open circuit to field current required to circulate rated current on short circuit.

$$SCR = \frac{\text{Field current for OC voltage}}{\text{Field current for SC current}}$$



Effect of SCR on Machine Performance

- **Voltage regulation**
- **Stability**
- **Parallel Operation**
- **Short circuit current**
- **Self excitation**

Turns per phase

Turns per phase can be calculated from the emff equation of alternator,

$$\boxed{E_{ph} = 4.44 f \phi_m T_{ph} K_w}$$

$$\boxed{T_{ph} = \frac{E_{ph}}{4.44 f \phi_m K_w}}$$

Where E_{ph} - induced emf per phase,

f - frequency of induced emf,

T_{ph} - Number of turns per phase

K_w - winding factor

Current per phase

Current per phase $\boxed{I_{ph} = \frac{KVA \times 1000}{3 \times E_{ph}}}$

This is the current through the conductor, when all the turns pare phase are in series.
If there are 'A" number of parallel paths, then the current through the conductor is given by,

$$\boxed{I_Z = \frac{I_{ph}}{A}}$$

Area or cross-section of stator conductor

Area of cross section of stator conductor, $\boxed{a_s = \frac{I_Z}{\delta}}$

Current density In stator conductors δ = 3 to 5 A/mm²

Design of Damper winding

- Damper winding is used to reduce the oscillations developed in the rotor of alternator when it is suddenly loaded.
- Damper winding is used to start the synchronous motor as an induction motor.

Area per pole of damper bars, $\boxed{A_d = \frac{0.2ac\tau}{\delta_d}}$

Where ac - specific electric loading,

τ - pole pitch

δ_d - current density in the bars (3 to 5 A/mm^2)

Pole arc = Number of bars per pole x y_s x 0.8

= $N_d Y_s$ 0.8

Where y_s - slot pitch

Number of damper bars, $\boxed{N_d = \frac{polearc}{0.8y_s}}$

Length of damper bars, $\boxed{L_d = 1.1L}$

Area of cross-section of each damper bar, a_d = $\dfrac{\text{Total area or damper bars per pole}}{\text{Number of damper bars per pole}}$

$$\boxed{a_d = \frac{A_d}{N_d}}$$

For circular bars, $\boxed{a_d = \frac{\pi}{4} d_d^{\,2}}$

Where d_d - diameter of damper bars

Area of each ring short circuiting the bars, A_{ring} = (0.8 to 1) A_d

Design of Turbo Alternator

The values of specific loading for conventionally cooled generators

B_{av} = 0.54 to 0.65 wb/m²

ac = 50,000 to 75,000 Amp. Cond. / m

The values of specific loading for large water cooled generators

B_{av} = 0.54 to 0.62 wb/m²

ac = 1,80,000 to 2,00,000 Amp. Cond. / m

The maximum peripheral speed is 175 m/s

Length of Air gap

The length of air gap in induction motor is decided by

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

For small machines, length o f air gap $\boxed{l_g = 0.2 + 2\sqrt{DL}}$ in mm

or

$\boxed{l_g = 0.2 + D}$ in mm