EE 8002 DESIGN OF ELECTRICAL APPARATUS

UNIT I

DESIGN OF FIELD SYSTEM AND ARMATURE

Prepared by

Dr . T. Dharma Raj

Asso.Prof /EEE

1.1 Major Considerations in Electrical machine Design.

The major considerations to evolve a good design are i) Cost ii) Durablity iii) Compliance with performance Criteria as laid down in Specifications

1.2 Electrical Engineering Materials.

The Electrical Engineering materials are divided into following groups

a) Electrical Conducting Materials
b) Electrical Carbon Materials
c) Magnetic Materials
d) Insulating Materials.

a) Electrical Conducting materials

The Electrical Conducting materials are divided into two groups.

Electrical Conducting materials

- High conductivity materials
  - eg) Copper, aluminium
- High resistivity materials.
  - eg) Constantan, Manganin.

High conductivity materials.

These materials are used for making all types of windings required in electrical machines, apparatus and devices. These materials should have the least possible resistivity.

The fundamental Requirements of high conductivity materials are

i) least resistivity
ii) high conductivity
iii) low temperature coefficient of resistance.
iv) rollability and drawability
v) adequate resistance to corrosion
vi) good weldablity and salderability.

Copper

Hard drawn copper wires are used : electrical machines as wire drawing increases the mechanical strength although the resistivity also increases a little.

Aluminium

* Aluminium which is the conductor material next to copper is used
* Freely available conductor material.
* Pure Aluminium is softer than copper and therefore it can be rolled in to thin sheets.

High resistivity materials.

* Used for making resistances and heating device.
* Conductors of high resistance are used, where it is desired to dissipate electrical energy into heat.

Materials of high resistivity are primarily alloys of different metals. They are nickel, silver and iron. This alloys can be classified according to their purpose. The three categories are.

i) The first group consists of materials used for precision work. ie) measuring instruments, standard resistances and boxes.

The material used for this group is Manganin. it consists of Cu → 86%, Mn → 12%, Ni → 2%.

(Copper) (Magganin) (Nickel)

ii) The second group consists of materials used for Rheostats and control devices.

The material used for this group is Constantan. It Consists of cu 60 to 65% and 40 to 35% of Nickel.

iii) The third group consists of materials used for heating devices. ie) electric furnaces, loading Rheostats.

The material used for this group is alloys of nickel, chrominum and iron called Nichrome and alloy of aluminium iron and chromium.

* Aluminium cannot be drawn into very fine wires, due to its low mechanical strength.

* For induction motors with power outputs upto 100 kW, aluminium can be used as material for bars and squirrel cage. Die cast aluminium windings are extensively used for rotors of induction motors.

* Super enamelled aluminium wires are used for stator windings of small induction motors.

* Aluminium is also used for windings of transformers due to decrease of overall cost of the transformer.

* The use of aluminium in transformer tanks instead of steel tanks reduas the weight and stray load loss.

Alloys of copper

↓

Bronze

↓

i) Cadmium copper

* It is used for making contact wires and commutator segments

* it is also used for cage windings.

ii) Beryllium copper

* It is used for current carrying springs, brush holders, sliding contacts and knife switch blades.

Brass

↓

i) used in the manufacture of electrical apparatus

ii) it generally contains 66% Cu and 34% zinc.

Copper silver alloy

↓

i) used in turbo alternators, because of its resistance to thermal shortening and creep.

b) Electrical Carbon materials.

Electrical carbon materials are manufactured from graphite and other forms of carbon coal etc.

The conductivity of carbon used is slightly less than metals and alloys and therefore it is used for making brushes for electrical machines.

Brush carbons are often graphited to raise the conductivity of the brushes and reduces their hardness.

c) Magnetic materials

All magnetic materials posses magnetic properties to a greater (or) a lessor degree. The magnetic properties of materials are characterized by their relative permeablity.

Based on relative permeablity, the materials are classified into three types.

Ferromagnetic materials : The relative permeablity is much greater than unity and these permeablity values are dependent upon the magnetizing force.

Paramagnetic materials : These materials having μ_r only slightly greater ~~less~~ than unity. The value of susceptibility is thus positive for these materials.

Diamagnetic materials : These materials having μ_r only slightly less than unity.

Both Paramagnetic and Diamagnetic materials the value of permeablity is independent of the magnetising force.

Types of magnetic materials.

- Soft magnetic materials
- Hard magnetic materials

→ Solid core materials

→ Electrical sheet and strip

→ Special purpose alloys

Materials which are easy to magnetise and demagnetise are called <u>Soft magnetic materials</u>. These materials are used for making temporary magnets. These materials are used for making temporary magnets.

Solid core materials are used for parts of magnetic circuits carrying steady flux such as cores of dc electro-magnets, relays and field frames of dc machines.

Electrical sheet materials are used for the magnetic circuits of electrical machines and the cores of the transformers was iron with a low content of carbon and other impurities. This had one major disadvantage. that of <u>ageing</u>

Ageing is the term used to denote the deterioration of magnetic performance in service, caused by increase in

Coercive force and hysteresis loss which inturn caused cumulative overheating and subsequent breakdown.

In rotating electrical machines, ~~we~~ the use of steels with low silicon content are termed as dynamo grade steel.

The sheet steels possessing higher silicon content (4-5%) silicon are called transformer grade steels.

The Cold Rolled Grain oriented Steel (CRGO) is manufactured by a series of cold reductions and intermediate annealings. This cold reduced material has strong directional magnetic properties, the rolling direction being the direction of highest permeability. This direction is also the direction of lowest hysteresis loss.

Hard magnetic materials

materials which retain their magnetism and are difficult to demagnetise are called hard magnetic materials. These material retain their magnetism even after the removal of the applied magnetic field.

d) Insulating materials.

An ideal insulating material should have the following properties

* high dielectric strength
* igh resistivity or specific resistance.

* low dielectric hysteresis
* good thermal Conductivity
* high degree of thermal stability.

The following insulating materials are used in modern electrical machines.

mica, micafolium, Fibrous glass, ~~As~~ Asbestos, Cotton fibre, Synthetic Resin, Petroleum based mineral oils.

Applications of insulating materials.

* wires for magnet coils and windings of machines.
* lamitions
* machines and transformers.

Insulating material for laminations

The following are the common insulating materials for laminations.

i) Insuline

This is a kaolin mixture which is sprayed on to one or both sides of the lamination.

ii) Oxide.

A natural oxide ~~co~~ coating is formed on the sheets during hot rolling process, but this insulation cannot be depended upon as it may be inadequate.

iii) Varnish.

it makes the laminations rust proof and it is not affected by temperature produced in electrical Machines.

Insulating materials for machines

DC and AC motors and generators for industrial purposes are usually insulated with class A or E materials, but turbo generators, traction motors and aircraft machines are insulated with class B materials to enable higher operating temperatures to be used for the purpose of obtaining larger output from a given frame size.

Insulating materials for transformers.

* Fibrous materials are employed for both air cooled and oil cooled transformers.

* Cotton or oiled cambric is used for taping the Coils of air cooled transformer.

* Synthetic resin bonded paper is used for the insulation between core and Coils and also b/w primary and secondary winding.

* Press board or press paper is used as spacers, packing b/w coils.

Classification of Insulating Materials

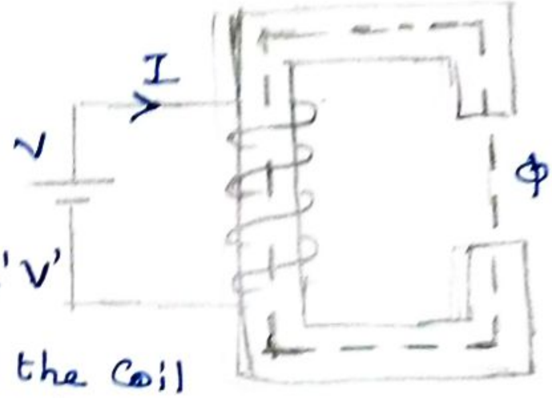
class	Temperature	materials
class Y (o)	90°C	Cotton, Silk, paper, wood Cellulose

Class A	105°c	materials of class impreganeted with natural resins Cellulose.
Class E	120° c	Synthetic resign enamels, Cotton and paper lamination
Class B	130° c	mica, glass, fibre, with suitable bonding Substances.
Class F	155° c	material of class B with bonding substances.
Class H	180° c	Glass Fibre and a material with silicon resins
Class C	above 180° c	Mica, Ceramics, glass, Quartz without binders

Magnetic circuit Calculations

1) Magnetic circuit

The path of magnetic flux is called magnetic circuit.



Consider a coil with "n" no:. of turns is wounded on a core is connected to supply voltage 'V'

The current flows through the coil creates the mmf and this mmf produce a flux in the core.

Important terms used in Magnetic circuit

i) MMF (magnetic motive force).

It is the ability of coil to produce magnetic flux

$$\left.\begin{aligned} mmf &= NI, \text{ also} \\ &= \phi S \end{aligned}\right\} \rightarrow ① \quad \text{Its unit is Ampere turns (AT).}$$

ii) Magnetic field Intensity (or) Magnetising force (H or at)

It is defined as mmf per unit length of flux path

$$(H \text{ or } at) = \frac{mmf}{l}.$$

From Equation ①

$$H = \frac{NI}{l}$$

$$H = \frac{\phi S}{l}$$

$$H = \frac{BAS}{l}$$

$$H = \frac{BAl}{\mu A} \Rightarrow \boxed{H = \frac{B}{\mu}}$$

Flux density B

$$B = \phi/A$$

$$\boxed{\phi = BA}$$

Reluctance S

$$S = \frac{l}{\mu A}$$

b) mmf Calculation for Airgap

mmf Calculation for Air gap is not easy. because of the following challenges.

i) One or both of the Iron Surfaces around the air gap may be slotted

→ Flux tends to concentrate on teeth

→ Non uniform distribution of flux in the air gap.

ii) There are radial ventilating ducts for Cooling

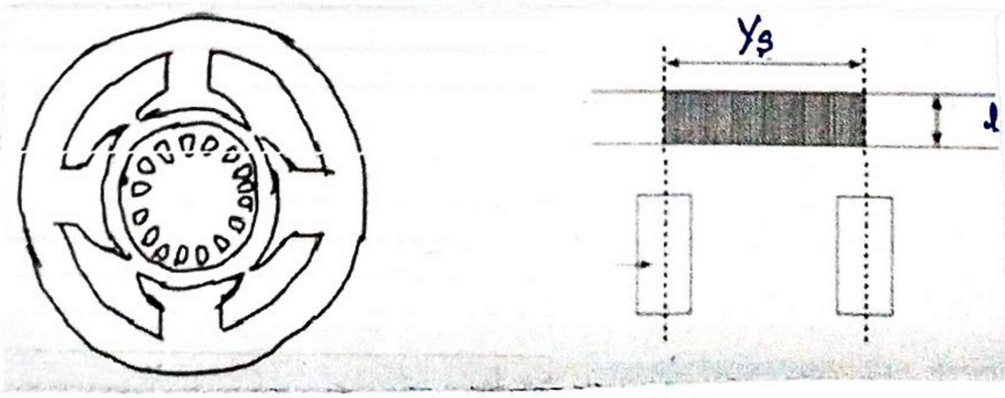
→ Contraction of flux in the axial direction

iii) Salient pole machines

→ non uniform air gap.

Because of the above Challenges, the reluctance of the airgap is not uniform, So it varies depends on the type of slots used.

Case I: Smooth iron Surfaces on both sides of the airgap (Flux distribution is uniform)



Reluctance of airgap $S_g = \frac{l_g}{\mu A} = \frac{l_g}{\mu_0 \mu_r A} = \frac{l_g}{\mu_0 A}$

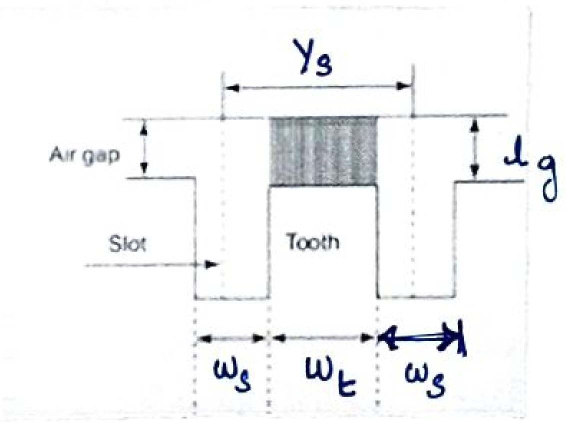
From the above figure

$A = L Y_s$

Reluctance of airgap of smooth Armature

$$\boxed{S_g = \frac{l_g}{\mu_0 L Y_s}}$$

Case - 2 (one of the surface is slotted)



Here we see the flux is concentrated on tooth width
Therefore the effective area of flux is decreased
ie) The reluctance of air gap is increased.

w_s = slot width (or) slot opening

w_t = tooth width

Y_s = slot pitch $= \frac{\pi D}{S}$

From the figure, $Y_s = w_t + w_s/2 + w_s/2$

$$Y_S = W_t + W_s$$

Reluctance of airgap of slotted Armature $S_g = \frac{l_g}{\mu_0 A}$

From the figure, $A = L Y_s'$

$$Y_s' = W_t$$

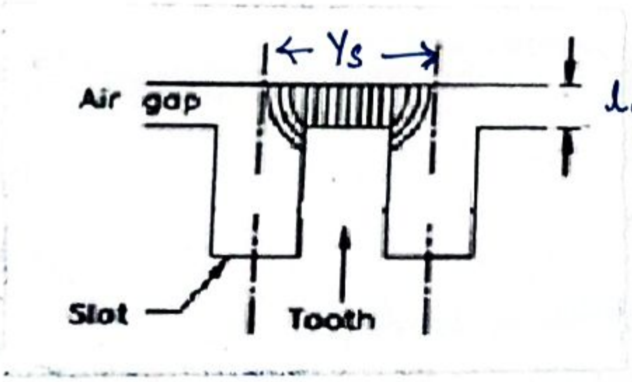
(or)

$$Y_s' = Y_s - W_s$$

Reluctance of airgap of slotted Armature

$$\boxed{S_g = \frac{l_g}{\mu_0 L Y_s'} = \frac{l_g}{\mu_0 L (Y_s - W_s)}}$$

In slotted Armature, the flux will not pass like a straight line towards the tooth. But in practical, the flux would fringe around the tooth and this fringing of flux would increase the area of cross section of flux path.



From the Figure, $A = L Y_s'$

$$Y_s' = W_t + \delta W_s$$

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

$$= (W_t + W_s) + \delta W_s - W_s$$

$$Y_s' = Y_s + w_s(\delta - 1)$$

$$Y_s' = Y_s - w_s(1-\delta)$$

$$Y_s' = Y_s - w_s k_{cs}$$

where k_{cs} is the Carter's coefficient for slots. It depends on the ratio $\frac{\text{slot width}}{\text{gap length}}$.

For parallel sided open slots (Induction motor)

$$k_{cs} = \frac{2}{\pi}\left[\underbrace{\tan^{-1} y}_{\text{(radian mode)}} - \frac{1}{y}\log\sqrt{1+y^2}\right]$$

where $y = \frac{w_s}{2l_g}$

Therefore, $A = L(Y_s - w_s k_{cs})$

Reluctance of air gap with slotted armature is

$$S_g = \frac{l_g}{\mu_0 L Y_s'} = \frac{l_g}{\mu_0 L(Y_s - k_{cs} w_s)}$$

Gap contraction factor for slots (k_{gs}) is defined as the ratio of

$$k_{gs} = \frac{\text{Reluctance of airgap of slotted Armature}}{\text{Reluctance of air gap of Smooth Armature}}$$

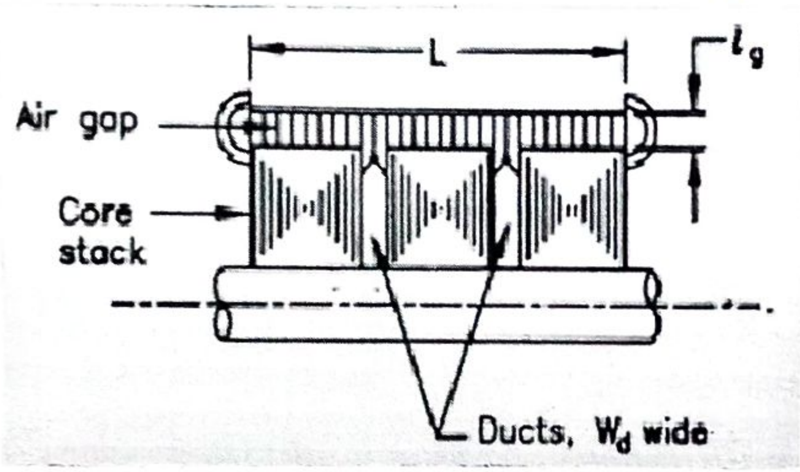
$$k_{gs} = \frac{\dfrac{l_g}{\mu_0 L Y_s'}}{\dfrac{l_g}{\mu_0 L . Y_s}}$$

$$k_{gs} = \frac{l_g}{\mu_0 L y_s'} \times \frac{\mu_0 L y_s}{l_g}$$

$$k_{gs} = \frac{y_s}{y_s'}$$

$$\boxed{k_{gs} = \frac{y_s}{y_s - k_{cs} w_s}}$$

Case - 3 : Effect of Ventilating Ducts



From the figure, it is seen that length of the core is reduced due to the presence of radial ventialating Ducts

Therefore effective length L' is

$$L' = L - k_{cd} n_d w_d$$

Where

$k_{cd} \rightarrow$ Carter Coefficient of ducts

$n_d \rightarrow$ number of Ducts

$W_d \rightarrow$ width of duct.

Carter Coefficient of Ducts depends on the ratio

$$\frac{\text{Duct width}}{\text{Air gap length}}$$

The empirical formula used for parallel sided open Slots is

$$K_{cd} = \frac{2}{\pi}\left[\tan^{-1} y - \frac{1}{y}\log\sqrt{(1+y^2)}\right]$$

$$\text{where } y = \frac{w_d}{2 l_g}.$$

Gap contraction factor for ducts (K_{gd}) is defined as the ratio of

$$K_{gd} = \frac{\text{Reluctance of air gap of Slotted armature with ducts}}{\text{Reluctance of air gap of Slotted armature without Ducts.}}$$

$$K_{gd} = \frac{\dfrac{l_g}{\mu_0 L' Y_s'}}{\dfrac{l_g}{\mu_0 L Y_s'}}$$

$$K_{gd} = \frac{l_g}{\mu_0 L' Y_s'} \times \frac{\mu_0 L Y_s'}{l_g}$$

$$K_{gd} = \frac{L}{L'}$$

$$\boxed{K_{gd} = \frac{L}{L - K_{cd} n_d w_d}}$$

Total gap contraction factor (k_g) is defined as the ratio of

$$k_g = \frac{\text{Reluctance of airgap of slotted Armature with Ducts}}{\text{Reluctance of airgap of Smooth Armature}}$$

$$k_g = \frac{\dfrac{l_g}{\mu_0 L' y_s'}}{\dfrac{l_g}{\mu_0 L y_s}}$$

$$k_g = \frac{l_g}{\mu_0 L' y_s'} \times \frac{\mu_0 L y_s}{l_g}$$

$$k_g = \frac{L}{L'} \times \frac{y_s}{y_s'}$$

$$\boxed{k_g = k_{gd} \times k_{gs}}$$

When both stator and rotor are slotted, then

$$k_{gs} = k_{gss} \times k_{gsr}$$

where

$k_{gss} \rightarrow$ gap contraction factor for stator slots.

$k_{gsr} \rightarrow$ gap contraction factor for rotor slots.

Therefore this gap contraction factor which explains the relation b/w reluctance of smooth armature and the reluctance slotted armature with and without ducts. By using this factor, we can easily find the mmf required for air gap.

Calculation for mmf :

we know that

mmf / unit length is called magnetising force (H or at)

$$\text{at or } H = \frac{mmf}{l}$$

$$= \frac{\phi S}{l}$$

$$= \frac{BAl}{l\mu A}$$

$$H = \frac{B}{\mu}$$

$$\therefore \quad mmf / \text{unit length} = \frac{B}{\mu}$$

$$mmf = \frac{Bl}{\mu} \Rightarrow AT = \frac{Bl}{\mu}$$

$$\boxed{\underset{(AT)}{mmf} = \frac{Bl}{\mu_0 \mu_r} = \frac{Bl}{4\pi \times 10^{-7} \mu_r}}$$

By using the above concept,

→ The mmf Required for airgap of Smooth armature

$$AT_g = \frac{B_{av}\, l_g}{4\pi \times 10^{-7} \times 1}$$ For air $\mu_r = 1$

$$\boxed{AT_g = 8{,}00{,}000\, B_{av}\, l_g}$$ → For Smooth Armature

But for Slotted Armature, the mmf Required for air gap is greater than the mmf Required for Smooth armature. Therefore mmf Required for air gap of Slotted Armature is kg greater than mm Required for airgap of Smooth Armature.

→

MMF Required for airgap of Slotted Armature is

= kg x mmf Required for airgap of Smooth Armature

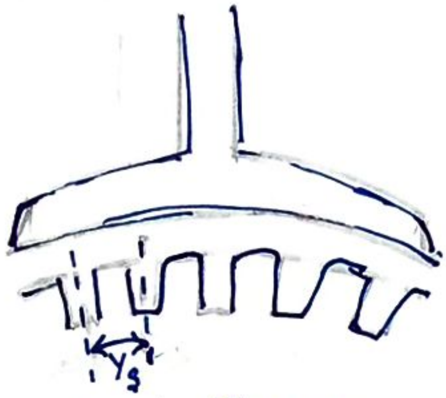
$$\boxed{AT_g = 8{,}00{,}000\, k_g\, B_{av}\, l_g}$$ → For Slotted Armature

Due to Slotting in the Armature, the air gap length is increased but air gap area is decreased.

Therefore the effective air gap length (l_g') is given by $k_g l_g$

The effective air gap area (A_g') is given by

$$\boxed{A_g' = \frac{A_g}{k_g}}$$



From the above Figure

Air gap area/pole = Slots/pole x Slot pitch x Core length

$$A_g = \frac{S}{P} \times Y_s \times L$$

$$\boxed{A_g = \frac{S}{P} \times \underbrace{Y_s}_{\frac{\pi D}{S}} \times L} \quad \text{or} \quad \boxed{A_g = \frac{\pi D L}{P}}$$

→ In case of Salient pole machies, the flux density is not uniform over the air gap.

At the pole centre, the flux density is Maximum, hence B_{av} is replaced by B_g.

Mmf Required for air gap of Salient pole Machine is

$$\boxed{AT_g = 8,00,000\ k_g B_g l_g}$$

Calculate the mmf Required for the airgap of a machine having Core length of 0.32 m including 4 ducts of 10 mm each. Pole arc = 0.19 m, Slot pitch = 65.4 mm, Slot opening = 5mm, airgap length = 5mm, flux per pole = 52 mwb. Given Carter's Coefficient is 0.18 for opening/gap = 1 and is 0.28 opening/gap is 2.

Given data

$L = 0.32\,m$, $n_d = 4$, $w_d = 10\,mm$, pole arc $= 0.19\,m$,
$Y_s = 65.4\,mm$, $w_s = 5\,mm$, airgap length $= 5\,mm$,
$\phi = 52\,mwb$, For opening/gap $= 1$, then Carter coefficient is 0.18. For opening/gap $= 2$, then Carter coefficient $= 0.28$.

To find

MMF required for air gap of DC machine

Solution

$$AT_g = 8{,}00{,}000\ B_g\, l_g\, k_g.$$

$$AT_g = 8{,}00{,}000\ B_g \times 5\times10^{-3} \times k_g \rightarrow (1)$$

We know that

$$k_f = \frac{\text{pole arc}}{\text{pole pitch}} = \frac{B_{av}}{B_g}$$

$$\frac{0.19}{\frac{\pi D}{P}} = \frac{\frac{P\phi}{\pi D L}}{B_g}$$

$$0.19\,B_g = \frac{P\phi}{\pi D L} \times \frac{\pi D}{P}$$

$$0.19\,B_g = \frac{\phi}{L}$$

$$B_g = \frac{\phi}{0.19 \times L}$$

$$B_g = \frac{52 \times 10^{-3}}{0.19 \times 0.32}$$

$$B_g = \underline{\underline{0.8553}}\ \text{wb/m}^2$$

we know that

$$k_g = \frac{L}{L'} * \frac{Y_s}{Y_s'} \rightarrow (2)$$

we know that

$$L' = L - k_{cd}\, n_d\, w_d$$

$$L' = L - k_{cd} \times 4 \times 10 \times 10^{-3} \rightarrow (3)$$

k_{cd} depends on the ratio $\frac{\text{duct opening}}{\text{air gap length}}$

$$\frac{\text{Duct openining}}{\text{air gap length}} = \frac{10 \times 10^{-3}}{5 \times 10^{-3}} = 2.$$

Given Carter Coefficient is 0.28, for opening/airgap length $= 2$

$$\therefore\ k_{cd} = 0.28$$

From equation (3)

$$L' = 0.32 - (0.28 \times 4 \times 10 \times 10^{-3})$$

$$L' = \underline{0.3088}, m$$

We know that

$$Y_s' = Y_s - K_{cs} W_s.$$

~~We know that~~

$$Y_s' = (65.4 \times 10^{-3}) - (K_{cs} \times 5 \times 10^{-3}) \rightarrow (4)$$

K_{cs} depends on the ratio $\frac{\text{slot opening}}{\text{air gap length}}$.

$$\frac{\text{slot opening}}{\text{air gap length}} = \frac{5 \times 10^{-3}}{5 \times 10^{-3}} = 1$$

Given Carter coefficient is 0.18, for $\frac{\text{opening}}{\text{airgaplength}} = 1$

$$\therefore K_{cs} = 0.18$$

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From Eq (4)

$$Y_s' = (65.4 \times 10^{-3}) - (0.18 \times 5 \times 10^{-3})$$

$$Y_s' = \underline{0.0645}, m$$

From Equation (2)

$$k_g = \left(\frac{0.32}{0.3088}\right) \times \left(\frac{(65.4 \times 10^{-3})}{0.0645}\right)$$

$$K_g = 1.0507$$

Substitute K_g and B_g value in equation (1)

$$AT_g = 8,00,000 \times 0.8553 \times 5\times10^{-3} \times 1.0507$$

$$AT_g = 3594.7541 \text{ , AT}$$

Ans

$$AT_g = 3594.7541 \text{ , AT.}$$

The stator of a machine has a smooth surface but its rotor has open type slots with slot width = tooth width = 12 mm and the length of air gap is 2 mm. Find the effective length of air gap, If the carter's coefficient is equal to $\frac{1}{1+5l_g/w_s}$. There are no radial ducts.

Given data

$w_s = w_t = 12 \times 10^{-3}$ m, $l_g = 2 \times 10^{-3}$ m, $k_{cs} = \frac{1}{1+5l_g/w_s}$

To find

Effective length of air gap (l_g')

Solution

The effective length of air gap is given by

$$l_g' = k_g l_g$$

$$l_g' = k_g \times (2 \times 10^{-3}) \rightarrow (1)$$

where $k_g = k_{gs} \times k_{gd} \rightarrow (2)$

Given there is no radial Ducts, $\therefore k_{gd} = 1$

$$k_{gs} = \frac{Y_s}{Y_s'}$$

$$k_{gs} = \frac{Y_s}{Y_s - k_{cs} w_s} \rightarrow (3)$$

$$Y_s = \omega_t + \omega_s$$

$$= (12 \times 10^{-3}) + (12 \times 10^{-3})$$

$$Y_s = \underline{24 \times 10^{-3}}, \ m$$

Given $k_{cs} = \dfrac{1}{1 + 5 l_g / \omega_s}$

$$k_{cs} = \frac{1}{1 + \left(\dfrac{5 \times 2 \times 10^{-3}}{12 \times 10^{-3}}\right)}$$

$$k_{cs} = \frac{1}{1 + \left(\frac{10}{12}\right)} \Rightarrow k_{cs} = \underline{0.5455}$$

From Equation 3

$$k_{gs} = \frac{(24 \times 10^{-3})}{((24 \times 10^{-3}) - (0.5455 \times 12 \times 10^{-3}))}$$

$$k_{gs} = \underline{1.375}$$

From Equation 2

$$k_g = 1.375 \times 1 \Rightarrow k_g = 1.375$$

From Equation 1

$$l_g' = 1.375 \times (2 \times 10^{-3}) = 0.0028 \ m$$

$$l_g' = \underline{2.8}, \ mm$$

Answer

The effective air gap length $(l_g') = \underline{2.8}$ mm

Determine the air gap length of a DC machine from the following particulars. gross length of core = 0.12 m, no:: of ducts = 1 and is 10 mm wide, slot pitch = 25 mm, slot width = 10 mm, Carter's Coefficient for slots and ducts = 0.32. The gap density at pole centre = 0.7 wb/m². field mmf / pole = 3900 AT, mmf Required for iron parts of magnetic circuit. is 800 AT

Given data

$L = 0.12\,m$, $n_d = 1$, $w_d = 10 \times 10^{-3}\,m$, $y_s = 25 \times 10^{-3}\,m$, $w_s = 10 \times 10^{-3}\,m$, $k_{cs} = k_{cd} = 0.32$, $B_g = 0.7\,wb/m^2$, $AT_f = 3900\,AT$, mmf Required for Iron part = 800 AT

To find

Air gap length (l_g)

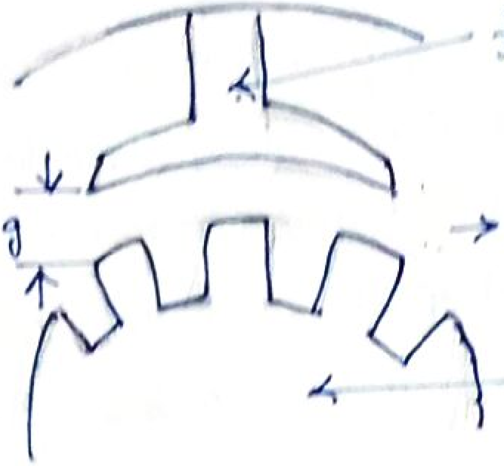
Solution

Mmf Required for airgap of DC Machine is given by (Salient pole M/c)

$$AT_g = 8{,}00{,}000\, B_g k_g l_g$$

$$l_g = \frac{AT_g}{8{,}00{,}000\, B_g k_g}$$

$$l_g = \frac{AT_g}{8{,}00{,}000 \times 0.7 \times k_g} \longrightarrow (1)$$



From the Figure,

Field mmf/pole = mmf Required for air gap + mmf Required for iron parts

$$3900 = \text{mmf Required for air gap} + 800$$

Mmf Required for Air gap $(AT_g) = 3900 - 800$

$$AT_g = \underline{\underline{3100}}\ AT$$

we know that $k_g = k_{gs} \cdot k_{gd} \rightarrow (2)$

$$k_{gs} = \frac{Y_s}{Y_s'} = \frac{Y_s}{Y_s - k_{cs} w_s}$$

$$k_{gs} = \frac{25\times10^{-3}}{(25\times10^{-3}) - (0.32\times10\times10^{-3})}$$

$$k_{gs} = 1.1468$$

$$k_{gd} = \frac{L}{L'} = \frac{L}{L - k_{cd}\, n_d\, \omega_d}$$

$$k_{gd} = \frac{0.12}{0.12 - (0.32 \times 1 \times 10 \times 10^{-3})}$$

$$k_{gd} = 1.0274$$

From Equation (2)

$$k_g = 1.1468 \times 1.0274$$

$$k_g = \underline{\underline{1.1782}}$$

From Equation (1)

$$l_g = \frac{3100}{8,00,000 \times 0.7 \times 1.1782}$$

$$l_g = 0.0047 \text{ m} = \underline{\underline{4.7}} \text{ mm}$$

Answer

Air gap length $l_g = \underline{\underline{4.7}}$ mm

A 15 kw, 230V, 4 pole dc machine has the following data.

Armature diameter = 0.25 m, armature core length = 0.125 m, length of air gap at pole centre = 2.5 mm, flux per pole = 11.7×10^{-3} wb, ratio of $\frac{\text{Pole arc}}{\text{Pole pitch}} = 0.66$

Calculate the mmf Required for the air gap for

i) If the armature surface is treated as smooth.

ii) If the armature is slotted and the gap contraction factor is 1.18

Given data

$P_o = 15$ kw, $V = 230V$, $P = 4$, $D = 0.25$ m, $L = 0.125$ m,

$l_g = 2.5$ mm $= 2.5 \times 10^{-3}$ m, $\phi = 11.7 \times 10^{-3}$,

$$k_f = \frac{\text{Pole arc}}{\text{pole pitch}} = \frac{B_{av}}{B_g} = 0.66, \quad k_g = 1.18$$

To find

i) Mmf Required for smooth Armature.

ii) Mmf Required for slotted Armature.

Solution

i) MMF Required for airgap of smooth Armature

$$AT_g = 8,00,000\, B_g l_g.$$

$$AT_g = 8,00,000 \times B_g \times 2.5 \times 10^{-3} \rightarrow (1)$$

Given

$$\frac{\text{Pole arc}}{\text{pole pitch}} = \frac{B_{av}}{B_g} = 0.66$$

$$\frac{B_{av}}{B_g} = 0.66$$

We know that

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

$$\frac{\frac{P\phi}{\pi DL}}{B_g} = 0.66$$

$$\frac{\left(\frac{4 \times 11.7 \times 10^{-3}}{\pi \times 0.25 \times 0.125}\right)}{0.66} = B_g$$

$$\frac{0.4767}{0.66} = B_g$$

$$B_g = \underline{\underline{0.7223}}\ wb/m^2$$

From Equation (1)

$$AT_g = 8,00,000 \times 0.7223 \times 2.5 \times 10^{-3}$$

$$AT_g = \underline{\underline{1444.5481}}\ AT$$

ii) MMF Required for Airgap of Slotted Armature

$$AT_g = 8,00,000\ B_g k_g l_g$$

$$AT_g = 8,00,000 \times 0.7233 \times 1.18 \times 2.5 \times 10^{-3}$$

$$AT_g = \underline{\underline{1704.628}}\text{, AT}$$

Answers

i) mmf Required for airgap of Smooth Armature

$$AT_g = \underline{\underline{1444.5481}}\text{, AT}$$

ii) mmf Required for airgap of Slotted Armature

$$AT_g = \underline{\underline{1704.628}}\text{, AT}$$

Calculate the mmf Required for airgap of a DC machine with an axial length of 20 cm (No ducts) and a pole arc of 18 cm, the slot pitch is 27 mm, slot opening = 12 mm, air gap = 6mm and the useful flux/pole = 27 mWb. Take Carter's coefficient for slot as 0.3.

Given data

$L = 20\text{ cm} = 20 \times 10^{-2}\text{ m}$, Pole arc $= 18\text{ cm} = 18 \times 10^{-2}\text{ m}$

$Y_s = 27 \times 10^{-3}\text{ m}$, $W_s = 12 \times 10^{-3}\text{ m}$, $l_g = 6 \times 10^{-3}\text{ mm}$, $\phi = 27 \times 10^{-3}\text{ wb}$,

$K_{cs} = 0.3$

To find

Mmf Required of airgap of DC machine

Solution

MMF Required for airgap of DC machine (Salient pole)

$$AT_g = 8{,}00{,}000\, k_g B_g l_g$$

$$AT_g = 8{,}00{,}000 \times k_g \times B_g \times 6 \times 10^{-3} \rightarrow (1)$$

We know that

$$k_g = k_{gs} \times k_{gd}$$

$$k_g = \frac{Y_s}{Y_s'} \times \frac{L}{L'}$$

$$k_g = \frac{Y_s}{(Y_s - k_{cs} \omega_s)} \times \frac{L}{(L - K_{cd} n_d \omega_d)}$$

In this problem, ducts are not used, Hence $n_d = 0$

$$k_g = \frac{(27 \times 10^{-3})}{((27 \times 10^{-3}) - (0.3 \times 12 \times 10^{-3}))} \times \frac{20 \times 10^{-2}}{(20 \times 10^{-2} - 0)}$$

$$k_g = 1.1538 \times 1$$

$$\underline{\underline{K_g = 1.1538}}$$

we know that

$$k_f = \frac{\text{Pole arc}}{\text{Pole pitch}} = \frac{B_{av}}{B_g}$$

$$\frac{18 \times 10^{-2}}{\frac{\pi D}{P}} = \frac{\frac{P\phi}{\pi D L}}{B_g}$$

$$B_g \times 18 \times 10^{-2} = \frac{P\phi}{\pi D L} \times \frac{\pi D}{P}$$

$$B_g \times 18 \times 10^{-2} = \frac{\phi}{L}$$

$$B_g = \frac{\phi}{18 \times 10^{-2} \times L}$$

$$B_g = \frac{27 \times 10^{-3}}{18 \times 10^{-2} \times 20 \times 10^{-2}} \Rightarrow \frac{27 \times 10^{-3}}{18 \times 20 \times 10^{-4}}$$

$B_g = \underline{0.75}\ wb/m^2$

From Equation (1)

$$AT_g = 8,00;000 \times 1.1538 \times 0.75 \times 6 \times 10^{-3}$$

$$AT_g = \underline{4153.6800},\ AT$$

Answers

mmf Requiered for Airgap for DC machine

$$AT_g = \underline{4153.6800},\ AT$$

Estimate the effective gap area / pole of a 12 pole slip ring Induction motor with following data.

Stator bore = 0.7 m, Core length = 0.3 m, No of Stator slots = 90, stator slot opening = 3 mm, rotor slots = 120, rotor slot opening = 3 mm, Carter's Coefficient for ducts = 0.68, Carter's Coefficient for slots = 0.46, No. of Ventilating ducts = 3 each on Stator and rotor, width of each ventilating duct = 10 mm, airgap length = 0.95 mm.

Given data

$P = 12$, $D = 0.7\,m$, $L = 0.3\,m$, $S_s = 90$, $\omega_{ss} = 3 \times 10^{-3}\,m$

$S_r = 120$, $\omega_{sr} = 3 \times 10^{-3}\,m$, $k_{cd} = 0.68$, $k_{cs} = 0.46$,

$n_d = 3$, on Stator and rotor, $\omega_d = 10 \times 10^{-3}\,m$,

$l_g = 0.95 \times 10^{-3}\,mm$.

To find

Effective gap area / pole (A_g')

Solution

Effective gap area / pole

$$A_g' = \frac{A_g}{k_g} \rightarrow (1)$$

$A_g \rightarrow$ Gap area / pole

$$A_g = \frac{\pi D L}{P}$$

$$= \frac{\pi \times 0.7 \times 0.3}{12}$$

$$A_g = \underline{0.0550}\ m^2$$

we know that

$$k_g = k_{gs} \times k_{gd} \rightarrow (2)$$

For Induction motor, Both stator and rotor have slots.

$$k_{gs} = k_{gss} \times k_{gsr} \rightarrow (3)$$

where $k_{gss} \rightarrow$ gap contraction factor for stator slots

$k_{gsr} \rightarrow$ gap contraction factor for Rotor slots.

$$k_{gss} = \frac{Y_{ss}}{Y_{ss}'}$$

$$k_{gss} = \frac{Y_{ss}}{Y_{ss} - k_{cs} w_{ss}} \rightarrow (4)$$

we kno that

$$Y_{ss} = w_{ts} + w_{ss} = \frac{\pi D}{S_s}.$$

From the given data

$$Y_{ss} = \frac{\pi D}{S_s}$$

$$Y_{ss} = \frac{\pi \times 0.7}{90}$$

$$Y_{ss} = \underline{\underline{0.0244}}, \text{ m.}$$

From Equation 4

$$k_{gss} = \frac{0.0244}{(0.0244 - (0.46 \times 3\times10^{-3}))}$$

$$k_{gss} = \underline{\underline{1.0599}}$$

$$k_{gsr} = \frac{Y_{sr}}{Y'_{sr}}$$

$$k_{gsr} = \frac{Y_{sr}}{(Y_{sr} - k_{cs} w_r)}$$

$$Y_{sr} = wt_r + w_{sr} = \frac{\pi D_r}{S_r}$$

$$D_r = D - 2l_g$$

$$D_r = 0.7 - (2 \times 0.95 \times 10^{-3})$$

$$D_r = \underline{\underline{0.6981}} \text{ m}$$

$$Y_{sr} = \frac{\pi \times 0.6981}{120}$$

$$Y_{sr} = \underline{\underline{0.0183}}$$

$$k_{gsr} = \frac{0.0183}{(0.0183 - (0.46 \times 3 \times 10^{-3}))}$$

$$k_{gsr} = \underline{\underline{1.0816}}$$

From Equation (3)

$$k_{gs} = 1.0599 \times 1.0816$$

$$k_{gs} = \underline{\underline{1.1463}}$$

$$k_{gd} = \frac{L}{L'}$$

$$= \frac{L}{L - k_{cd} n_d \omega_d}$$

$$k_{gd} = \frac{0.3}{0.3 - (0.68 \times 3 \times 10 \times 10^{-3})}$$

$$k_{gd} = \underline{\underline{1.0730}}$$

From Equation (2)

$$k_g = 1.1463 \times 1.073$$

$$k_g = 1.23$$

From Equation (1)

$$A_g' = \frac{0.055}{1.23}$$

$$A_g' = \underline{\underline{0.0447}},\ m^2$$

<u>Answers</u>

Gap area/pole = $\underline{0.055}$, m^2

Gap Contraction factor k_g = $\underline{\underline{1.23}}$

Effective gap area/pole = $\underline{\underline{0.0447}}$, m^2

A 175 MVA, 20 pole water wheel generator has a core length of 1·72 m and a diameter of 6.5 m. The stator slots (open) have a width of 22 mm. the slot pitch being 64 mm and the air gap length at the centre of pole is 30 mm. There are 41 radial ventilating ducts each 6mm wide. The total mmf/pole is 27000 A, The mmf required for the air gap is 87% of the total mmf per pole. Estimate the average flux density in the air gap, if the field form factor is 0·7.

Given data

$Q = 175$ MVA, $P = 20$, $L = 1·72$ m, $D = 6·5$ m, $W_s = 22$ mm $= 22 \times 10^{-3}$, $Y_s = 64$ mm $= 64 \times 10^{-3}$ m, $l_g = 30$ mm $= 30 \times 10^{-3}$ m

$n_d = 41$, $W_d = 6 \times 10^{-3}$ m, Total mmf/pole $= 27000$ A,

$AT_g = 87\%$ of total mmf/pole, $K_f = 0·7$

To find

Average flux density (B_{av})

Solution

$$AT_g = 8,00,000\, k_g B_g l_g \quad \text{(for salient pole m/c)}$$

$$B_g = \frac{AT_g}{8,00,000 \times k_g \times l_g}$$

$$B_g = \frac{AT_g}{8,00,000 \times k_g \times 30 \times 10^{-3}} \rightarrow (1)$$

Given $AT_g = 87\%$ of total mmf/pole

$$AT_g = 0.87 \times 27,000$$

$$AT_g = \underline{\underline{23490}}, \text{ AT}$$

we know that

$$k_g = \frac{L}{L'} \times \frac{Y_s}{Y_s'}$$

$$k_g = \frac{1072}{L'} \times \frac{64 \times 10^{-3}}{Y_s'} \rightarrow (2)$$

$$L' = L - k_{cd}\, n_d\, w_d$$

$$L' = 1072 - (k_{cd} \times 41 \times 6 \times 10^{-3}) \longrightarrow (3)$$

$$k_{cd} = \frac{2}{\pi}\left[\tan^{-1} y - \frac{1}{y} \log\sqrt{(1+y^2)}\right.$$

For ducts, $y = \dfrac{w_d}{2l_g}$

$$y = \frac{6 \times 10^{-3}}{2 \times 30 \times 10^{-3}} = 0.1$$

$$k_{cd} = \frac{2}{\pi}\left[\underset{\text{radian}}{\tan^{-1} 0.1} - \frac{1}{0.1} \log\sqrt{(1+0.1^2)}\right.$$

$$= \frac{2}{\pi}\left[0.0997 - (10 \times 0.0022)\right]$$

$$k_{cd} = \underline{\underline{0.0497}}$$

From Equation (3)

$$L' = 1.72 - (0.0497 \times 41 \times 6 \times 10^{-3})$$

$$L' = \underline{\underline{1.7078}}, \ m.$$

$$Y_s' = Y_s - K_{cs} W_s$$

$$Y_s' = (64 \times 10^{-3}) - (K_{cs} \times 22 \times 10^{-3}) \rightarrow (4)$$

$$K_{cs} = \frac{2}{\pi}\left[\tan^{-1} y - \frac{1}{y} \log \sqrt{(1+y^2)}\right]$$

For Slots, $y = \dfrac{W_s}{2 l_g}$

$$y = \frac{22 \times 10^{-3}}{2 \times 30 \times 10^{-3}} = 0.3667$$

$$K_{cs} = \frac{2}{\pi}\left[\underset{\text{radian}}{\tan^{-1} 0.3667} - \frac{1}{0.3667} \log \sqrt{(1 + 0.3667^2)}\right]$$

$$K_{cs} = \frac{2}{\pi}\left[0.3515 - (2.7270 \times 0.0274)\right]$$

$$K_{cs} = \underline{\underline{0.1762}}$$

From Equation (4)

$$Y_s' = (64 \times 10^{-3}) - (0.1762 \times 22 \times 10^{-3})$$

$$y_s' = \underline{\underline{0.0601}}$$

From Equation (2)

$$k_g = \frac{1.072}{1.07078} \times \frac{64 \times 10^{-3}}{0.0601}$$

$$k_g = 1.0071 \times 1.0649$$

$$k_g = \underline{\underline{1.0725}}$$

From Equation (1)

$$B_g = \frac{23490}{8,00,000 \times 1.0725 \times 30 \times 10^{-3}}$$

$$B_g = \underline{\underline{0.9126}}, \ wb/m^2$$

~~From~~ We know that form factor $k_f = \frac{B_{av}}{B_g}$

$$\therefore \ B_{av} = B_g \times k_f$$

$$B_{av} = 0.9126 \times 0.7$$

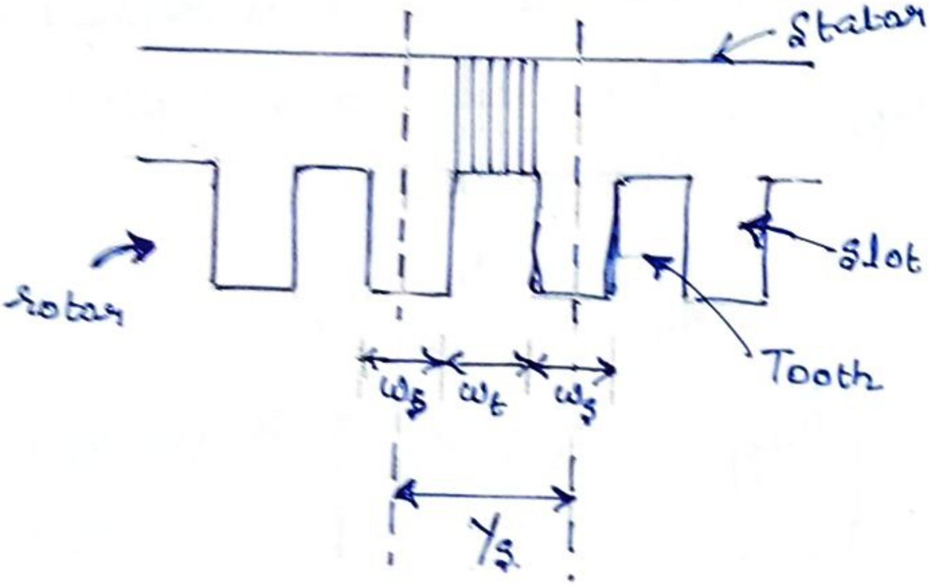
$$B_{av} = \underline{\underline{0.6388}}, \ wb/m^2$$

Ans

$$B_{av} = \underline{\underline{0.6388}}, \ wb/m^2$$

Real and apparent flux densities

Consider a rotating machine, the stator flux passes through the airgap and enter to the rotor.



$$Y_s = \omega_t + \omega_s/2 + \omega_s/2$$

$$\boxed{Y_s = \omega_t + \omega_s}$$ where $\omega_t \to$ tooth width

$\omega_s \to$ Slot width (or) Slot opening

$Y_s \to$ Slot pitch.

Tooth Area $(A_t) = L_i \omega_t$

where L – length of the core.

From this figure, we observed that the major part of the flux from stator passes through the tooth.

At lower flux densities, the flux passing through slot can be neglected. But at higher flux densities, flux from stator choose an alternate path through slot due to magnetic saturation at tooth.

Hence the real flux passing through the teeth is always less than the total (Apparent) flux

As a result, the real flux density in the tooth is always less than the apparent flux density

The apparent flux density is defined as

$$B_{app} = \frac{\text{Total flux in a slot pitch}}{\text{Tooth Area}}$$

$$\boxed{B_{app} = \frac{\phi_t + \phi_A}{A_t}} \rightarrow (1)$$

where $\phi_t \rightarrow$ flux over the tooth

$\phi_A \rightarrow$ Flux over the slot gap.

$A_t \rightarrow$ Area of tooth $= L\omega_t$

The real flux density is defined as

$$B_{real} = \frac{\text{Actual flux in a slot pitch}}{\text{Tooth Area.}}$$

$$\boxed{B_{real} = \frac{\phi_t}{A_t}} \rightarrow (2)$$

Relation b/w B_{app} and B_{real}

From Equation (1)

$$B_{app} = \frac{\phi_t + \phi_a}{A_t}$$

$$B_{app} = \frac{\phi_t}{A_t} + \frac{\phi_a}{A_t}$$

From Equation (2)

$$B_{app} = B_{real} + \frac{\phi_a}{A_t}$$

$$B_{app} = B_{real} + \frac{\phi_A}{A_t} \times \frac{A_a}{A_a}$$

$$B_{app} = B_{real} + \frac{\phi_a}{A_a} \times \frac{A_a}{A_t}$$

$$B_{app} = B_{real} + (B_{air} \times k)$$

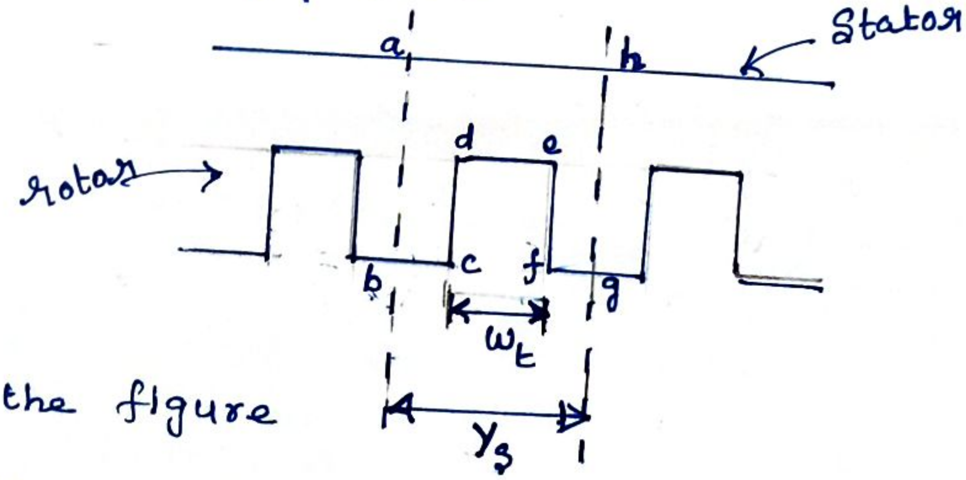
Where $k = \frac{A_a}{A_t}$

$A_t \rightarrow$ tooth Area $= L_i w_t$

$L_i \rightarrow$ net iron length $= S_f L \rightarrow$ (without duct)

$= S_f (L - n_d w_d) \rightarrow$ with Duct

$A_a \rightarrow$ Air gap area



From the figure

$A_a =$ Area of abcdefgha

$=$ Area over the slot pitch $-$ Tooth Area

$=$ Area of abgha $-$ Tooth Area

$$\boxed{A_a = L y_s - L_i w_t}$$

we know that $B = \mu H = \mu at = \mu_0 \mu_r at$

For air, $B_a = \mu_0 at_{real} = B =$ $| \mu_r = 1$

$B_a = 4 \times 10^{-7} at_{real}$

$\therefore$

$$\boxed{B_{app} = B_{real} + (4 \times 10^{-7} at_{real} \times k)}$$

$at_{real} \rightarrow$ real Magnetising force.

Calculate the apparent flux density at a particular section of a tooth from the following data

Tooth width = 12 mm, Slot width = 10 mm, Gross Core length = 0.32 m, No of Ventilating ducts = 4 and each 10 mm wide. real flux density = 2.2 wb/m². Permeability of teeth Corresponding to real flux density = 31.4×10^{-6} H/m. Stacking factor = 0.9

Given data

$w_t = 12\ mm = 12 \times 10^{-3}\ m$, $w_s = 10\ mm = 10 \times 10^{-3}\ m$, $L = 0.32\ m$, $n_d = 4$, $w_d = 10\ mm = 10 \times 10^{-3}\ m$, $B_{real} = 2.2\ wb/m^2$, $\mu = 31.4 \times 10^{-6}\ H/m$, $S_f = 0.9$

To find

Apparent flux density (B_{app})

Solution

$$B_{app} = B_{real} + 4\pi \times 10^{-7}\ at_{real} \times k$$

$$B_{app} = 2.2 + (4\pi \times 10^{-7} \times at_{real} \times k) \rightarrow (1)$$

we know that $B = \mu H$

(or)

$$B = \mu\ at$$

$$\therefore B_{real} = \mu\ at_{real}$$

$$at_{real} = \frac{B_{real}}{\mu}$$

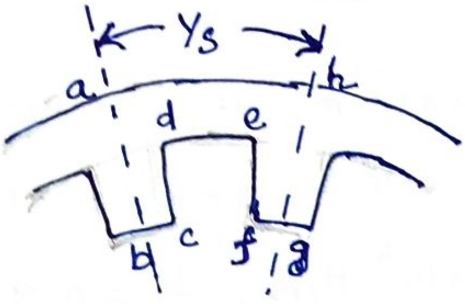
$$at_{real} = \frac{2 \cdot 2}{31.4 \times 10^{-6}}$$

$$at_{real} = \underline{\underline{70063.6943}} \ , \ AT/m$$

$$k = \frac{A_a}{A_t} \rightarrow (2)$$

$A_a \rightarrow$ gap area over the Slot pitch

$A_t \rightarrow$ tooth Area



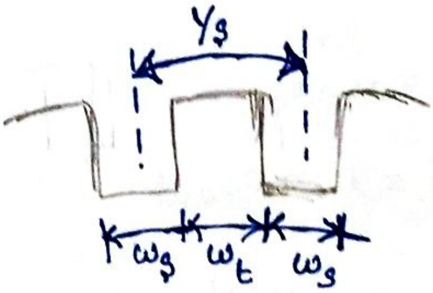
A_a (gap area over the Slot pitch) = Total area over the Slot pitch − Tooth area

(Area of abcdefgha) = (Area of abgha) − (Area of cdefc)

Therefore

$$A_a = LY_s - L_i w_t$$

$$A_a = (0.32 \times Y_s) - (L_i \times 12 \times 10^{-3})$$



From Figure

$$Y_s = w_t + w_s/2 + w_s/2$$

$$Y_s = w_t + w_s$$

$$Y_s = (12 \times 10^{-3}) + (10 \times 10^{-3})$$

$$Y_s = \underline{\underline{22 \times 10^{-3}}}, m$$

$$L_i = S_f (L - n_d w_d)$$

$$= 0.9 (0.32 - 4 \times 10 \times 10^{-3})$$

$$L_i = \underline{\underline{0.252}}, m$$

$$A_a = (0.32 \times 22 \times 10^{-3}) - (0.252 \times 12 \times 10^{-3})$$

$$A_a = \underline{\underline{0.0040}}, m^2$$

$$A_t = L_i w_t$$

$$= 0.252 \times 12 \times 10^{-3}$$

$$A_t = \underline{\underline{0.0030}}, m^2$$

From Equation (2)

$$k = \frac{0.0040}{0.0030}$$

$$k = 1.3228$$

From Equation (1)

$$B_{app} = 2.2 + (4\pi \times 10^{-7} \times 70063.6943 \times 1.3228)$$

$$B_{app} = \underline{\underline{2.3165}}, wb/m^2$$

__Answer__

Apparent flux density $(B_{app}) = \underline{\underline{2.3165}}, wb/m^2$

Calculate the apparent flux density at a section of teeth of an armature of DC machine from the following data

Slot pitch = 24 mm, Slot width = tooth width = 12 mm, length of armature core including 5 ducts of 10 mm each is 0.38 m. Iron stacking factor = 0.92, tooth flux density in teeth at that section is 2.2 wb/m^2 for which the mmf is 70,000 AT/m.

Given data

$y_s = 24\,mm = 24$ m, $w_t = w_s = 12\,mm = 12\times10^{-3}$ m

$L = 0.38$ m, $n_d = 5$, $w_d = 10\,mm = 10\times10^{-3}$ m, $S_f = 0.92$

$B_{real} = 2.2$ wb/m^2, $at_{real} = 70,000$ AT/m

To find

Apparent flux density (B_{app})

Solution

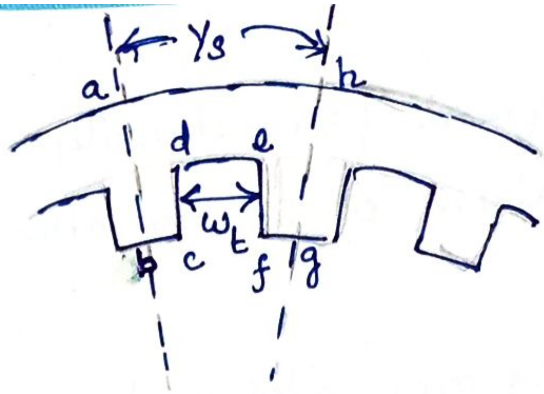
$$B_{app} = B_{real} + 4\pi\times10^{-7}\, at_{real} \times K$$

$$B_{app} = 2.2 + (4\pi\times10^{-7} \times 70,000 \times K) \rightarrow 1$$

$$K = \frac{A_a}{A_t} \rightarrow 2$$

$A_a \rightarrow$ gap area in a slot pitch

$A_t \rightarrow$ tooth area.



A_a (gap area in the slot pitch) = Total Area in the slot pitch − tooth Area

Area of abcdefgha = Area of abgha − Area of dcfed

$$A_a = L y_s - L_i w_t$$

$$A_a = (0.38 \times 24 \times 10^{-3}) - (L_i \times 12 \times 10^{-3}) \rightarrow 3$$

$$L_i = S_f (L - n_d w_d)$$

$$= 0.92 (0.88 - 5 \times 10 \times 10^{-3})$$

$$L_i = \underline{\underline{0.3036}}, m$$

From 3

$$A_a = (0.38 \times 24 \times 10^{-3}) - (0.3036 \times 12 \times 10^{-3})$$

$$A_a = \underline{\underline{0.00548}}, m^2$$

$$A_t = L_i \times w_t$$

$$= 0.3036 \times 12 \times 10^{-3}$$

$$A_t = \underline{\underline{0.00364}}, m^2$$

From 2

$$K = \frac{A_a}{A_t} = \frac{0.00548}{0.00364}$$

$$K = \underline{\underline{1.5042}}$$

From Equation ①

$$B_{app} = 2.2 + (4\pi \times 10^{-7} \times 70{,}000 \times 1.5042)$$

$$B_{app} = \underline{\underline{2.3323}} \ wb/m^2$$

Answers

Apparent flux density (B_{app}) = $\underline{\underline{2.3323}}$ wb/m^2

Find the permeability at the root of the teeth of a DC machine armature from the following data

Slot pitch = 2.1 cm, tooth width at the root = 1.07 cm Gross length = 32 cm, stacking factor = 0.9, real flux density at the root of the tooth = 2.25 tesla, apparent flux ~~densi~~ density at the root = 2.36 tesla

Given data

$Y_s = 2.1\ cm = 2.1 \times 10^{-2}\ m$, $\omega_t = 1.07\ cm = 1.07 \times 10^{-2}\ m$

$L = 32\ cm = 32 \times 10^{-2}\ m$, $S_f = 0.9$, $B_{real} = 2.25$, $B_{app} = 2.36$ tesla

To find

Permeability at the root of the teeth (μ)

Solution

$$\text{Permeability}\ (\mu) = \frac{B_{real}}{at_{real}}$$

$$\mu = \frac{2.25}{at_{real}} \rightarrow (1)$$

We know that

$B = \mu H$

or

$B = \mu\, at$

$\therefore \mu = \frac{B}{at}$

We know that

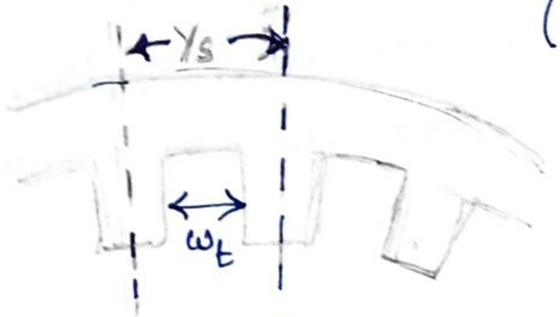
$$B_{app} = B_{real} + 4\pi \times 10^{-7}\, at_{real} \times K.$$

$$4\pi \times 10^{-7}\, at_{real}\, K = B_{app} - B_{real}$$

$$at_{real} = \frac{B_{app} - B_{real}}{4\pi \times 10^{-7} \times k} = \frac{2.36 - 2.25}{4\pi \times 10^{-7} \times k} \rightarrow (2)$$

$$\text{Where } k = \frac{A_a}{A_t} \rightarrow (3)$$

($A_a \rightarrow$ gap area over the slot pitch)



From the Figure

A_a = Total area over the slot pitch − teeth Area

$$A_a = LY_s - L_i w_t$$

$$A_a = (32\times10^{-2} \times 2.1 \times 10^{-2}) - (L_i \times 1.07 \times 10^{-2}) \rightarrow$$

$$L_i = S_f(L - n_d w_d)$$

$$L_i = 0.9\,(32\times10^{-3} - 0)$$

$$L_i = \underline{0.288}, m$$

If there is no duct then $n_d = 0$

From Equation

$$A_a = (32\times10^{-2} \times 2.1\times10^{-2}) - (0.288 \times 1.07\times10^{-2})$$

$$= (32\times2.1\times10^{-4}) - (0.288\times1.07\times10^{-2})$$

$$A_a = \underline{0.0036}, m^2$$

A_t = Area of the tooth $= L_i w_t$

$$A_t = 0.288 \times 1.07 \times 10^{-2}$$

$$A_t = \underline{0.0031}, m^2$$

From Equation (3)

$$k = \frac{0.0036}{0.0031}$$

$$k = \underline{\underline{1.1682}}$$

From Equation (2)

$$at_{real} = \frac{2.36 - 2.25}{4\pi \times 10^{-7} \times 1.1682}$$

$$at_{real} = \underline{\underline{74931.7058}}, \ AT/m$$

From Equation (1)

$$\mu = \frac{2.25}{74931.7058}$$

$$\mu = 0.00003 = \underline{\underline{3 \times 10^{-5}}}, \ H/m$$

Answer

permeability at the root of the teeth = $\underline{\underline{3 \times 10^{-5}}}$, H/m

Flux leakage (Magnetic leakage)

The flux which passes through unwanted path is called the leakage flux. It is impossible to confine all the magnetic flux in a given path.

The leakage flux does not contribute to either transfer or conversion of energy. The leakage flux affects the following performance

i) Excitation demand of salient pole machines

ii) Performance of ac machines depends on the leakage reactance.

iii) Voltage regulation of generators and transformers

iv) Commutation conditions in DC machines.

v) Stray load losses

vi) Circulating currents in transformer tank walls.

For magnetic circuit calculations, leakage coefficient is introduced in order to take into account the leakage flux. The leakage coefficient is defined as the ratio of total flux to useful flux

$$\text{Leakage Coefficient } C_l = \frac{\text{Total flux}}{\text{Useful flux}}$$

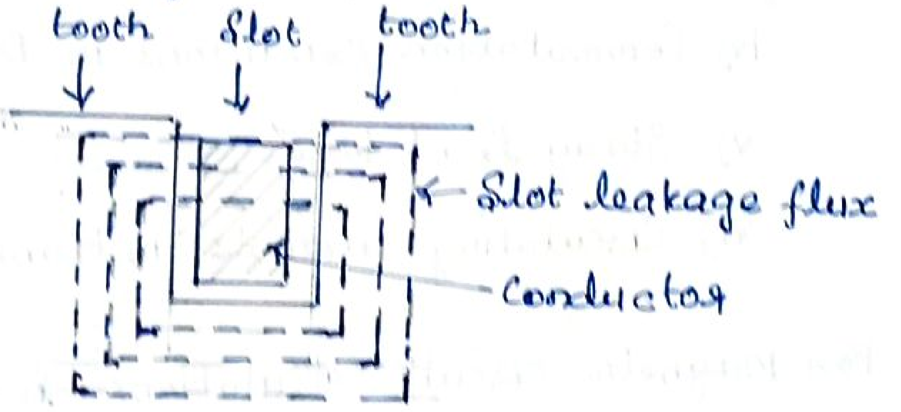
$$C_l = \frac{\text{Useful flux} + \text{Leakage flux}}{\text{Useful flux}}$$

Types of Leakage flux

The different types of armature leakage fluxes are

i) Slot leakage flux
ii) Tooth top leakage flux
iii) Zigzag leakage flux
iv) Overhang leakage flux
v) Differential leakage flux
vi) Skew leakage flux
vii) Peripheral leakage flux

i) Slot leakage flux

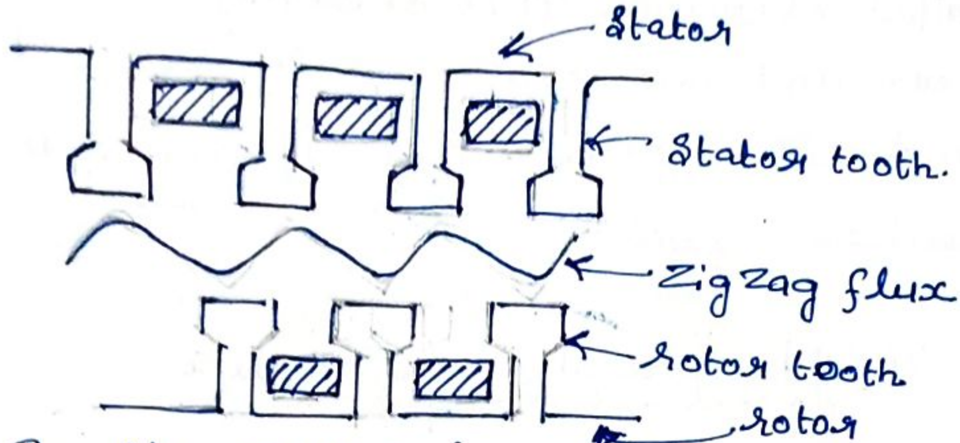


The flux that crosses the slot from one tooth to the next and returning through iron are called slot leakage flux.

ii) Tooth top leakage flux

The flux flowing from top of one tooth to the top of another tooth is called tooth top leakage flux. This leakage flux is considered only the machine having large airgap length.

iii) Zigzag Leakage flux



The flux passing from one tooth to another in a zigzag fashion is called zigzag leakage flux.

The magnitude of this flux depends on the length of air gap and the relative positions of the tips of stator and rotor tooth

iv) Overhang leakage flux

The conductors which connects the two coil sides of a coil are called overhang. The fluxes produced by the overhang portion of the armature winding are called overhang leakage flux.

v) Differential leakage flux

This leakage flux is due to dissimilar mmf distribution in the stator and rotor.

vi) Skew leakage flux

A twist provided on the rotor of Induction motor to eliminate harmonic torques and noise is Called Skewing. This Skewing reduces the mutual flux and thus Creating a difference b/w total flux and mutual flux. This difference is Called Skew leakage flux.

vii) Pheripheral leakage flux

The fluxes flowing Circumferentially around the air gap without linking with any of the winding is Called peripheral leakage flux.

EE 8002 DESIGN OF ELECTRICAL APPARATUS

UNIT II

DESIGN OF TRANSFORMER

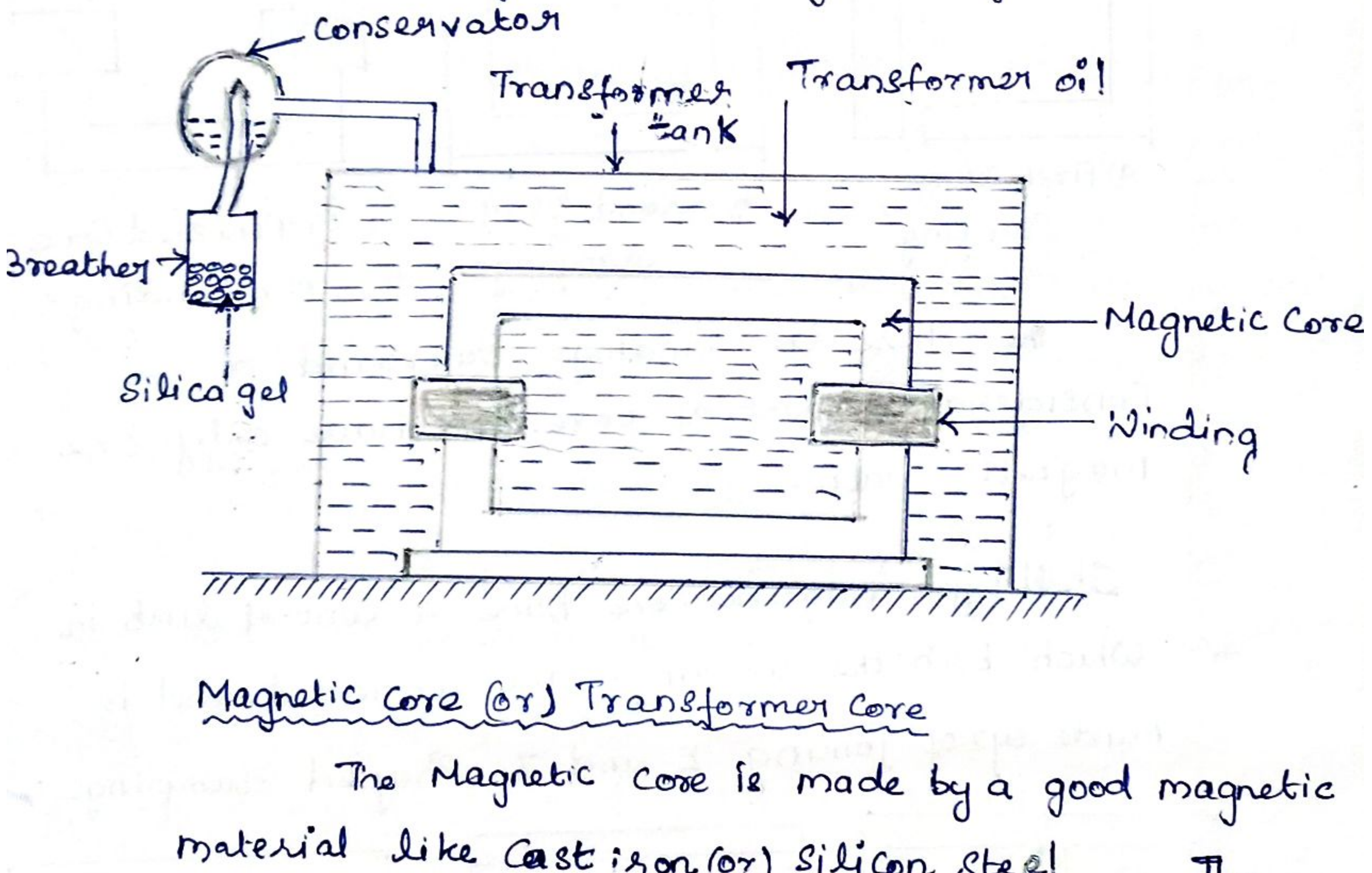
Prepared by

Dr . T. Dharma Raj

Asso.Prof /EEE

Constructional Details of a Transformer

The main Component of a transformer are i) The magnetic Core ii) primary and Secondary windings iii) Insulation of windings iv) Expansion tank or Conservator v) Insulating oil vi) Buchholz Relay vii) Breather vii) oil gauge viii) Bushings. ix) Cooling Arrangement.



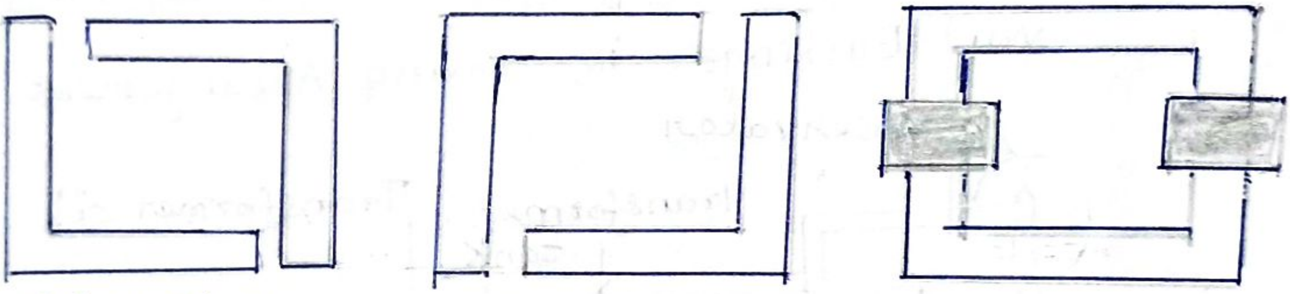
Magnetic Core (or) Transformer Core

The Magnetic core is made by a good magnetic material like Cast iron (or) Silicon steel. The magnetic Core are generally laminated with thickness of 0.35mm to 0.5mm. The laminations are insulated from each other by coating with a thin coat of Varnish.

The two types of Magnetic Core are

a) Core type   b) Shell type

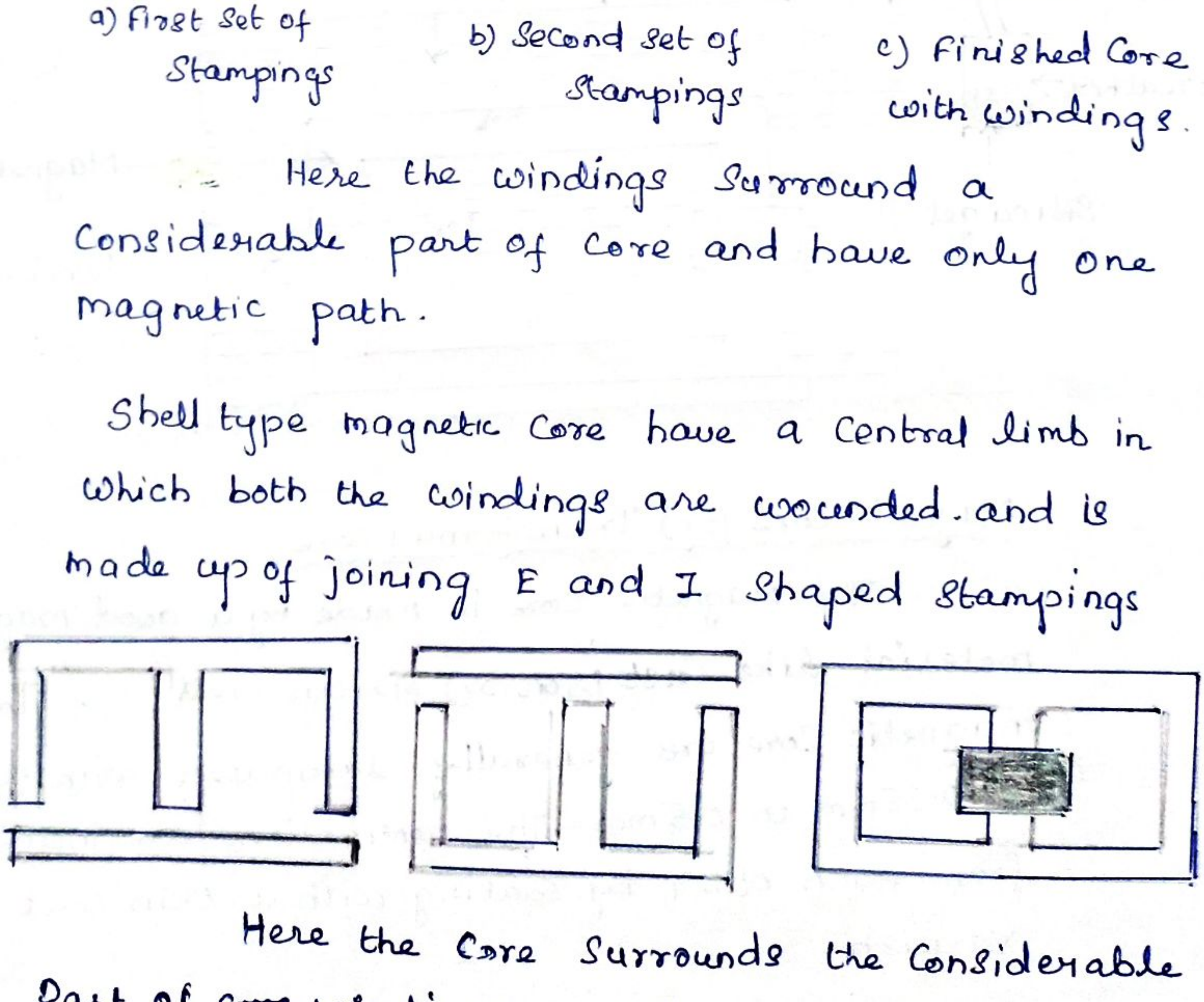
Core type Magnetic Core has two limbs for the windings and is made up of joining two L Shaped stampings.



a) First set of Stampings   b) Second set of Stampings   c) Finished Core with windings.

Here the windings surround a considerable part of core and have only one magnetic path.

Shell type magnetic core have a central limb in which both the windings are wounded. and is made up of joining E and I shaped stampings



Here the core surrounds the considerable part of ~~core~~ windings. and have ~~two~~ two magnetic paths.

In both types of Cores, the joints are staggered due to following advantages

i) Avoid Continuous gap b/w joints Causing increase in the magnetising current.

ii) To increase the mechanical strength of the Core

iii) Avoid undue humming noise.

Insulation of windings

Paper is still used as the basic conductor insulation. Enamel Insulation is used as the inter-turn insulation for low Voltage transformers.

For Power transformers enamelled Copper with paper insulation is also used.

Expansion tank or Conservator

It is an small auxillary tank mounted above the transformer and Connected to the main tank by a pipe. It function is to keep the transformer tank full of oil during expansion and Contraction of the Coil when subjected to Change in temperature.

Insulating oil or Transformer oil

It protect the paper from dirt and moisture and removes the heat produced in the core and coils. The oil must posses the following properties.

i) High dielectric strength

ii) free from inorganic acid, alkali and corrosive sulphur to prevent injury to the conductor or Insulation

iii) Low viscosity to provide good heat transfer

iv) Good Resistance to emulsion

~~Buchhol~~. Buchholz Relay

It is an gas operated relay placed inside the pipe which connects the tank and conservator.

This relay will give an alarm incase of minor fault and in case of severe fault this relay disconnect the transformer from the supply mains

Breather

The breather is connected one side of the conservator and it is filled with some drying agent such as calcium chloride (or) silica gel to prevent the entry of the moisture inside the transformer tank. The drying agent is replaced periodically as routine maintenance.

Oil gauge

Every transformer have a oil gauge to indicate the oil present inside the tank. The oil gauge is provided with an alarm contact which gives an alarm, when the oil level has dropped below the permissible height due to oil leak or due to any other reason.

Bushings

Connections from the transformer windings are brought out by means of bushings. Bushings are fixed on the transformer tank.

Cooling Arrangement

The various methods of cooling employed in a transformer are

a) Oil immersed natural cooled transformers
b) Oil immersed forced air cooled tfr's
c) oil immersed water cooled transformers
d) Oil immersed forced oil cooled transformers
e) Air blast transformers.

Output Equation of transformer

a) Single phase transformer

Consider an ideal transformer, the output power is given by

$$Q = E_p I_p \times 10^{-3} \text{ kVA (or) } E_s I_s \times 10^{-3} \text{ kVA} \rightarrow ①$$

where E_p, E_s are the emf induced in the primary and secondary windings.

I_p, I_s are the primary and secondary currents

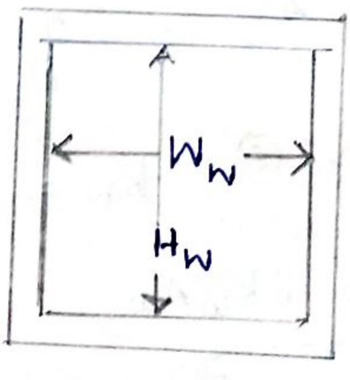
From Emf Equation

$$E_p = 4.44 f \phi_m T_p \text{, Volts} \rightarrow ②$$

From Equation ①

$$Q = 4.44 f \phi_m T_p I_p \times 10^{-3} \text{, kVA}$$

$$Q = 4.44 f \phi_m AT \times 10^{-3} \text{, kVA}$$



From the figure

$$\text{Window Space factor} = \frac{\text{Copper area in the window}}{\text{Total area in the window}}$$

$$K_w = \frac{A_c}{A_w} \rightarrow ③$$

where $A_w = H_w \cdot W_w$

Copper Area in the window (A_c) = Copper Area in the primary winding + Copper area in the secondary wdg

A_c = (Primary turns x area of conductors in primary wdg) + (Secondary turns x area of conductors in secondary wdg)

$$A_c = T_p a_p + T_s a_s \rightarrow (4)$$

For an ideal transformer, current density is same for both sides, then

$$\delta = \frac{I_p}{a_p} = \frac{I_s}{a_s}, \quad a_p = \frac{I_p}{\delta}, \quad a_s = \frac{I_s}{\delta}$$

from (4)

$$A_c = \frac{T_p I_p}{\delta} + \frac{T_s I_s}{\delta}$$

neglecting the magnetising mmf, then

$$T_p I_p = T_s I_s = AT$$

$$A_c = \frac{AT}{\delta} + \frac{AT}{\delta} \Rightarrow \frac{2AT}{\delta} \rightarrow (5)$$

Substitute (5) in (3) $\quad K_w = \frac{2AT}{\delta A_w}$

$$AT = \frac{\delta K_w A_w}{2}$$

From Equation (1)

$$Q = 4.44 f \phi_m \frac{\delta K_w A_w}{2} \times 10^{-3}, \text{ kVA}$$

$$\boxed{Q = 2.22 f \phi_m \delta K_w A_w \times 10^{-3}, \text{ kVA}}$$

b) Three phase transformer

The output power of 3ϕ Ideal transformer is given by

$$Q = 3 E_p I_p \times 10^{-3} \text{ (or) } 3 E_s I_s \times 10^{-3} \text{ kVA} \rightarrow (1)$$

where E_p, E_s are the emf induced/phase in the primary and secondary windings

I_p, I_s are the primary and secondary current/phase.

For Star Connection

Line Voltage $(V_L) = \sqrt{3}$ phase voltage (V_{ph})

Line Current (I_L) = Phase current (I_{ph})

For Delta Connection

Line Voltage (V_L) = Phase Voltage (V_{ph})

Line Current $(I_L) = \sqrt{3}$ phase current (I_{ph})

From emf Equation

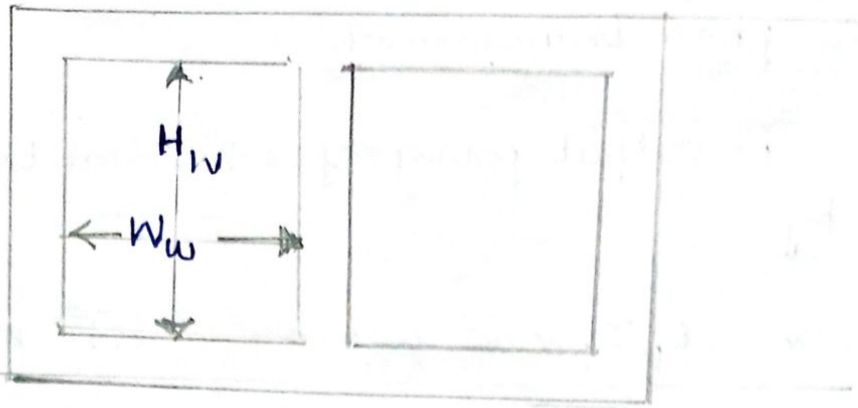
$$E_p = 4.44 f \phi_m T_p \text{, Volts}$$

where T_p is the number of primary turns/phase.

From equation (1)

$$Q = 3 \times 4.44 f \phi_m T_p I_p \times 10^{-3} \text{, kVA}$$

$$Q = 3 \times 4.44 f \phi_m AT \times 10^{-3} \text{, kVA}$$



From the figure

Window space factor (k_w) = $\dfrac{\text{Copper area in the window}}{\text{Total area in the window}}$

$$k_w = \frac{A_c}{A_w} \rightarrow (3)$$

$$A_w = H_w W_w$$

From the figure, It is observed that each window ~~~~ have two limbs. Each limb carries a primary and secondary winding for a phase.

∴ Therefore copper area in the window A_c = (copper area of the primary and secondary winding in the first limb) + (copper area of the primary and secondary winding in the second limb.

$$A_c = (T_p \cdot a_p + T_s a_s) + (T_p a_p + T_s a_s)$$

$$A_c = 2 T_p a_p + 2 T_s a_s \rightarrow (4)$$

For an ideal transformer, current density is same for primary and secondary, then

$$\delta = \frac{I_p}{a_p} = \frac{I_s}{a_s}$$

$$a_p = \frac{I_p}{\delta}, \quad a_s = \frac{I_s}{\delta}$$

from equation (4)

$$A_c = \frac{2 T_p I_p}{\delta} + \frac{2 T_s I_s}{\delta}$$

neglecting magnetising mmf, then $T_p I_p = T_s I_s = AT$

$$A_c = \frac{2AT}{\delta} + \frac{2AT}{\delta}$$

$$A_c = \frac{4AT}{\delta} \rightarrow (5)$$

Substitute (5) in (2)

$$K_w = \frac{4AT}{\delta A_w}$$

$$AT = \frac{K_w \delta A_w}{4} \rightarrow (6)$$

Substitute eq (6) in (2), we get

$$Q = 3 \times 4.44 f \phi_m \frac{K_w \delta A_w}{4} \times 10^{-3}, \text{ kVA}$$

$$\boxed{Q = 3.33\, f\, \phi_m\, k_w\, \delta\, A_w \times 10^{-3}\ ,\ \text{KVA}}$$

1, Show that output of the 3ϕ core type transformer is given by $Q = 5.23 f B_m H d^2 H_w \times 10^{-3}$ kVA, where f is the frequency in Hz, B_m is the flux density in the core, H is the magnetic potential gradient in limb A/m, d is the effective diameter of the core?

Solution

The basic output equation of 3ϕ transformer is

$$Q = 3 E_p I_p \times 10^{-3} = 3 E_s I_s \times 10^{-3} \text{ kVA} \rightarrow (1)$$

where $E_p = 4.44 f T_p \phi$, Volts.

$$B_m = \frac{\phi}{A_i} \Rightarrow \phi = A_i B_m$$

From Equation (1)

$$Q = 3 \times 4.44 f T_p A_i B_m I_p \times 10^{-3} \text{ kVA} \rightarrow (2)$$

Given d is the effective diameter of the core

ie) $A_i = \frac{\pi d^2}{4} \rightarrow (3)$

Substitute (3) in (2)

$$Q = 3 \times 4.44 f T_p \left(\frac{\pi d^2}{4}\right) B_m I_p \times 10^{-3} \text{ kVA}$$

$$Q = 13.32 f B_m \frac{\pi d^2}{4} (T_p I_p) \times 10^{-3} \text{ kVA}$$

$$Q = 13.32 f B_m \frac{\pi d^2}{4} AT \times 10^{-3} \text{ kVA} \rightarrow (4)$$

A 3 ϕ core transformer has 3 limbs. Each limb Consists of one primary and secondary winding.

mmf acting in limb = mmf acting in the primary + mmf acting in the secondary

$$= T_p I_p + T_s I_s$$

For an ideal transformer,

$$T_p I_p = T_s I_s = AT$$

$\therefore$ mmf acting in the limb = AT + AT

$$= 2AT$$

From the given data $H = AT/l$

ie) $$H = \frac{\text{mmf acting in the limb}}{\text{length of the limb}}$$

$$H = \frac{2AT}{H_w}$$

$$AT = \frac{H \times H_w}{2}$$

From (A)

$$Q = 13.32 \, f \, B_m \, \frac{\pi d^2}{4} \, \frac{H \cdot H_w}{2} \times 10^{-3}$$

$$Q = 5.23 \, f \, B_m \, H \, d^2 \, H_w \times 10^{-3}, \text{ KVA}$$

Hence proved.

Volt per turn interms of Output Equation

We know that

$$E_p = 4.44 f \phi_m T_p$$

$$E_t = 4.44 f \phi_m \rightarrow (1)$$

The output Equation Q is given by

$$Q = E_p I_p \times 10^{-3}, \text{ kVA}$$

$$Q = 4.44 f \phi_m T_p I_p \times 10^{-3}, \text{ kVA}$$

$$Q = 4.44 f \phi_m AT \times 10^{-3}, \text{ kVA}$$

Let we take $\gamma = \dfrac{\phi_m}{AT}$

$$AT = \frac{\phi_m}{\gamma}$$

$$Q = 4.44 f \phi_m \frac{\phi_m}{\gamma} \times 10^{-3}, \text{ kVA}$$

$$Q = 4.44 f \frac{\phi_m^2}{\gamma} \times 10^{-3}, \text{ kVA}$$

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

$$\phi_m = \sqrt{\frac{Q\gamma}{4.44 f \times 10^{-3}}}$$

$$\phi_m = \sqrt{Q} \cdot \sqrt{\frac{\gamma}{4.44 f \times 10^{-3}}}$$

From Eq (1)

$$E_t = 4.44 f \sqrt{Q} \cdot \sqrt{\frac{r}{4.44 f \times 10^{-3}}}$$

$$E_t = \sqrt{Q} \cdot \sqrt{\frac{(4.44 f)^2 r}{4.44 f \times 10^{-3}}}$$

$$\boxed{E_t = \sqrt{Q} \cdot \sqrt{4.44 f r \times 10^{3}}} \text{ Volts.}$$

The ratio of flux to full load mmf in a 400 kVA, 50 Hz, 1ϕ Core type transformer is 2.4×10^{-6}. Calculate the net iron area and window area of the transformer. Maximum flux density in the core is 1.3 wb/m^2; Current density is 2.7 A/mm^2 and window space factor is 0.26. Also Calculate the full load mmf.

Given data

$r = \dfrac{\phi}{AT} = 2.4 \times 10^{-6}$, $Q = 400$ kVA, $f = 50$ Hz, 1ϕ Core

$B_m = 1.3$ wb/m^2, $\delta = 2.7$ A/mm^2, $k_w = 0.26$

To find

i) Net iron Area (A_i)

ii) Window Area (A_w)

iii) ~~Fu~~ Full load mmf (AT)

Solution

i) net Iron Area (A_i)

$$B_m = \frac{\phi_m}{A_i} \quad (\text{or}) \quad S_f = \frac{A_i}{A_{gi}}$$

From the given data, Select $B_m = \dfrac{\phi_m}{A_i}$

$$A_i = \frac{\phi_m}{B_m}$$

$$A_i = \frac{\phi_m}{1.3} \rightarrow (1)$$

We know that

$$E_p = 4.44 f \phi_m T_p \text{ , Volts}$$

$$E_p / T_p = 4.44 f \phi_m$$

$E_t \rightarrow$ Volt/ turn

$$E_t = 4.44 f \phi_m$$

$$\phi_m = \frac{E_t}{4.44 f} = \frac{E_t}{4.44 \times 50} \rightarrow (2)$$

From the given data, we can express the E_t interms of Q

$$E_t = \sqrt{Q} \cdot \sqrt{4.44 f \gamma \times 10^3}$$

$$E_t = \sqrt{400} \times \sqrt{(4.44 \times 50 \times 2.4 \times 10^{-6} \times 10^3)}$$

$$E_t = \underline{\underline{14.5986}} \text{, Volts}$$

From equation (2)

$$\phi_m = \frac{14.5986}{4.44 \times 50}$$

$$\phi_m = \underline{\underline{0.0658}} \text{, wb}$$

From Equation (1)

$$A_i = \frac{0.0658}{1.3}$$

$$A_i = 0.0506 \text{ , } m^2.$$

ii) Area of the window (A_w)

$$Q \text{ in kVA} = 2.22 f \phi_m \delta k_w A_w \times 10^{-3} \text{, kVA}$$

$$A_w = \frac{Q \text{ in kVA}}{2.22 f \phi \delta K_w \times 10^{-3}}$$

$$A_w = \frac{400}{2.22 \times 50 \times 0.0658 \times 2.7 \times 10^{6} \times 0.26 \times 10^{-3}}$$

$$A_w = 0.0780 \quad m^2$$

iii) Full load mmf (AT)

Given $\frac{\phi_m}{AT} = 2.4 \times 10^{-6}$

$$AT = \frac{\phi_m}{2.4 \times 10^{-6}}$$

$$AT = \frac{0.0658}{2.4 \times 10^{-6}} = 27416.6667 \text{ AT.}$$

Answers

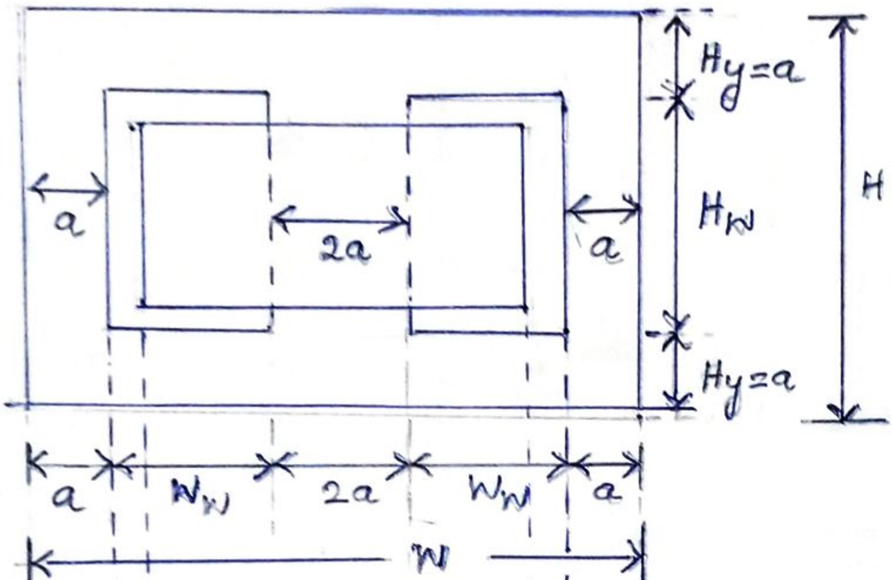
$A_i = 0.0506$, m^2

$A_w = 0.0780$, m^2

$AT = 27416.6667$, AT.

Overall Dimensions of a transformer.

i) Single phase shell type transformer



Figure, Side view of Shell type transformer

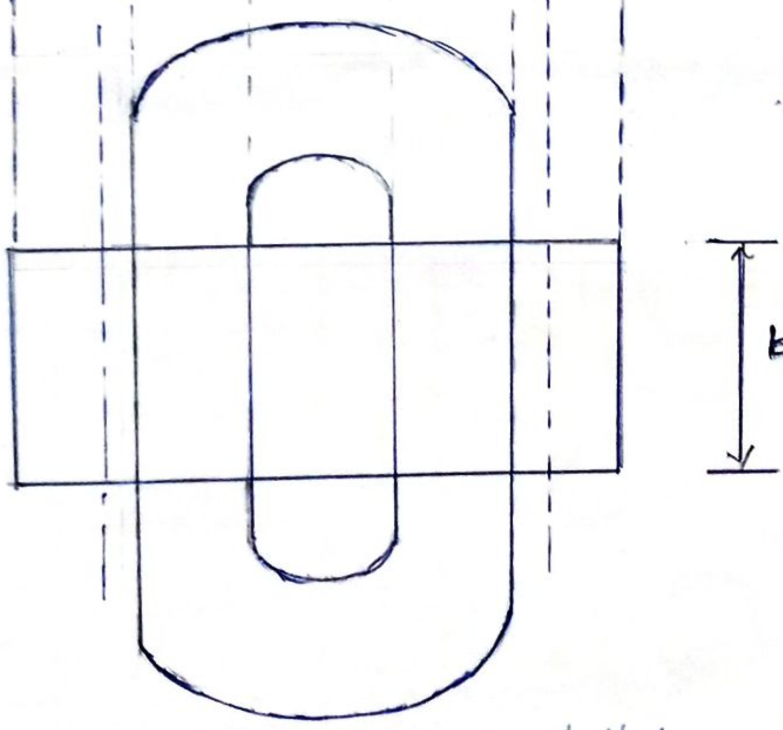


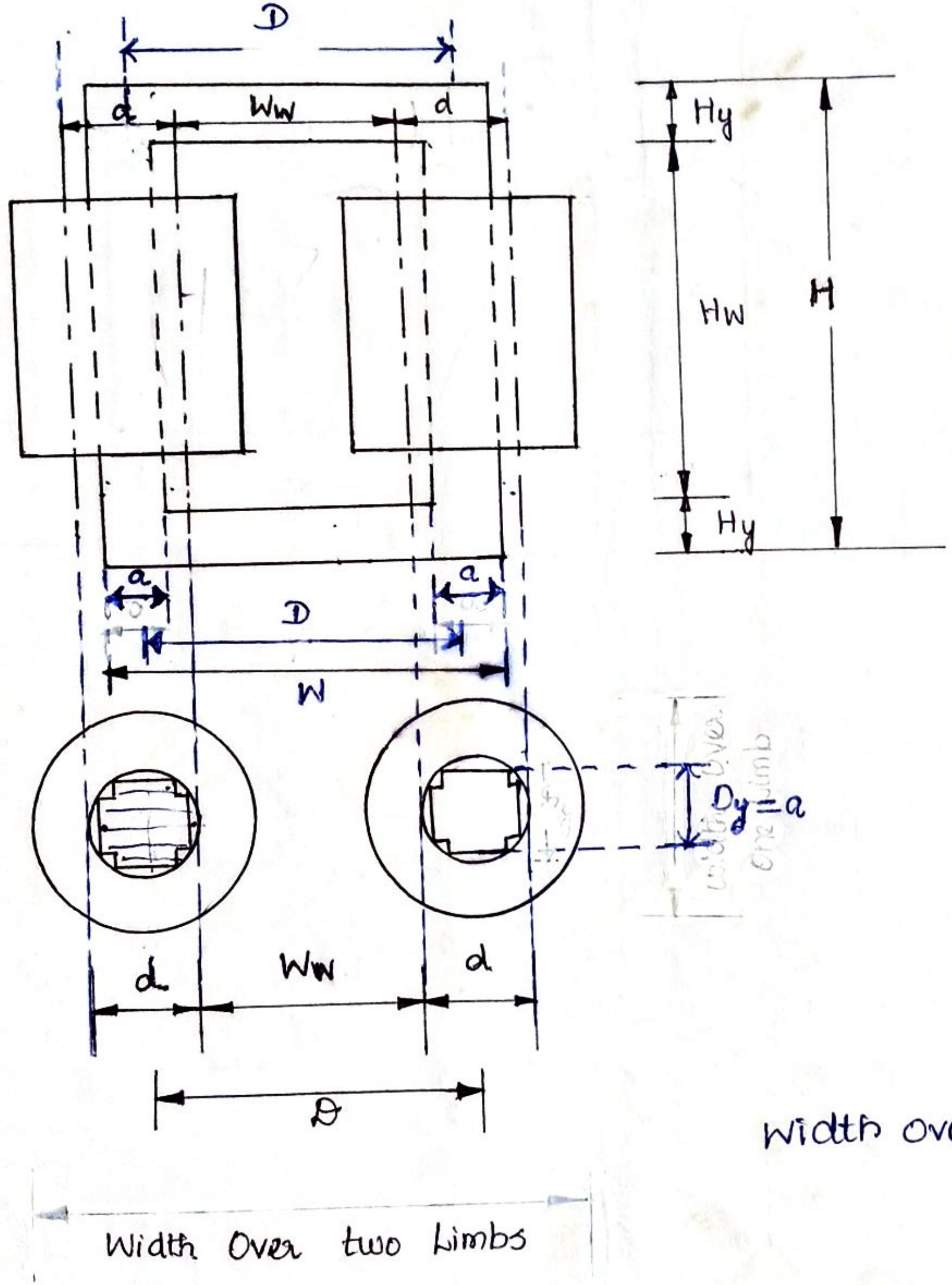
Figure Top View of Shell type transformer

Depth of the Yoke $D_y = b$, Height of Yoke $H_y = a$

Overall width $W = 2W_w + 4a$

Overall Height $H = 2H_y + H_w = H_w + 2a$

ii) SINGLE PHASE CORE TYPE TRANSFORMER



Distance b/w centres of adjacent limbs,

$$\boxed{D = d + W_w}$$

where, d → diameter of circumscribing circle

W_w → Width of window.

Depth of yoke,

$$\boxed{D_y = a = H_y}$$

where a → Width of largest stamping

Overall height,

$$\boxed{H = H_w + 2H_y}$$

where, H_w → height of window

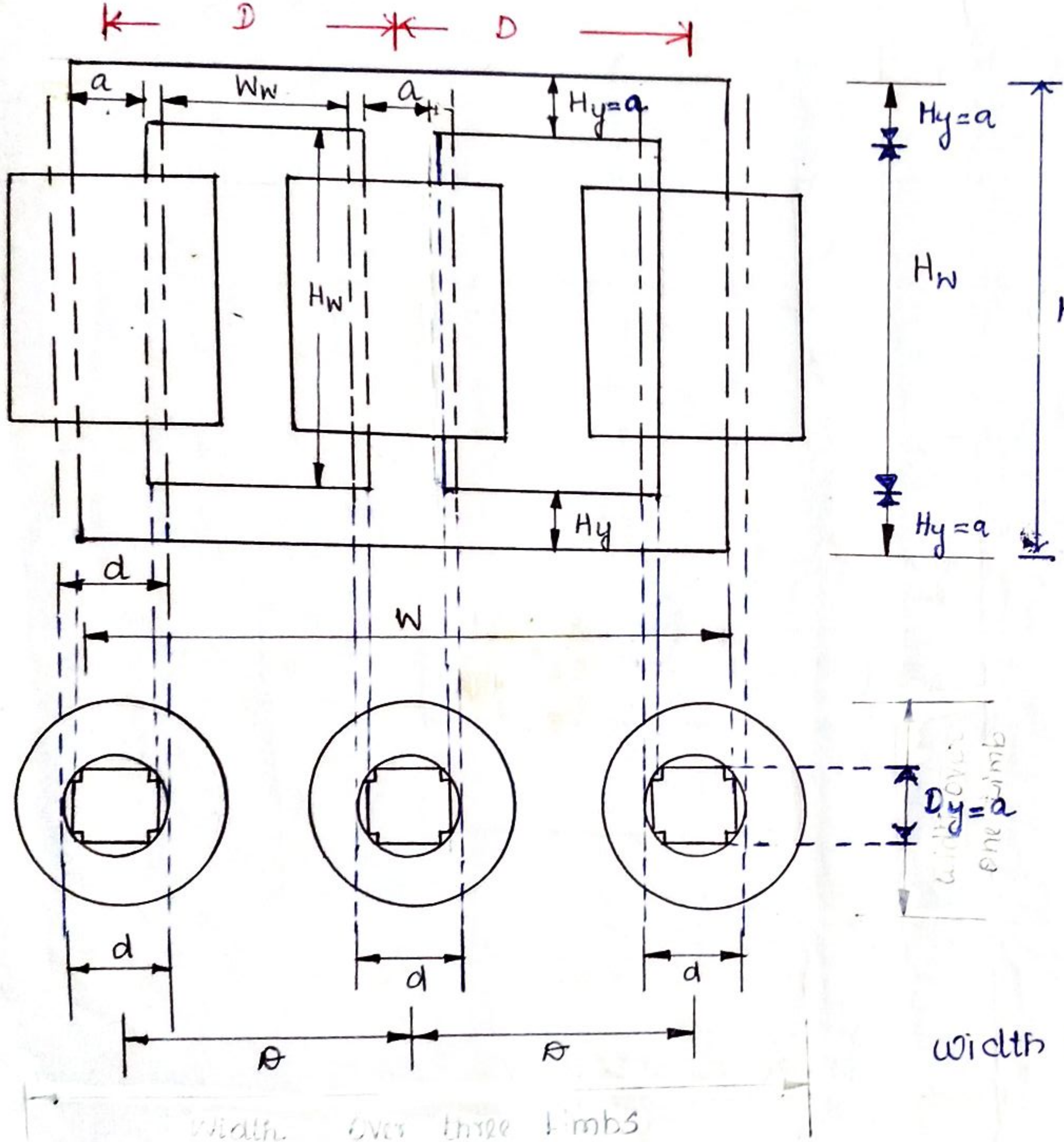
H_y → height of yoke

Overall width,

$$\boxed{W = D + a}$$

Width over two limbs = D + outer diameter of H.V. winding.

iii) THREE PHASE CORE TYPE TRANSFORMER



Distance between centres of adjacent limbs, $\boxed{D = d + W_w}$

where, $d \rightarrow$ dia of circumscribing circle
$W_w \rightarrow$ width of window.

Depth of yoke, $\boxed{D_y = a}$

where, $a \rightarrow$ width of largest stamping

Overall height,

$$\boxed{H = H_w + 2H_y}$$

where $H_w \rightarrow$ height of window
$H_y \rightarrow$ height of yoke

Overall width,

$\boxed{W = 2D + a}$ = Width over 3 limbs

Width over one limb = outer diameter of H.V. winding.

Calculate the main dimensions and winding details of a 100 kVA, 2000/400 V, 50 Hz, 1ϕ shell type tfr. Assume voltage per turn is 10 V, flux density in the core is 1.1 wb/m², current density is 2 A/mm², window space factor is 0.33, ratio window height to width of the window is 3 and the ratio of core depth to the width of central limb is 2.5 and the stacking factor is 0.9.

Given data

$Q = 100\,kVA$, $V = 2000/400\,V$, $f = 50\,Hz$, 1ϕ shell type,

$E_t = 10\,V$, $B_m = 1.1$, $\delta = 2\,A/mm^2 = \frac{2}{10^{-6}} = 2\times10^{6}\,A/m^2$,

$K_w = 0.33$, $\frac{H_w}{W_w} = 3$, $\frac{b}{2a} = 2.5$, $S_f = 0.9$

To find

Main dimensions and winding details.

Solution

i) Main dimensions

The output equation of 1ϕ shell type tfr is

$Q = 2.22 f \phi_m \delta K_w A_w \times 10^{-3}$, kVA.

$$A_w = \frac{Q}{2.22 f \phi_m \delta K_w \times 10^{-3}}$$

$$A_w = \frac{100}{2.22\times 50\times \phi_m \times 2\times10^{6}\times 0.33\times 10^{-3}} \longrightarrow (1)$$

$$\phi_m \begin{cases} \rightarrow B_m = \dfrac{\phi_m}{A_i}, & \phi_m = B_m A_i \rightarrow (2) \\ \rightarrow E_t = 4.44 f \phi_m, & \phi_m = \dfrac{E_t}{4.44 f} \rightarrow (3) \end{cases}$$

From (3) $\phi_m = \dfrac{10}{4.44 \times 50}$

$\phi_m = \underline{\underline{0.045}}$ wb

From (1)

$$A_w = \frac{100}{2.22 \times 50 \times 0.045 \times 2 \times 10^6 \times 0.33 \times 10^{-3}}$$

$A_w = \underline{\underline{0.0303}}\ m^2$

We know that

$A_w = H_w W_w \rightarrow (4)$

Given $\dfrac{H_w}{W_w} = 3$

$H_w = 3 W_w$

From eq (4)

$A_w = 3 W_w W_w$

$$W_w^2 = \frac{A_w}{3} = \frac{0.0303}{3} = 0.0101$$

$W_w = \underline{\underline{0.1006}}\ m$

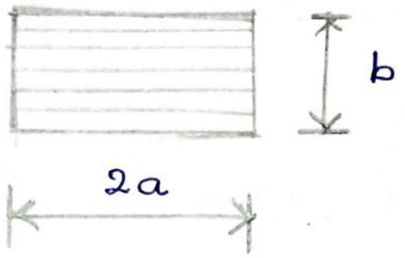
From eq (4)

$$H_w = \frac{A_w}{W_w} = \frac{0.0303}{0.1006} = \underline{\underline{0.3013}}\ m$$

Given $\dfrac{b}{2a} = 2.5$

$$\therefore \; a = \frac{b}{5} \rightarrow (5)$$

In shell type tfr, Rectangular shape core is used.



$$A_{gi} = 2ab \rightarrow (6)$$

We know that $S_f = \dfrac{A_i}{A_{gi}} \rightarrow (7)$

From (2) $\quad A_i = \dfrac{\phi_m}{B_m} = \dfrac{0.045}{1.1} = \underline{0.0409 \; m^2}$

From (5) $\quad A_{gi} = \dfrac{A_i}{S_f} = \dfrac{0.0409}{0.9} = \underline{0.0454 \; m}$

From (6)

$$2ab = 0.0454 \rightarrow (8)$$

Substitute (5) in equation (8)

$$2 \times \frac{b}{5} \times b = 0.0454$$

$$b^2 = \frac{0.0454 \times 5}{2} = 0.1135$$

$$b = \underline{0.3369} \; m$$

From (5)

$$a = \underline{\underline{0.0674}} \text{ m}$$

Determine the dimension of the core and yoke for a 200 KVA, 50 Hz, 1ϕ Core type transformer. A stepped Core is used with distance between adjacent limbs equal to 1.6 times the width of core laminations. Assume voltage per turn 14V, maximum flux density 1.1 wb/m^2 window space factor 0.32, current density 3 A/mm^2 and stacking factor = 0.9. The net iron area is 0.56d^2 in a cruciform core, where d is the diameter of circumscribing circle. ~~Asto~~ Also the widht of largest stamping is 0.85d.

Given

$$Q = 200\,kVA, \; f = 50\,Hz, \; D = 1.6 \times a, \; E_t = 14\,V,$$

$$B_m = 1.1\,wb/m^2, \; k_w = 0.2, \; \delta = 3\,A/mm^2, \; S_f = 0.9,$$

$$A_i = 0.56\,d^2, \; a = 0.85\,d$$

To find

Dimension of the core and yoke

Solution

Output Equation of 1ϕ transformer is

$$Q = 2.22 f \phi_m \delta k_w A_w \times 10^{-3}, \; kVA$$

$$A_w = \frac{Q}{2.22 f \phi_m \delta k_w \times 10^{-3}}$$

$$A_w = \frac{200}{2.22 \times 50 \times \phi_m \times 3 \times 10^6 \times 0.32 \times 10^{-3}}$$

We know, $B_m = \frac{\phi_m}{A_i}$

$$\phi_m = B_m A_i$$

$$\phi_m = 1.1\, A_i \rightarrow (2)$$

From the given data

$$A_i = 0.56\, d^2 \rightarrow (3)$$

Also we know that

$$E_p = 4.44 f \phi_m T_p$$

$$E_p / T_p = 4.44 f \phi_m$$

$$E_t = 4.44 f \phi_m$$

$$\phi_m = \frac{E_t}{4.44 f}$$

$$\phi_m = \frac{14}{4.44 \times 50}$$

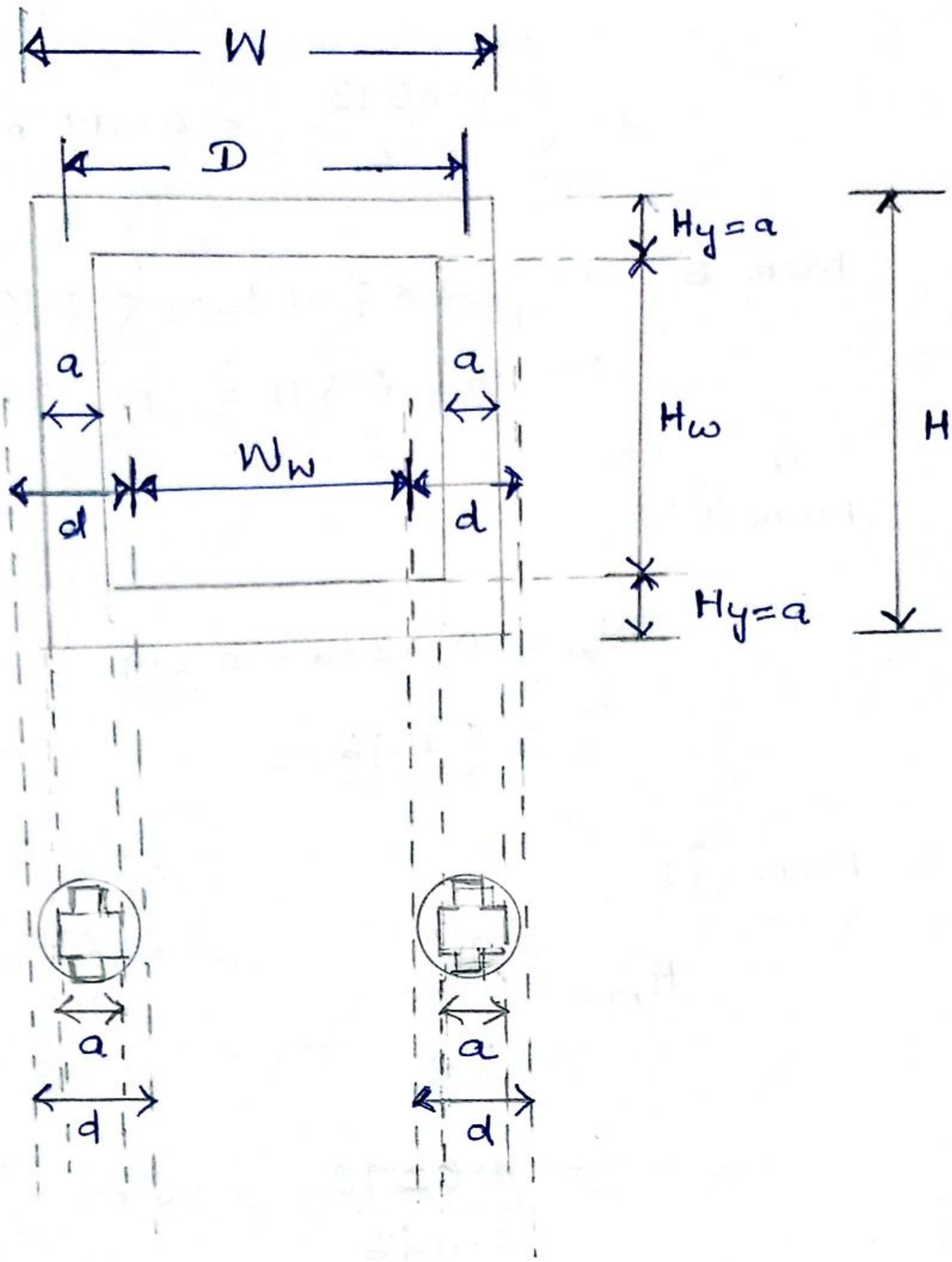
$$\phi_m = \underline{0.063} \text{ wb}$$

from (1)

$$A_w = \frac{200}{2.22 \times 50 \times 0.063 \times 3 \times 10^6 \times 0.32 \times 10^{-3}}$$

$$A_w = \underline{0.0298} \text{ m}^2$$

$$A_w = H_w W_w. \rightarrow (4)$$



From the figure

$$W_w = D - d/2 - d/2$$

$$W_w = D - d. \rightarrow (5)$$

Given $D = 1.6a$ and $a = 0.85d \rightarrow (6)$

From (2)

$$A_i = \frac{\phi_m}{1.1} = \frac{0.063}{1.1} = 0.0573\,m^2$$

From (3)

$$0.0573 = 0.56 d^2$$

$$d = \sqrt{\frac{0.0573}{0.56}} = 0.319 \text{ m}$$

From (5) $a = 0.85 \times 0.319 = 0.2712 \text{ m}$

$D = 1.6 \times 0.271 = 0.4336 \text{ m}$

From (5)

$$W_w = 0.4336 - 0.319$$

$$= 0.1146 \text{ m}$$

From (4)

$$H_w = \frac{A_w}{W_w}$$

$$= \frac{0.0298}{0.1146} = 0.26 \text{ m}$$

From figure

$$W = D + 2a$$

$$= 0.4336 + (2 \times 0.2712)$$

$$W = 0.976 \text{ m}$$

$$H = H_w + 2H_y$$

$$= H_w + 2a$$

$$= 0.26 + (2 \times 0.2712)$$

$$H = 0.8024 \text{ m}$$

Answers

$A_w = 0.0298\ m^2$

$H_w = 0.26\ m$

$W_w = 0.1146\ m$

$D = 0.4836\ m$

$d = 0.319\ m$

$a = 0.2712\ m$

$H = 0.8024\ m$

$W = 0.976\ m.$

$H_y = D_y = a = 0.2712\ m$

Determine the main dimensions of the core of a 5 kVA, 11000/400V, 50 Hz, 1ϕ Core type distribution transformer. The net Conductor area in the window is 0.6 times the net cross section area of iron in the core. The core is of square cross section, maximum flux density is 1 wb/m², current density is 1.4 A/mm². Window space factor is 0.2. Height of the window is 3 times its width.

Given data

$Q = 5\,kVA$, 11000/400, $f = 50\,Hz$, 1ϕ core type,

$A_c = 0.6\,A_i$, Core → square, $B_m = 1\,wb/m^2$, $\delta = 1.4\,A/mm^2$

$K_w = 0.2$, $H_w = 3\,W_w$

To find

Main Dimensions

Solution

The output Equation of 1ϕ core type ~~trans~~ transformer is given by

$$Q = 2.22\, f\, \phi_m\, \delta\, k_w\, A_w \times 10^{-3},\ kVA$$

$$A_w = \frac{Q}{2.22\, f\, \phi_m\, \delta\, k_w \times 10^{-3}}$$

$$A_w = \frac{5}{2.22 \times 50 \times \phi_m \times 1.4 \times 10^{6} \times 0.2 \times 10^{-3}}$$

→ 1

$$\phi_m \begin{cases} \rightarrow B_m = \dfrac{\phi_m}{A_i}, \quad \phi_m = B_m A_i & \rightarrow (2) \\ \rightarrow E_t = 4.44 f \phi_m, \quad \phi_m = \dfrac{E_t}{4.44 f} \end{cases}$$

Given $A_c = 0.6 A_i$

$$A_i = \frac{A_c}{0.6}$$

From (2)

$$\phi_m = \frac{B_m A_c}{0.6} \rightarrow (3)$$

We know that $k_w = \dfrac{A_c}{A_w}$

$$A_c = k_w A_w$$

$$A_c = 0.2 A_w$$

From eq (3)

$$\phi_m = \frac{1 \times 0.2 A_w}{0.6}$$

$$\phi_m = \underline{\underline{0.3333}} A_w \rightarrow (4)$$

From eq (1)

$$A_w = \frac{5}{2.22 \times 50 \times 0.3333 A_w \times 1.4 \times 10^{6} \times 0.2 \times 10^{-3}}$$

$$A_w^2 = \frac{5}{2.22 \times 50 \times 0.3333 \times 1.4 \times 10^6 \times 0.2 \times 10^{-3}}$$

$$= 0.0005$$

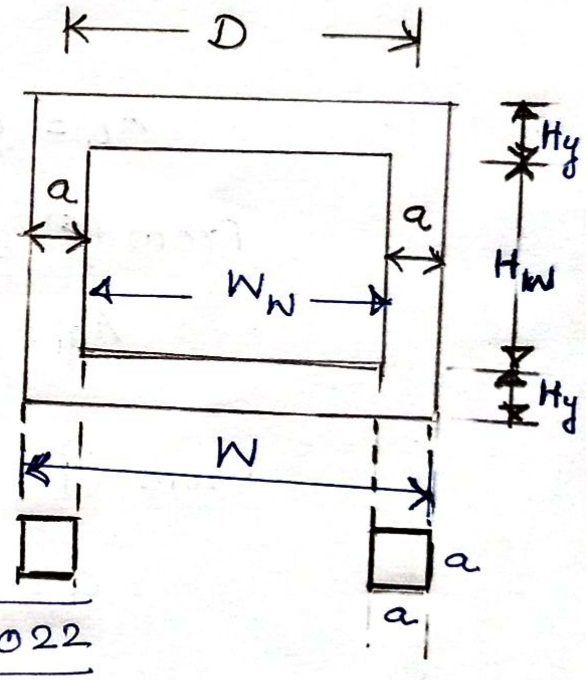
$$A_w = \underline{\underline{0.0220}},\ m^2$$

$$A_w = H_w W_w \rightarrow (5)$$

$$W_w = D - d$$

For Square cross section of the Core $\boxed{d = a}$

$$W_w = D - a \rightarrow (6)$$



Given $H_w = 3 W_w$

From Equation (5)

$$A_w = 3 W_w W_w$$

$$W_w^2 = \frac{A_w}{3}$$

$$W_w = \sqrt{\frac{A_w}{3}} = \sqrt{\frac{0.022}{3}}$$

$$W_w = \underline{\underline{0.0856}},\ m$$

From Equation (5)

$$0.022 = H_w \times 0.0856$$

$$H_w = \frac{0.022}{0.0856}$$

$$H_w = \underline{\underline{0.2571}},\ m.$$

For square cross section of core

$$A_{gi} = a^2 \rightarrow (7)$$

we know that $S_f = \frac{A_i}{A_{gi}} = 0.9$

$$A_{gi} = \frac{A_i}{0.9} \rightarrow (8)$$

From equation (2)

$$A_i = \frac{\phi_m}{B_m} = \frac{0.3333\, A_w}{1} = 0.3333 \times 0.022$$

$$A_i = \underline{0.0073}, \ m^2$$

From (8)

$$A_{gi} = \frac{0.0073}{0.9} = \underline{0.0081}, \ m^2$$

From (7)

$$a = \sqrt{A_{gi}} = \underline{0.0901}, \ m$$

From (6)

$$D = W_w + a = 0.0856 + 0.0901$$

$$= \underline{0.1757}, \ m$$

$$H = H_w + 2a$$

$$= 0.2571 + (2 \times 0.0901)$$

$$H = \underline{0.4373}, \ m$$

$$W = D + a$$

$$= 0.1757 + 0.0901$$

$$= \underline{\underline{0.2658}}, m$$

$$H_y = P_y = a = \underline{\underline{0.0901}}, m$$

Ans

$A_\omega = \underline{0.022}, m^2$

$H_\omega = \underline{\underline{0.2571}}, m$

$N_\omega = \underline{\underline{0.0856}}, m$

$a = \underline{\underline{0.0901}}, m$

$D = \underline{0.1757}, m$

$N = \underline{0.2658}, m$

$H = \underline{\underline{0.4373}}, m$

$H_y = D_y = \underline{0.0901}, m.$

Calculate the kVA output of the 1φ transformer from the following data

Core height to the distance between core = 2.8, diameter of circumscribing circle to the Distance between core centre is 0.56. Net iron area to the area of circumscribing circle is 0.7, Current density = 2.3 A/mm². Frequency is 50 Hz. Window space factor is 0.27. flux density in the core is 2 wb/m² and Distance b/w core centre is 0.4 m.

Given

Core height to the distance b/w core centre $\frac{H_w}{D} = 2.8$

Diameter of circumscribing circle to the Distance between core centre $\frac{d}{D} = 0.56$

$$\frac{\text{Net iron area } (A_i)}{\text{Area of circumscribing circle}} = 0.7$$

$\delta = 2.3 \text{ A/mm}^2$

$K_w = 0.27$

$f = 50 \text{ Hz}$

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

$D = 0.4 \text{ m}$

To find

Q in kVA

Solution

For 1 ϕ transformer

$$Q = 2.22 f \phi_m \delta k_w A_w \times 10^{-3} \text{ kVA}$$

$$Q = 2.22 \times 50 \times \phi_m \times \frac{2.3}{10^{-6}} \times 0.27 \times A_w \times 10^{-3} \text{ kVA} \rightarrow (1)$$

$$E_t = 4.44 f \phi_m \text{ (or) } B_m = \frac{\phi_m}{A_i}$$

$$\phi_m = B_m \times A_i$$

$$\phi_m = 1.2 \times A_i \rightarrow (2)$$

Given $\dfrac{A_i}{\text{Area of circumscribing circle}} = 0.7$

$$\frac{A_i}{\pi r^2} = 0.7$$

$$\frac{A_i}{\pi (d/2)^2} = 0.7$$

$$A_i = 0.7 \times \frac{\pi}{4} \times d^2 \rightarrow (3)$$

given $\dfrac{d}{D} = 0.56$

$$d = 0.56 D$$

$$= 0.56 \times 0.4$$

$$d = 0.224 \text{ m}$$

From (3)

$$A_i = 0.028\ m^2$$

From (2)

$$\phi_m = 0.033\ wb$$

$$A_w = H_w \times W_w \rightarrow (4)$$

$$W_w = D - d = 0.4 - 0.224 = 0.176\ m$$

given $\frac{H_w}{D} = 2.8$

$$H_w = 2.8 \times 0.4 = 1.12\ m$$

From (4)

$$A_w = 0.176 \times 1.12 = 0.19\ m^2$$

From eq (1)

$$Q_r = 2.22 \times 50 \times 0.033 \times \frac{2.3}{10^{-6}} \times 0.27 \times 0.19 \times 10^{-3}$$

$$\boxed{Q_r = 448.12}\ kVA$$

Calculate the approximate overall dimensions for a 200 kVA 6600/420 V, 50 Hz, 3ϕ Core type transformer. The following data may be assumed as Emf/turn = 10 V, maximum flux density is 1.3 Wb/m^2, current density is 2.5 A/mm^2, window space factor is 0.3, Overall height is equal to overall width, stacking factor is 0.9, Use a 3 stepped core.

For a three stepped core: width of largest stamping = 0.9 d, and Net iron area = 0.6 d^2, where d is the diameter of circumscribing circle.

Given

$Q = 200$ kVA, Voltage rating = 6600/420 V, $f = 50$ Hz, 3ϕ

$E_t = 10$ V, $B_m = 1.3$ wb/m^2, $\delta = 2.5$ A/mm^2, $K_w = 0.3$,

$H = W$, $S_f = 0.9$, $a = 0.9\,d$, $A_i = 0.6\,d^2$.

To find

Overall dimensions?

Solution

For a 3ϕ transformer

$$Q = 3.33 f \phi_m \delta A_w K_w \times 10^{-3}, \text{ kVA}$$

$$A_w = \frac{Q}{3.33 \times f \times \phi_m \times \delta \times A_w \times K_w \times 10^{-3}}$$

$$A_w = \frac{200}{3.33 \times \phi_m \times 50 \times 2.5 \times 10^6 \times 0.3 \times 10^{-3}} \rightarrow (1)$$

ϕ_m

$$\rightarrow B_m = \frac{\phi_m}{A_i} \Rightarrow \phi_m = B_m A_i \rightarrow (2)$$

$$\rightarrow E_t = 4.44 f \phi_m \Rightarrow \phi_m = \frac{E_t}{4.44 f} \rightarrow (3)$$

From $\phi_m = \dfrac{E_t}{4.44f} = \dfrac{10}{4.44 \times 50}$

$$\phi_m = \underline{\underline{0.045}} \ \text{wb}$$

From Equation (1)

$$A_w = \frac{200}{3.33 \times 0.045 \times 50 \times 2.5 \times 10^6 \times 0.3 \times 10^{-3}}$$

$$A_w = \underline{\underline{0.0356}} \ m^2$$

$$A_w = H_w W_w \rightarrow (4)$$

We know that

$$W_w = D - d \rightarrow (5)$$

Given

$$A_i = 0.6 d^2 \rightarrow (6)$$

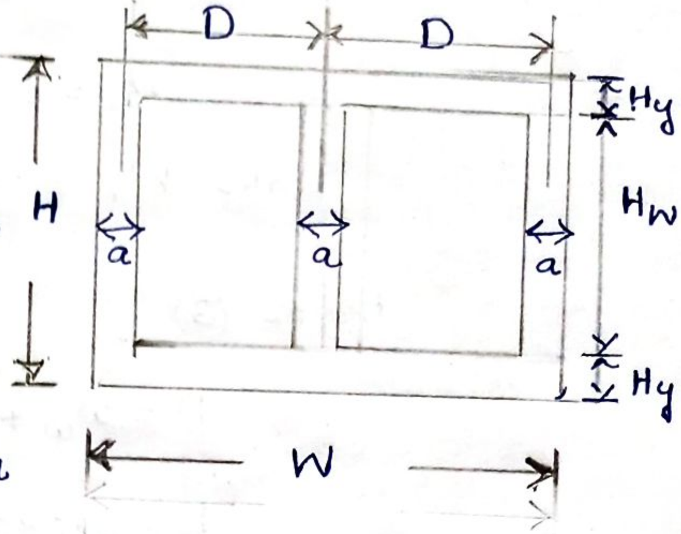
From Equation (2)

$$A_i = \frac{\phi_m}{B_m} = \frac{0.045}{1.3} = \underline{\underline{0.0346}} \ m^2$$

From Equation (6)

$$d^2 = \frac{0.0346}{0.6}$$

$$d = \underline{0.2401\ m}$$



Given $H = W$

$$H_w + 2H_y = 2D + a$$

$$H_w + 2a = 2D + a$$

$$H_w = 2D - a \rightarrow (7)$$

Given

$$a = 0.9\,d$$

$$a = 0.9 \times 0.2401$$

$$a = \underline{0.2161}\ m$$

From eq (7)

$$H_w = 2(W_w + d) - a$$

$$H_w = 2W_w + (2 \times 0.2401) - 0.2161$$

$$H_w = 2W_w + 0.2641$$

From eq (4)

$$0.0356 = (2W_w + 0.2641)\,W_w$$

$$0.0356 = 2W_w^2 + 0.2641\,W_w$$

$$2W_W^2 + 0.2641\,W_W - 0.0356 = 0$$

$$W_\omega = 0.0828\,,\ -0.2149\ m$$

take $W_W = \underline{0.0828}\ m$

From (3)

$$D = W_\omega + d$$

$$D = 0.0828 + 0.2401$$

$$D = \underline{0.3229}\ m$$

From (4)

$$H_\omega = \underline{0.43}\ m$$

<u>Answers</u>

$A_\omega = \underline{0.0356\ m^2}$

$H_\omega = \underline{0.43}\ m$

$W_\omega = \underline{0.0828}\ m$

$D = \underline{0.3229}\ m$

$a = \underline{0.2161}\ m$

$d = \underline{0.2401}\ m$

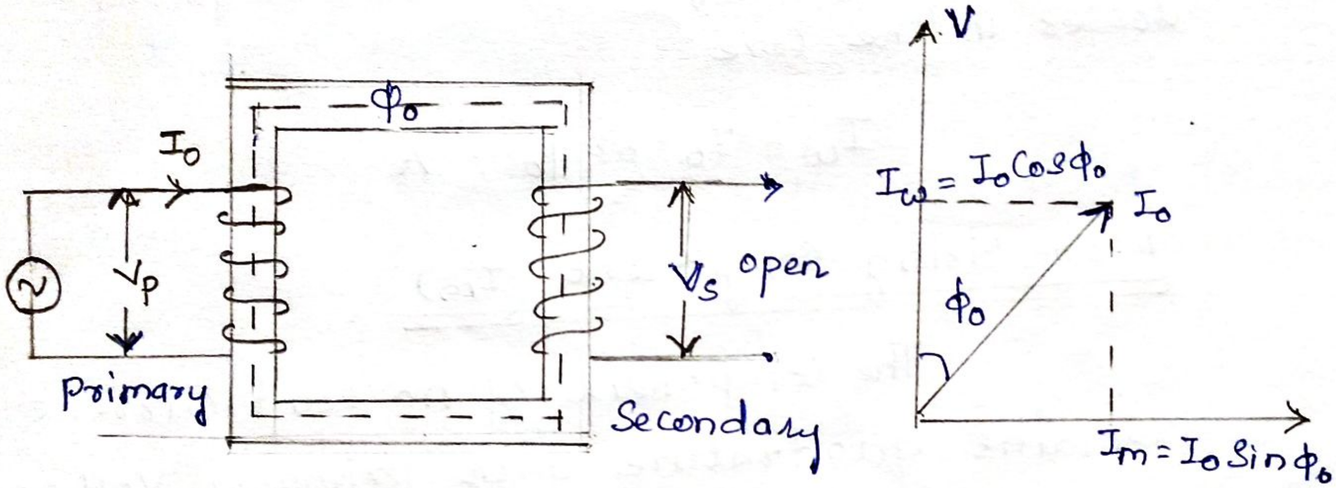
$H = H_\omega + 2a = 0.43 * (2 * 0.2161) = \underline{0.8622}\ m$

$W = 2D + a = (2 \times 0.3229) + 0.2161 = \underline{0.8619}\ m$

$H_y = D_y = a = \underline{0.2161}\ m$

No load of a transformer

When there is no load in secondary side, the transformer is said to be under no load or open circuit. Since the primary winding is connected to the ~~sup~~ supply, a small current is drawn from the supply is called no load current.



a) circuit diagram　　　　c) Phasor diagram

As the primary winding is both Resistive and Inductive, the no load current lags the primary voltage by an angle ϕ_0. This angle ϕ_0 is called no load power factor angle (or) hysteresis angle of advance.

The no load current I_0 can be resolved into two components like loss component and magnetising components.

$$I_0 = \bar{I_w} + \bar{I_m}$$

$$I_0 = \sqrt{I_m^2 + I_w^2}$$

Loss Component (I_w)

The component of no load current (I_w) which remains inphase with primary voltage is called loss component. It is also called active (or) working (or) wattfull component. This component causes losses in the core.

$$I_w = I_0 \cos \phi_0 \text{ , A.}$$

Magnetising Component (I_m)

The component of no load current which remains quadrature with primary voltage is called magnetising component. It is also called reactive (or) watt less component. This component causes flux in the core.

$$I_m = I_0 \sin \phi_0 \text{ , A}$$

No load current (I_0) for 1ϕ core type transformer

a) Calculation of magnetising component (I_m)

The magnetising mmf required at no load is given by AT_0 (or) $AT_m = I_m T_p$

$$I_m = \frac{AT_0}{T_p}$$

where T_p is the number of primary turns.

The R.m.s value of magnetising current at no load is given by

$$\boxed{I_m = \frac{AT_0}{\sqrt{2}\, T_p}}, \quad A$$

The magnetising current is not sinusoidal, therefore the peak factor should be used in the place $\sqrt{2}$.

$$I_m = \frac{AT_0}{k_p . T_p}$$

Calculation of AT_0

Method I

we know that mmf = flux x Reluctance.

$$AT_0 = \phi_m \times S$$

$$AT_0 = \phi_m \times \frac{l_c}{\mu A_c} \Rightarrow AT_0 = \phi_m \times \frac{l_c}{\mu_0 \mu_r A_c}$$

where

$\phi_m \rightarrow$ flux in the core., wb

$l_c \rightarrow$ length of the core $= (2 \times$ length of the limb$) + (2 \times$ length of the Yoke$)$., m

$\mu_r \rightarrow$ relative permeablity of the Core.

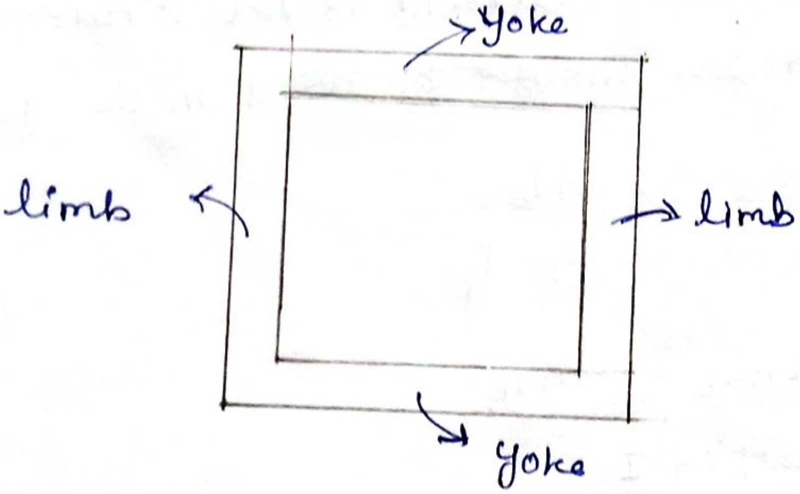
$\mu_0 \rightarrow 4\pi \times 10^{-7}$

$A_c \rightarrow$ net area of the core, m^2

Method II

mmf Required to produce the flux in the Core = mmf Reqired for iron path + mmf required for jointe (gap)

ie) $AT_o = AT_i + AT_g \rightarrow (1)$



From the figure; mmf required for iron path is given by

$$AT_i = 2 at_y l_y + 2 at_l l_l \rightarrow (2)$$

$at_y \rightarrow$ magnetising force required for yoke, AT/m

$l_y \rightarrow$ length of flux path in the yoke, m

$at_l \rightarrow$ magnetising force required for limb, AT/m

$l_l \rightarrow$ length of flux path in the limb, m mmf Required for joints (gap) $= 8,00,000\, B_g l_g k_g$ → (3)

where

B_g → maximum flux density, wb/m^2

l_g → air gap length, m

k_g → Gap contraction factor

= 1, for transformer.

b) Calculation of loss Component (I_w)

The loss component at any load is given by

$$W_o = I_w V_p \quad , \text{watts}$$

$$\boxed{I_w = \frac{W_o}{V_p}} \quad , A$$

where

W_o → power loss at no load. (coreloss)

V_p → primary voltage.

Let

W_s → Specific iron loss, watts/kg

D_i → Density of iron, kg/m^3

V_i → Volume of iron in the Core, m^3

= Area of iron × length of iron in the Core

∴ $\boxed{\text{Power loss at no load } (W_o) = W_s \times D_i \times V_i}$, watts

A 1ϕ, 400V, 50 Hz, transformer is built from stampings have a relative permeablity of 1000, the length of the flux path is 2.5 m. The area of cross section of the core is 2.5×10^{-3} m^2 and the primary winding has 800 turns. Estimate the maximum flux density and the no load current of the transformer. The Iron loss at the working flux density is 2.6 watts/kg. Iron weight is 5.8×10^3 kg/m^3, stacking factor is 0.9.

Given data

1ϕ, $E_p = 400V$, $f = 50$ Hz, $\mu_r = 1000$, length of the flux path = 2.5 m, Area of cross section for the core = 2.5×10^{-3} m^2, $T_p = 800$, Iron loss = 2.6 watts/kg, Iron weight = 5.8×10^3 kg/m^3, $S_f = 0.9$

To find

i) Maximum flux density (B_m)

ii) No load current (I_0)

Solution

i) $$B_m = \frac{\phi_m}{A_i}$$

we know that, $E_p = 4.44 f \phi_m T_p$

$$E_p / T_p = 4.44 f \phi_m$$

$$\frac{400}{800} = 4.44 \times 50 \times \phi_m$$

$$0.5 = 4.44 \times 50 \times \phi_m$$

$$\phi_m = \frac{0.5}{4.44 \times 50}$$

$$\phi_m = \underline{\underline{0.0023}}, \text{ wb.}$$

We know that, $S_f = \frac{A_i}{A_{gi}}$

$$A_i = S_f \times A_{gi}$$

$$= 0.9 \times 2.5 \times 10^{-3}$$

$$A_i = \underline{\underline{0.0023}}, \ m^2$$

From Equation (1)

$$B_m = \frac{0.0023}{0.0023}$$

$$\boxed{B_m = 1 \ wb/m^2}$$

ii) No load Current (I_o)

$$I_o = \sqrt{I_w^2 + I_m^2} \rightarrow (2)$$

where $I_m = \frac{AT_o}{\sqrt{2}\, T_p} \rightarrow (3)$

$$I_w = \frac{P_i}{V_p \text{ (or) } E_p} \rightarrow (4)$$

$$AT_0 = \frac{\phi \, l_c}{\mu_0 \mu_r A_c}$$

$$AT_0 = \frac{0.0023 \times 2.5}{(4\pi \times 10^{-7}) \times 1000 \times 0.0023}$$

$$AT_0 = \underline{\underline{1989.4368}} \text{ , AT.}$$

From Equation (3)

$$I_m = \frac{1989.4368}{\sqrt{2} \times 800}$$

$$I_m = \underline{\underline{1.7584}} \text{ , A}$$

Given Iron loss = 2.6 watts/kg. and Iron weight = 5.8×10^3 kg/m^3.

Therefore Iron loss in watts (P_i) = Iron loss in watts/kg × Iron weight in kg/m^3 × Volume of iron

Iron loss (P_i) in watts $= 2.6 \times (5.8 \times 10^3) \times \underbrace{A_c\, l_c}_{= Ai}$

$= 2.6 \times (5.8 \times 10^3) \times 0.0023 \times 2.5$

$P_i = \underline{\underline{86.71}}$ watts

From Equation (4)

$$I_w = \frac{86.71}{400} = \underline{\underline{0.2168}},\ A$$

From Equation (2)

$$I_o = \sqrt{(0.2168)^2 + (1.7584)^2}$$

$$\boxed{I_o = \underline{\underline{1.7717}},\ A}$$

Answers

$B_m = 1\ wb/m^2$

$I_m = 1.7584$, A

$I_w = 0.2168$, A

$I_o = 1.7717$, A.

Temperature rise in transformers

When the transformer is in working conditions, losses are occurs in the transformer core and windings are converted into thermal energy and cause heating of corresponding transformer parts.

The path of heat flow is

i) From the internal most heated spots to the outer surfaces in contact with the oil (conduction)

ii) From the outer surface to the oil that cools it (convection)

iii) From the oil to the walls of the tank (convection)

iv) From the walls of the tank to the cooling medium (by convection and radiation).

To keep the temperature rise within the safe limit, the heat produced should be transferred to a cooling medium like air or water.

When the transformer rating is high, the natural air cooling method is not effective and hence oil immersed type of cooling is employed.

The specific heat dissipation due to convection of oil is

$$\lambda_{conv} = 40.3 \left(\frac{\theta}{H}\right)^{1/4} \text{ in } W/m^2 \cdot {}^\circ C$$

where

$\theta \rightarrow$ temperature rise of the transformer above ambient temperature, °C

$H \rightarrow$ Height of dissipating surface, m

From the test results, It has been observed that the heat dissipation of oil due to convection is 10 times higher than heat dissipation by air due to convection. Therefore in transformer, oil is used as a cooling medium.

The walls of the tank dissipate the heat by both radiation and convection. From the test results, the plain tank surface dissipates the heat by radiation is 6 $W/m^2\,°C$ and convection is 6.5 $W/m^2\,°C$ respectively.

The specific heat dissipation by tank walls due to convection and Radiation ($\lambda_{\text{conv and rad}}$) = 12.5 $W/m^2\,°C$

$$\text{Temperature rise } (\theta) = \frac{Q}{\lambda S_t}$$

$Q \rightarrow$ total loss $= P_i + P_c$

$\lambda \rightarrow$ Specific heat dissipation by tank wall $= 12.5\ W/m^2,\ °C$

$S_t \rightarrow$ Surface area of the tank.

$$\therefore \boxed{\text{Temperature rise } (\theta) = \frac{P_i + P_c}{12.5\, S_t}}$$

Design of tank with Cooling tubes

The 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,

The heat dissipating surface area of the tank be S_t

$$\boxed{S_t = 2(H_t \times L_t) + 2(H_t \times W_t)}\ , m^2$$

The heat dissipated by the surface of the tank due to convection and radiation $= (6+6.5)\,S_t$

$$= 12.5\,S_t$$

The heat dissipating surface of the cooling tube be taken as $xS_t \longrightarrow (1)$

But the increase in dissipation of heat is not proportional to increase in area, because the tubes would block the heat dissipation by the tank due to radiation. On the other hand, the tubes will improve the circulation of oil due to more effective heads produced by columns of oil in tubes. Therefore the specific heat dissipation due to Convection is taken as 35% more than that without tubes.

Therefore the heat dissipation by the surface of the Cooling tube due to Convection $= 6.5 \times \frac{135}{100} \times x S_t$

$= 8.8\, x S_t$

Temperature rise in transformer with tank and Cooling tubes $= \dfrac{\text{Total loss}}{\text{Total heat dissipation}}$

$$\theta^{\circ}(c) = \frac{P_i + P_c}{\text{Heat dissipation by tank and tubes}}$$

$$\theta^{\circ} = \frac{P_T}{12.5 S_t + 8.8\, x S_t}$$

$$\theta^{\circ}(12.5 S_t + 8.8\, x S_t) = P_T$$

$$12.5 S_t + 8.8\, x S_t = \frac{P_T}{\theta^{\circ}}$$

$$8.8\, x S_t = \frac{P_T}{\theta^{\circ}} - 12.5 S_t$$

$$\boxed{x = \frac{1}{8.8 S_t}\left[\frac{P_T}{\theta^{\circ}} - 12.5 S_t\right]}$$

From Equation ①

The heat dissipating surface area of the cooling tube $= \frac{1}{8.8 S_t}\left[\frac{P_T}{\theta^\circ} - 12.5 S_t\right] S_t$

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

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

The standard diameter of the cooling tubes is 50 mm and the length of the tube depends on the height of the tank. The tubes are arranged with a centre to centre spacing of 75 mm.

The tank of 1250 KVA, natural oil cooled transformer has the dimensions length, width and height as $0.65 \times 1.55 \times 1.85$ m respectively. The load loss = 13.1 kW loss dissipation due to radiations 6 W/m^2 °C, loss dissipation due to convection = 6.5 W/m^2, ~~Im~~ Improvement in convection due to provision of tubes = 40%, temperature rise is 40°C, length of each tube is 1 m, diameter of each tube is 50mm. Find the number of tubes for this convection. Neglect the top and bottom surface of the tank as regards the cooling?

Given data

$$Q = 1250 \text{ KVA}, \text{ Dimensions} = \underset{(L)}{0.65} \times \underset{(W)}{1.55} \times \underset{(H)}{1.85} \text{ m}$$

Total loss = 13.1 kW, $\lambda_{con} = 6.5$ W/m^2 °C, $\lambda_{rad} = 6$ W/m^2 °C. $\theta = 40°C$, Improvement in cooling due to tubes = 40%., $l_t = 1$ m, $d_t = 50$ mm

To find

no of tubes and arrangement of tubes

Solution

$$\text{Temperature rise } (\theta°) = \frac{\text{Total loss}}{(\lambda_t S_t + \lambda_{ct} S_{ct})} \rightarrow (1)$$

$\lambda_t \rightarrow$ Specific heat dissipation of the tank by radiation and convection

$\lambda_t = 6 + 6.5 = 12.5 \ W/m^2\,{}^\circ C$

$S_t \rightarrow$ Surface area of the tank

$S_t = 2H_T(W_T + L_T)$

$= 2 \times 1.85\,(1.55 + 0.65)$

$S_t = \underline{8.14}\ m^2$

$\lambda_{ct} \rightarrow$ Specific heat dissipation of Cooling tube by convection

$$\lambda_{ct} = 6.5 \times \frac{140}{100} = 9.1 \ W/m^2\,{}^\circ C$$

$S_{ct} \rightarrow$ Surface area of the Cooling tubes

Let us take $S_{ct} = x S_t \rightarrow (2)$

From Equation (1)

$$40 = \frac{13.1 \times 10^3}{(12.5 \times 8.14) + (9.1 \times x\, 8.14)}$$

$$40 = \frac{13.1 \times 10^3}{101.75 + 74.074x}$$

$$40(101.75 + 74.074x) = 13.1 \times 10^3$$

$$4070 + 2962.96x = 13.1 \times 10^3$$

$$2962.96x = (13.1 \times 10^3) - 4070$$

$$2962.96\,x = 9030$$

$$x = 3.0476$$

From Eq (2)

Surface area of the Cooling tube (S_{CT}) $= 3.0476 \times 8.14$

$$= \underline{24.8077}, \, m^2$$

Area of each tube $= \pi d_t l_t$

$$= \pi \times (50 \times 10^{-3}) \times 1$$

$$= \underline{0.1571}, \, m^2$$

$\therefore$ Total number of cooling (n_t) $= \dfrac{\text{Total area of tubes}}{\text{area of each tube}}$

$$n_t = \frac{24.8077}{0.1571}$$

$$n_t = 157.9102 \simeq 158$$

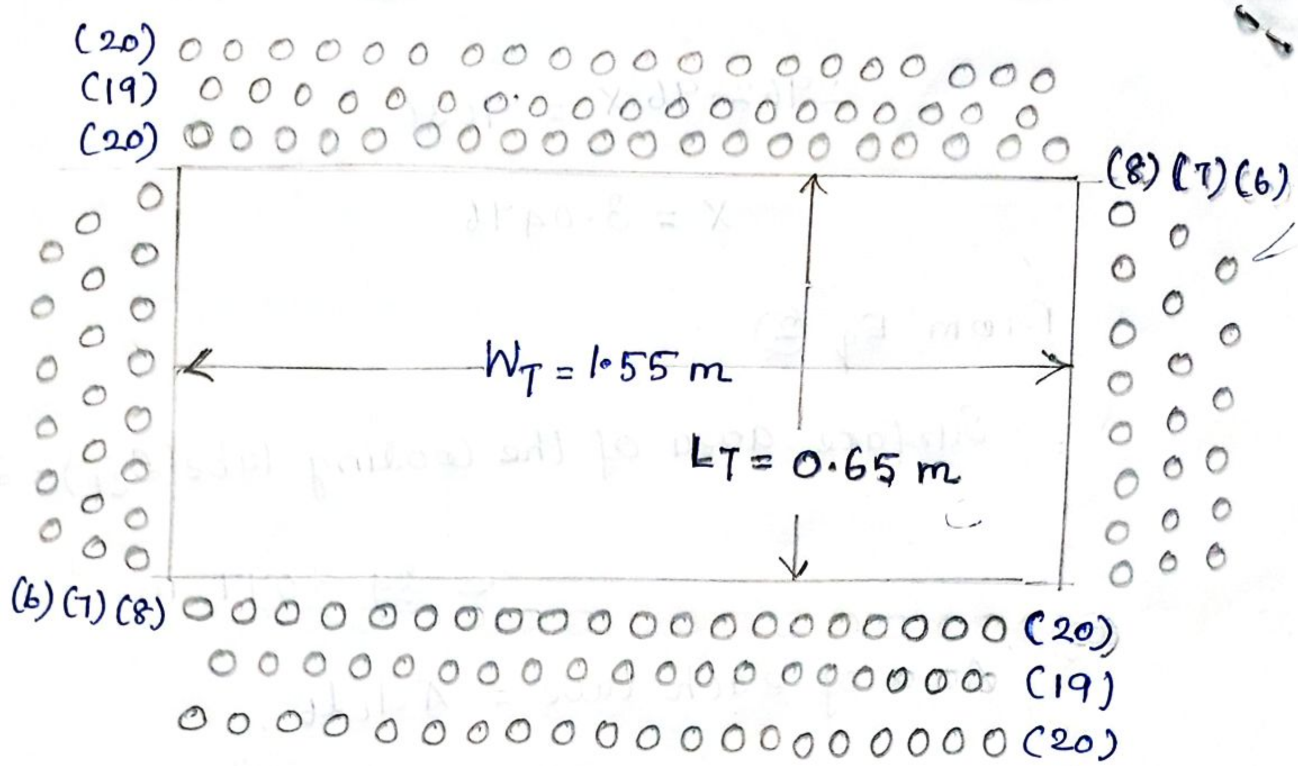
This tubes are placed in vertical position along widthwise and length of the tank with a Centre to Centre spacing of 75 mm.

No of tubes along length wise $= \dfrac{0.65}{75 \times 10^{-3}} = 8.6667$

$$= 8$$

No of tubes along width wise $= \dfrac{1.55}{75 \times 10^{-3}} = 20.6667$

$$= 20$$



Number of tubes in the first row along widthwise and lengthwise = $2(20+8) = 56$

Number of tubes in the first row and second row along widthwise and lengthwise $= 2(20+8) + 2(19+7)$

$= 108$

Number of tubes in the first row, second row and third row along widthwise and lengthwise $= 2(20+8) + 2(19+7) + 2(18+6) = 156$

Here Number of tubes arranged is less than number of tubes required

∴ Number of tubes arranged in first, second and third row along widthwise and lengthwise =

$2(20+8) + 2(19+7) + 2(20+6) = 160$

Ans The number of tubes provided = 160 //

EE 8002 DESIGN OF ELECTRICAL APPARATUS

UNIT III

DESIGN OF DC MACHINES

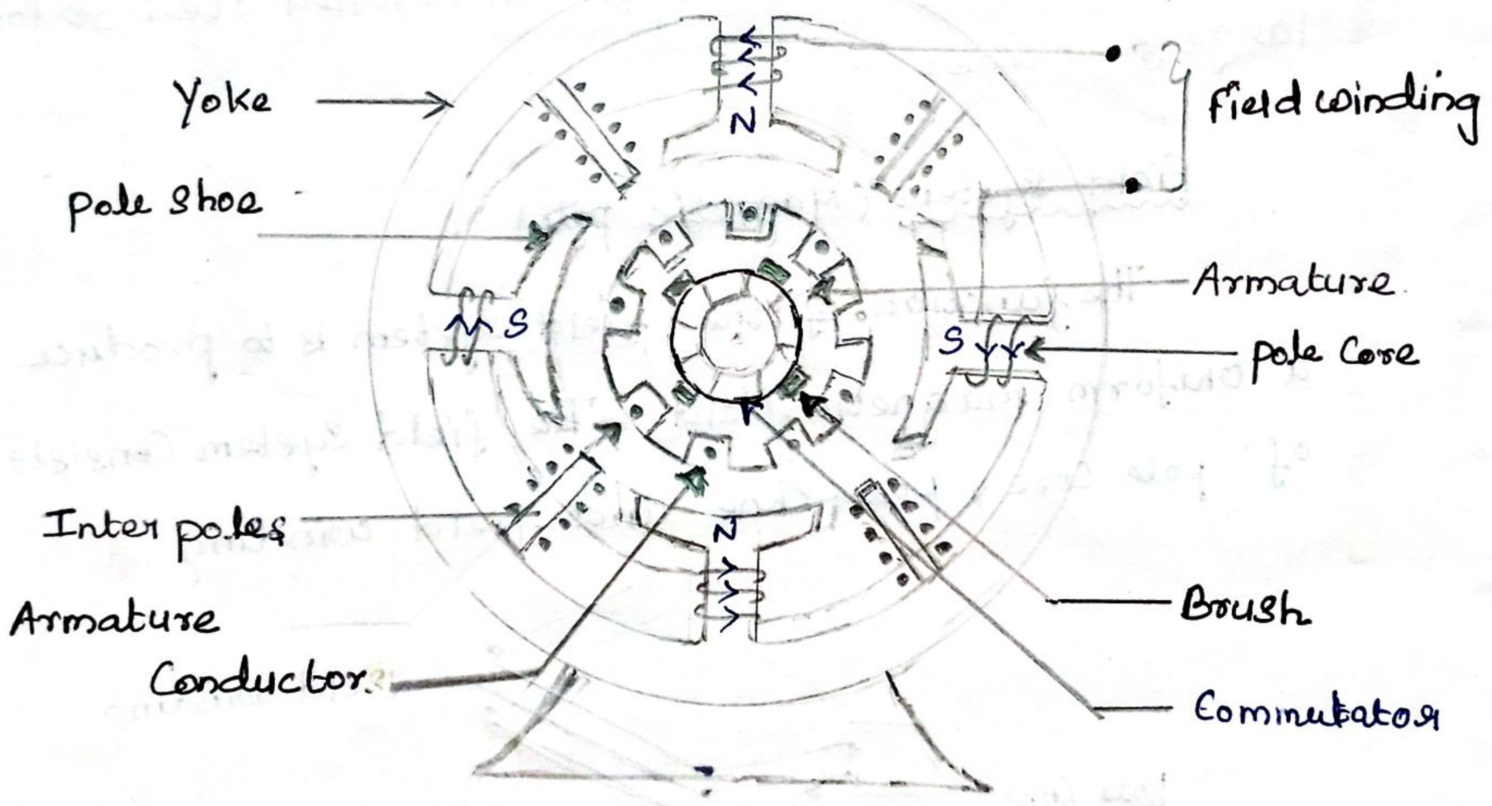
Prepared by
Dr . T. Dharma Raj
Asso.Prof /EEE

Constructional details of a DC machine

A DC machine has two main parts; Stator and rotor.

The Stator is the non rotating part and Consists of field System, Yoke, Interpoles and Brushes.

The rotor is the rotating part and consists Of Armature System, Commutator and Bearings



Yoke

It is the outer layer of the DC machine which protects the parts of the machine against dust, moisture and various gas like SO_2, Acidic fumes entering into it.

It provides a mechanical support to the poles

It provides a path for the ~~of~~ magnetic flux produced by the field system.

The magnetic material used for making yoke is must to provide low reluctance path for magnetic flux. Hence the material selected was

Cast iron → for small machines

Cast steel, silicon steel, rolled stell → for large machines.

Field System

The field system consists of pole core, pole shoe and field windings.

Pole Core carries the field winding and directs the magnetic flux through air gap, armature and to next pole.

To reduce the core losses, the pole cores are made up of magnetic material called cast iron (or) cast steel with laminated construction. These laminations are stacked and stamped together to form pole core, The pole core is fitted to the yoke by means bolts or welding.

The curved surface at the end of the pole core towards the armature is called pole shoe. It will serve two purposes.

i) It offer low reluctance for the magnetic flux, because of that magnetic flux are uniformly distributed over the air gap.

ii) It provides the mechanical support to the field windings.

Field winding is also called ~~exiting~~ exciting winding which is made up of copper. This field windings are wounded ~~on~~ around the pole core and causing the pole core as electro magnet, when the field windings carrying current.

The field coils are connected in series in such a way that adjacent poles have opposite polarity

Interpoles

Interpoles are usally made by cast iron or cast steel and is placed between two adjacent main poles. Just like field winding, the interpoles also have exciting coils which are connected in series with the armature. It will serve two purposes

i) Reduce the effect due to Armature Reaction
ii) Improve the Commutation.

Armature System

The armature System Consists ~~A~~ of armature Core and armature windings

Armature Core is in Cylindrical Shape and having alternate Slot and teeth on its outerperiphery. The ~~a~~ Slots are provided for ~~place~~ accomodating the armature windings.

The armature Core along with armature Conductors are rotated in the uniform magnetic field produced by the field system

To reduce the Core losses, the Armature core are made up of magnetic material Called Cast iron (or) Cast steel with laminated construction. These laminations are stacked and stamped together to form Armature Core.

Armature windings

Armature windings are usually made of Copper. There are two types of Armature windings namely (i) Lap Winding and (ii) Wave winding.

In lap ~~or~~ type Armature winding, the armature Coils are divided into ~~n~~ number of parallel paths which is equal to number of poles. This type of winding is preferred for low voltage, high current applications.

In wave type Armature winding, the armature coils are divided into number of parallel path which is equal to 2. This type of winding is preferred for high voltage, low current applications.

Commutator

It is in ~~a~~ cylindrical structure and made up of copper segments. But these copper segments are insulated from each other by thin sheet of Mica.

Its function is to collect the current from the Armature conductors and convert this alternating current into unidirectional ~~DC~~ current. So this commutator is called Mechanical Rectifier.

Brushes

It is in rectangular shape, made by carbon or graphite. The Brushes are placed in brush holders. A spring action in the Brush holder maintain a proper contact of Brush over the Rotating Commutator.

Its function is to (i) collect the current from Commutator and make it available to the load in the case of DC Generator.

ii) It supplies the current from the external circuit to Armature windings in case of DC motor.

Bearings

It function is to provide smooth rotation of armature system. The different types of bearings are ball and roller bearings.

~~Becaus~~ Because of their reliablity ball bearings are frequently used.

Main Dimensions

The armature diameter and armature core length are known as the main dimensions of a rotating machine.

Total loadings and Specific loadings

Total loadings can be divided into two types.

(i) Total magnetic loading
(ii) Total Electric loading

Total magnetic loading

The total flux around the armature pheriphery at the air gap is called total magnetic loading.

Total magnetic loading $= P\phi$

where

$P \rightarrow$ number of poles.

$\phi \rightarrow$ flux per pole, wb

Total Electric loading

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

Total electric loading $= I_z \cdot Z$

where

$I_z \rightarrow$ current flow in each conductor, A

$Z \rightarrow$ total number of armature conductor

Specific loadings

It can be divided into two types

i) Specific magnetic loading
ii) Specific electric loading

Specific magnetic loading (B_{av})

It is defined as the ratio of total flux around the airgap to the Area of flux path at the airgap.

$$B_{av} = \frac{\text{Total flux around the airgap}}{\text{Area of flux path at the airgap}}$$

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

Specific Electric loading (ac)

It is defined as the ratio of total ampere Conductors to the Armature periphery at airgap

$$ac = \frac{\text{Total ampere Conductors}}{\text{Armature periphery at air gap.}}$$

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

Choice of specific magnetic loading in DC machine.

The specific magnetic loading is defined as the ratio of Total flux around the airgap to Area of flux path around the air gap.

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

The following factors are to be considered to choose the specific magnetic loading

i) Flux density in teeth

ii) Frequency

iii) Voltage

i) Flux density in teeth

If a high value of airgap flux density (B_{av}) is used, the flux density in armature teeth also becomes high. The value of flux density at the root of teeth should not exceeds 2.2 wb/m^2. Otherwise it may lead to

→ increased Iron loss

→ higher ampere turns requires for passing the flux through teeth leading to increased copper losses and cost of copper.

ii) Frequency

$$N_s = \frac{120 f}{P} \Rightarrow f = \frac{N_s P}{120} = \frac{N_s}{60} \times \frac{P}{2} = \frac{P n_s}{2}$$

The frequency of flux reversa in the armature is given $f = \frac{P n_s}{2}$. Higher frequency leads to Increased Iron losses in the armature Core and teeth. So there is a limitation in choosing higher Bav for a machine having higher frequency.

iii) Voltage.

For high voltage machines, Spaced required for insulation is large. Therefore for a given diameter width of the slot increases which inturn decreases the width of the teeth.

If width of the teeth reduces, then area of cross section of teeth reduces, which increases the flux density of the teeth

$$\boxed{B_t = \frac{\phi_t}{A_t}}$$

Therefore for high voltage machine, low value of Bav is choosen, otherwise the flux density increases beyond the permissible limit.

The typical value of Bav varies from 0.4 to 0.8 wb/m^2.

Choice of Specific electric loading in DC Machine.

It is defined as the ratio of total ampere conductor to the armature periphery at the air gap

$$\boxed{ac = \frac{I_z \cdot Z}{\pi D}} \rightarrow (1)$$

The following factors are to be considered, while selecting the specific electric loading

i) Temperature rise

ii) Speed of machine

iii) Voltage

iv) Size of the machine

v) Armature Reaction

vi) Commutation.

i) Temperature rise

A higher value of "ac" results in a high temperature rise of windings. Temperature rise depends on method of cooling and type of enclosure.

ii) Speed of Machine

In high speed machines, the ventilation will be better and more losses can be dissipated, Hence higher value of ac can be used for higher speed machines.

iii) Voltage

High voltage machines require large space for insulation, therefore there is less space for conductors which inturn reduces the area of the conductors. Due to this reason, a small value of 'ac' should be used for high voltage machines.

iv) Size of the machine

In large size machines, there is more space for accommadating copper conductors. Therefore high value of "ac" can be used.

v) Armature Reaction

A higher value of "ac" results in a higher armature mmf. Under loaded condition, this armature mmf affects the field mmf which inturn reduce the value of net flux. To compensate this, field mmf should be increased. Thus overall cost of copper in the machine will increase.

vi) Commutation

From Equation ①, higher value of ac is achieved by either using more ampere conductor (or) with small diameter.

For small diameter, the deeper slots are used to accommadate this ampere conductors.

Deeper slots also give higher reactance voltage. Higher reactance voltage results in poor commutation. Hence, higher 'ac' leads to poor commutation.

The typical value of 'ac' varies from 15,000 to 50,000 ampere conductors/metre.

A 350 kW, 500V, 450 rpm, 6 pole DC generator is built with the armature diameter of 0.87 m and core length of 0.33 m. The lap wound armature has 660 conductors. Calculate the specific electric and magnetic loading.

Given data

$P = 350$ kW, $V_L = 500$V, $N = 450$ rpm, $P = 6$, $D = 0.87$m,

$L = 0.33$ m, lap wound, $Z = 660$

To find

i) Specific electric loading (ac)
ii) Specific magnetic loading (B_{av})

Solution

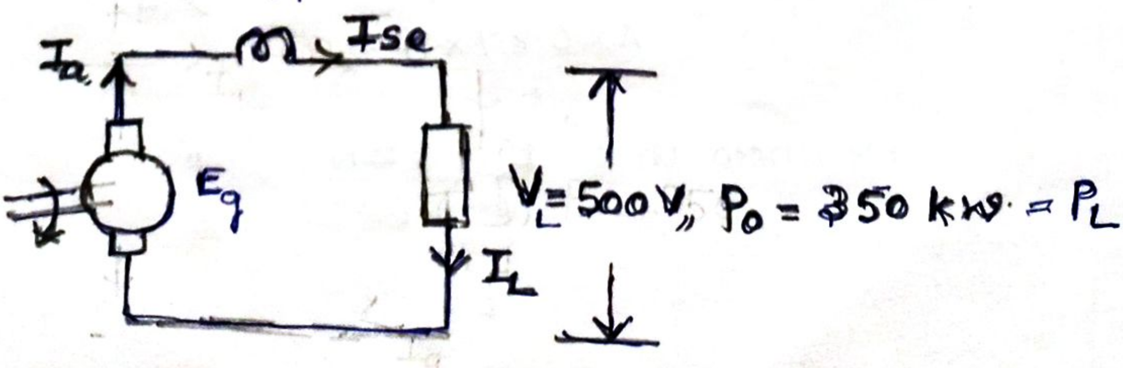
i) Specific electric loading

$$ac = \frac{I_z \cdot Z}{\pi \cdot D}$$

$$ac = \frac{I_z \times 660}{\pi \times 0.87} \rightarrow (1)$$

$I_z \rightarrow$ Current through the parallel path

$$I_z = \frac{I_a}{A} \rightarrow (2)$$



$$I_a = I_{se} = I_L \rightarrow (3)$$

From the Circuit diagram

$$P_L = V_L I_L$$

$$350 \times 10^3 = 500 \times I_L$$

$$I_L = \frac{350 \times 10^3}{500} = 700\ A$$

From (3)

$$I_a = 700\ A$$

From (2)

$$I_z' = \frac{700}{6} = 116.6667\ A$$

From (1)

$$ac = \frac{116.6667 \times 660}{\pi \times 0.87}$$

$$ac = 28,172.2623 \text{ ampere conductor/metre.}$$

ii) **Specific Magnetic loading (B_{av})**

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

$$B_{av} = \frac{6 \times \phi}{\pi \times 0.87 \times 0.33} \rightarrow (4)$$

We know that $E_g = \frac{\phi Z N}{60} \times \frac{P}{A}$

$$\phi = \frac{E_g \times 60 \times A}{Z \times N \times P}$$

$\boxed{A = P \text{ (given lap wound)}}$

$$\phi = \frac{E_g \times 60 \times 6}{660 \times 450 \times 6} \rightarrow (5)$$

From the circuit diagram

$$E_g = I_a R_a + I_{se} R_{se} + V_L$$

$$E_g \simeq V_L$$

$$E_g = 500 \text{ V}$$

From (5)

$$\phi = \frac{500 \times 60 \times 6}{660 \times 450 \times 6}$$

$$\phi = \underline{\underline{0.1010}} \text{ wb}$$

From (4)

$$B_{av} = \frac{6 \times 0.1010}{\pi \times 0.87 \times 0.33}$$

$$B_{av} = \underline{\underline{0.6719}}, \text{ wb/m}^2$$

Output Equation

The equation which describe the relationship between main dimension, Specific electric and magnetic loading and Speed is known as output Equation.

Power developed by the armature (Pa) in kW

$$Pa = \text{Generated emf} \times \text{Armature Current} \times 10^{-3}.$$

$$Pa = E \times Ia \times 10^{-3}, \text{ kW} \rightarrow (1)$$

$$\text{Generated emf}, E = \frac{\phi Z N P}{60 A} \rightarrow (2)$$

where, $N \rightarrow$ Speed in rpm, $\therefore n = \frac{N}{60}$

$$N = n \times 60 \rightarrow (3)$$

where

$n \rightarrow$ Speed in rps

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

$$Pa = \frac{\phi Z N P}{60 A} \times I_a \times 10^{-3}$$

$$= \frac{\phi z (n \times 60) P}{60 A} \times I_a \times 10^{-3}$$

$$Pa = \frac{\phi z n P}{A} \times Ia \times 10^{-3}, \text{ kW}.$$

Current in each Conductor $(I_z) = \frac{I_a}{A} \rightarrow$

$$I_a = I_z \cdot A \rightarrow (4)$$

hence $P_a = \frac{\phi Z n P}{A} \times I_z \cdot A \times 10^{-3}$

$$P_a = (P\phi)(I_z \cdot Z) \times n \times 10^{-3} \rightarrow (5)$$

Therefore P_a = Total magnetic loading × Total electrical loading × Speed in rps $\times 10^{-3}$.

We know that

Specific magnetic loading $B_{av} = \frac{P\phi}{\pi D L}$

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

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

$$I_z \cdot Z = ac \pi D$$

Substitute $(P\phi)$ and $(I_z \cdot Z)$ in (5)

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

$$\boxed{P_a = \pi^2 D^2 L n \, B_{av} \, ac \times 10^{-3}}, \text{ kw}$$

$$P_a = C_o D^2 L n$$

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

$C_o \rightarrow$ output coefficient

$D \rightarrow$ Armature Diameter (or) Stator bore, m

$L \rightarrow$ Length of core, m

Estimate the main dimensions of a 200 kW, 250 Volts, 6 poles, 1000 rpm DC generator. The maximum value of flux density in the air gap is 0.87 wb/m^2 and the ampere conductors per metre length of armature pheriphery are 31000, The ratio of pole arc to pole pitch = 0.67 and the efficiency is 91 %. Assume that the ratio of length of core to pole pitch = 0.75.

<u>Given data</u>

$P_o = 200$ kW, $V_L = 250$ V, $P=6$, $N = 1000$ rpm,

DC generator, $B_m = 0.87$ wb/m^2, $ac = 31000$,

$$K_f = \frac{\text{pole arc}}{\text{pole pitch}} = \frac{B_{av}}{B_g} = 0.67, \quad \eta = 91\%, \quad \frac{L}{\tau} = 0.75$$

<u>To find</u>

Main dimensions

<u>Solution</u>

Power developed in the armature is given by

$$P_a = \pi^2 D^2 L\, n_s\, B_{av}\, ac \times 10^{-3}, \text{ kW}$$

$$D^2 L = \frac{P_a}{\pi^2 n_s B_{av}\, ac \times 10^{-3}}$$

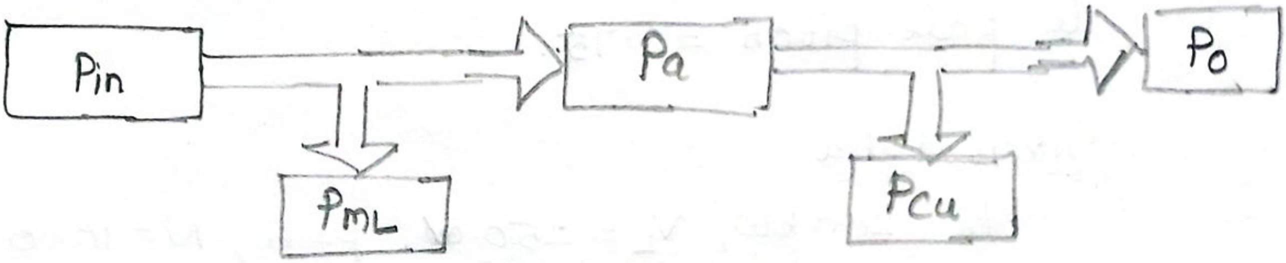
$$D^2 L = \frac{P_a}{\pi^2 \times \left(\frac{1000}{60}\right) \times B_{av} \times 31000 \times 10^{-3}} \rightarrow (1)$$

given $\frac{B_{av}}{B_g} = 0.67$

$B_{av} = 0.67 \times 0.87$

$B_{av} = \underline{0.5829}$, wb/m^2

From the power flow diagram



$P_a = P_{in} - P_{mL}$

$P_a = \frac{P_o}{\eta} - P_{mL}$

(For large size gnr, P_{mL} is neglected)

$\therefore \; P_a = \frac{P_o}{\eta}$

$P_a = \frac{200}{0.91} = \underline{\underline{219.7802}}$, kW

From Equation ①

$$D^2L = \frac{219.7802}{\pi^2 \times 16.6667 \times 0.5829 \times 31000 \times 10^{-3}}$$

$D^2L = \underline{\underline{0.0739}}$, m^3 $\rightarrow$ ②

Seperation of D and L from D^2L, Based on the ratio $\frac{L}{\tau}$ and is given $\frac{L}{\tau} = 0.75$

$$\frac{L}{\tau} = 0.75$$

$$L = 0.75\,\tau$$

$$L = 0.75 \times \frac{\pi D}{P}$$

$$L = 0.75 \times \frac{\pi D}{6}$$

$$L = 0.3927\,D \rightarrow (3)$$

From eq (2)

$$D^2 \times 0.3927\,D = 0.0739$$

$$D^3 = \frac{0.0739}{0.3927} = 0.1882$$

$$D = \underline{\underline{0.5731}}\ \text{m}$$

From eq (3)

$$L = 0.3927 \times 0.5731$$

$$L = \underline{\underline{0.2250}}\ \text{m}$$

A design is required for a 50 kW 4 pole, 600 rpm dc Shunt generator, the full load terminal voltage being 220V. If the maximum gap density is 0.83 wb/m^2 and the armature ampere conductor per metre are 30,000. Calculate suitable dimensions of armature core to give a square pole face.

Assume that the full load armature voltage drop is 3 percent of the rated terminal voltage. and that the field current is 1 percent of rated full load current. Ratio of pole arc to pole pitch is 0.67.

Given data

$P_o = 50\,kW$, $P=4$, $N = 600$ rpm, DC Shunt generator
$V_L = 220\,V$, $B_g = 0.83\, wb/m^2$, $ac = 30{,}000$ ampere conductor/metre, Square pole, $I_a R_a = 3\%$ of V_L
$I_f = 1\%$ of I_L, $K_f = \frac{\text{Pole arc}}{\text{pole pitch}} = \frac{B_{av}}{B_g} = 0.67$.

To find

Main Dimensions (D and L)

Solution

The power developed in thee armature is given by

$$P_a = \pi^2 D^2 L\, n_s\, B_{av}\, ac \times 10^{-3}, \text{ kW}$$

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

$$D^2L = \frac{P_a}{\pi^2 \times \left(\frac{600}{60}\right) \times B_{av} \times 30000 \times 10^{-3}} \rightarrow (1)$$

Given $k_f = \frac{B_{av}}{B_g} = 0.67$

$B_{av} = B_g \times 0.67$

$B_{av} = 0.83 \times 0.67$

$B_{av} = \underline{\underline{0.5561}}\ wb/m^2$

From the power flow diagram

$P_a = P_{in} + P_{mL}$

$P_o = \frac{P_o}{\eta} - P_{mL}$

$P_a = \frac{P_o}{\eta}$ (neglect P_{mL} if $P_o \geq 3.75\ kW$ (5hp))

$P_a = \frac{50}{\eta}$

Also the P_a is expressed as $P_a = E_g I_a \times 10^{-3}$, kW $\rightarrow$ (2)

$E_g = \frac{\phi Z N}{60} \times \frac{P}{A}$ and also $E_g = V + I_a R_a$

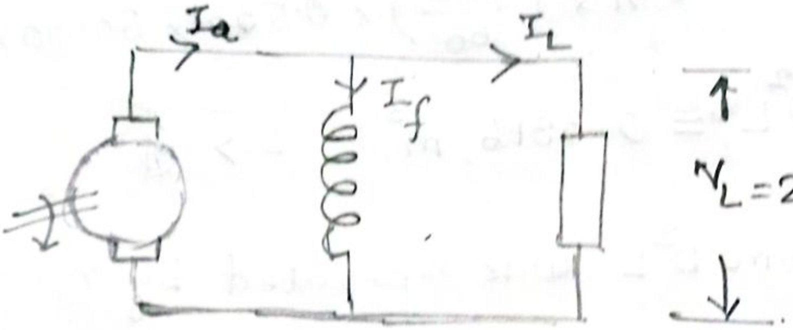
$$E_g = V + I_a R_a$$

$$= 220 + (3\% \text{ of } V_L)$$

$$= 220 + \left(\frac{3}{100} \times 220\right)$$

$$= 220 + 6.6$$

$$E_g = 226.6 \text{, V}$$



$V_L = 220V$, $P_L = P_o = 50$ kW

$$I_a = I_L + I_f \rightarrow (3)$$

$$P_L = V_L I_L$$

$$I_L = \frac{P_L}{V_L} = \frac{50 \times 10^3}{220}$$

$$I_L = 227.2727 \text{, A}$$

Given $I_f = 1\%$ of I_L

$$I_f = 0.01 \times 227.2727$$

$$I_f = 2.2727 \text{, A}$$

From (3)

$$I_a = 227.2727 + 2.2727$$

$$I_a = \underline{229.5454}\ A$$

From (2)

$$P_a = 226.6 \times 229.5454 \times 10^{-3},\ kW$$

$$P_a = \underline{52.0150},\ kW$$

From (1)

$$D^2L = \frac{52.015}{\pi^2 \times \left(\frac{600}{60}\right) \times 0.5561 \times 30000 \times 10^{-3}}$$

$$D^2L = \underline{0.0316},\ m^3 \rightarrow (4)$$

D and L from D^2L was seperated by ratio $\frac{L}{\tau}$.

Given Square pole face, ie) pole arc =

$$\frac{L}{\tau} = \frac{\text{pole arc}}{\text{pole pitch}} = 0.67$$

$$L = 0.67\ (\tau)$$

$$L = 0.67 \times \frac{\pi D}{P}$$

$$L = \frac{0.67 \times \pi \times D}{4}$$

$$L = \underline{0.526}\ D \rightarrow (5)$$

From eq (4)

$$D^2 \times 0.526D = 0.0316$$

$$D^3 = \frac{0.0316}{0.526}$$

$$D^3 = 0.0601$$

$$D = \underline{\underline{0.3917}}, m$$

From eq (5)

$$L = 0.526 \times 0.3917$$

$$L = \underline{\underline{0.2060}}, m$$

Ans

$$D = \underline{\underline{0.3917}}, m$$

$$L = \underline{\underline{0.2060}}, m$$

Calculate the diameter and length of armature for a 7.5 kW, 4 pole, 1000 r.p.m, 220 V Shunt motor. Given full load efficiency = 0.83, maximum gap flux density = 0.9 wb/m², Specific electric loading = 30,000 ampere conductor per metre. field form factor = 0.7. Assume that the maximum efficiency occurs at full load and the field current is 2.5% of rated current. The pole face is square.

Given data

$P_o = 7.5$ kW, $P = 4$, $N = 1000$ rpm, $V = 220$, Shunt motor

$\eta_{full} = 0.83$, $B_{gm} = 0.9$ wb/m², $ac = 30,000$, $k_f = 0.7$

Maximum efficiency occurs at full load and field current = 2.5% of I_L; Pole face is square.

To find

Diameter and length of Armature.

Solution

Power developed in the Armature is given by

$$P_a = \pi^2 D^2 L\, n_s B_{av}\, ac \times 10^{-3}, \text{ kW} \rightarrow (1)$$

$$D^2 L = \frac{P_a}{\pi^2 n_s B_{av}\, ac \times 10^{-3}}$$

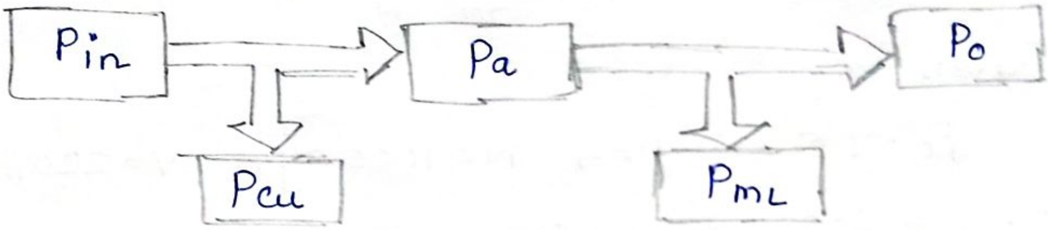
$$D^2 L = \frac{P_a}{\pi^2 \times \left(\frac{1000}{60}\right) \times B_{av} \times 30,000 \times 10^{-3}}$$

$$D^2L = \frac{P_a}{4934.8022 \times B_{av}} \rightarrow (1)$$

We know that $K_f = \frac{B_{av}}{B_{gm}} = \frac{\text{Pole arc}}{\text{Pole pitch}}$

$$B_{av} = K_f \times B_{gm}$$
$$= 0.7 \times 0.9$$
$$B_{av} = \underline{0.63} \text{ wb/m}^2$$

From power flow diagram



$$P_a = P_o + P_{mL} \rightarrow (2)$$

Given maximum efficiency occurs at full load.

At maximum efficiency.

Variable loss = Constant loss, hence P_{mL} cannot be neglected.

Constant loss = Field cu loss + Friction and windage loss + iron loss

$\therefore$ Friction and windage loss + iron loss = Constant loss - field cu loss

$$P_{mL} = \text{Constant loss} - \text{field cu loss} \rightarrow (3)$$

Total loss = Input power - Output power

$$\text{Total loss} = P_{in} - P_o$$

$$= \frac{P_o}{\eta} - P_o$$

$$\text{Total loss} = \left(\frac{7.5}{0.83} - 7.5\right)$$

$$\text{Total loss} = \underline{\underline{1.5361}}, \text{ kW}$$

Also the total loss can be expressed as

Total loss = Variable loss + Constant loss

At maximum efficiency, Variable loss = Constant loss

∴ Total loss = Constant loss + Constant Loss

$$\text{Constant loss} = \frac{\text{Total loss}}{2} = \frac{1.5361}{2}$$

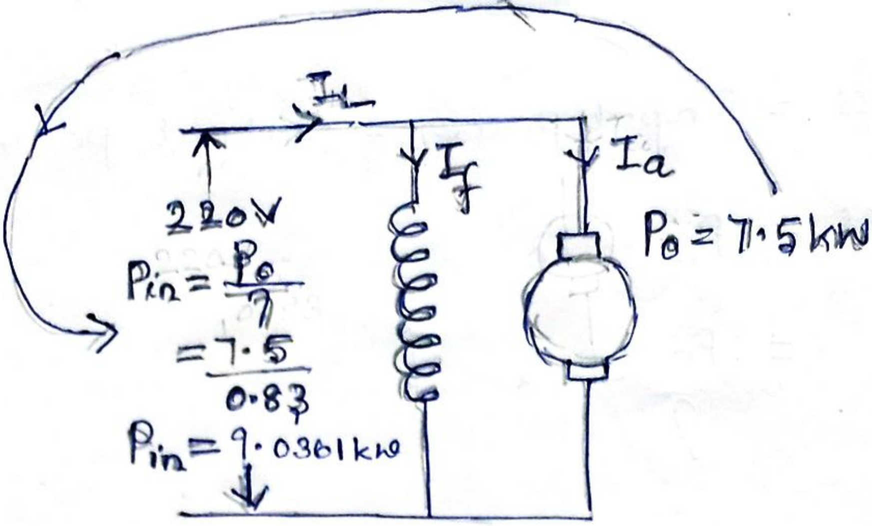
$$\text{Constant loss} = \underline{\underline{0.7681}}, \text{ kW.}$$

Field cu loss depends on the current flows through the Resistance of the field winding.

$$\text{Field cu loss} = I_f^2 R_{sh} = V_{sh} \cdot I_f$$

$$\text{Given, } I_f = \frac{2.5}{100} \times I_L$$

$$\text{Field cu loss} = V_{sh} \times \frac{2.5}{100} \times I_L \longrightarrow (4)$$



$P_{in} = \frac{P_o}{\eta}$

$= \frac{7.5}{0.83}$

$P_{in} = 9.0361$ kW

$$P_{in} = V_L I_L$$

$$I_L = \frac{P_{in}}{V_L} = \frac{9.0361 \times 10^3}{220}$$

$$I_L = 41.0732 \text{, A}$$

From (4)

$$\text{Field cu loss} = 220 \times \frac{2.5}{100} \times 41.0732$$

$$= 225.9025 \text{, Watts}$$

$$= 0.2259 \text{, kw}$$

from (3)

$$P_{mL} = 0.7681 - 0.2259$$

$$= 0.5422 \text{ kw.}$$

From (2)

$$P_a = 7.5 + 0.5422$$

$$= 8.0422 \text{, kw}$$

From (1)

$$D^2L = \frac{8.0422}{4934.8022 \times 0.63}$$

$$D^2L = \underline{\underline{0.0026}}, m^3 \rightarrow (5)$$

Given pole face is square, pole arc = core length

$$\frac{L}{\tau} = \frac{\text{Core length}}{\text{pole pitch}} = \frac{\text{Pole arc}}{\text{pole pitch}} = 0.7$$

$$\frac{L}{\tau} = 0.7$$

$$L = 0.7\tau$$

$$L = \frac{0.7\pi D}{P}$$

$$L = \left(\frac{0.7 \times \pi}{4}\right) D$$

$$L = \underline{\underline{0.5498}}\ D \rightarrow (6)$$

From Eq (5)

$$D^2 \times 0.5498\ D = 0.0026$$

$$D^3 = \frac{0.0026}{0.5498}$$

$$D = \sqrt[3]{0.0047} = \underline{\underline{0.1679}}, m$$

From Eq (6)

$$L = 0.5498 \times 0.1679 = \underline{\underline{0.0923}}, m$$

Selection of poles in DC machine

The factors to be Considered for Selection of poles are

i) Frequency
ii) Weight of iron parts
   a) Yoke area
   b) Armature Core area
   c) Overall diameter
iii) Weight of Copper
   a) Armature copper
   b) Field Copper
iv) Length of Commutator
v) Labour Charges
vi) Flash over
vii) Distortion of field flux.

i) Frequency

The frequency of flux Reversal is given by

$$f = \frac{Pn}{2}$$

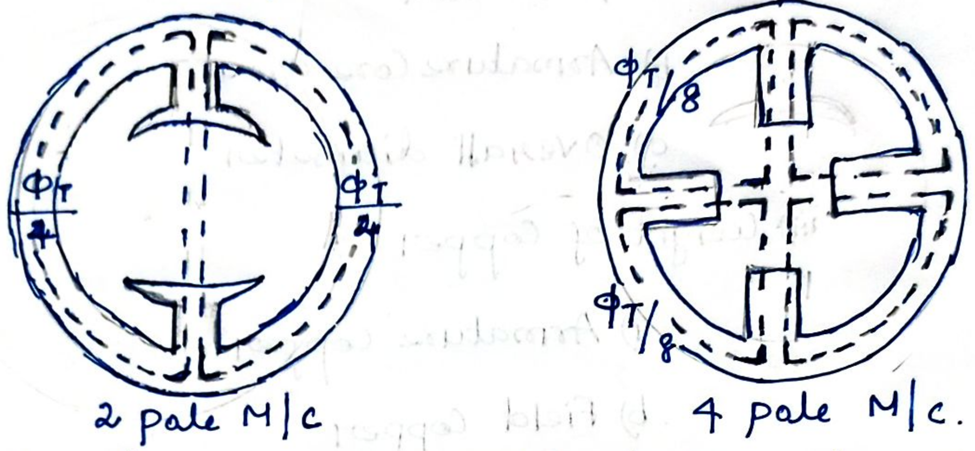
If we choose higher number of poles, the frequency will high. But for DC machine, frequency will be allowed lies b/w 25 to 50 Hz. Otherwise it would give rise to excessive iron loss in armature core and teeth.

ii) Weight of Iron parts

a) Yoke area

The total flux around the airgap is taken as ϕ_T

Consider a 2 pole and 4 pole DC machine



For 2 pole machine, the flux/pole is $\frac{\phi_T}{2}$. But at the yoke, this flux divides itself into two parts and therefore the yoke has to carry a flux $\frac{\phi_T}{4}$.

For 4 pole machine, the flux/pole is $\frac{\phi_T}{4}$, But at the yoke, this flux divides itself into two parts and therefore the yoke has to carry a flux of $\frac{\phi_T}{8}$.

From this 2 pole and 4 pole machines, we conclude that, by using greater number of poles, the flux carried by the yoke decreases which inturn decreases the area of cross section of yoke.

If area of cross section of yoke decreases means the weight of yoke decreases with selecting higher number of poles.

b) Armature core area

Consider a 2 pole and 4 pole machine shown in above figure

For 2 pole machine, flux carried by the Armature is $\frac{\phi_T}{4}$

For 4 pole machine, flux carried by the Armature is $\frac{\phi_T}{8}$

From this we conclude, If we using higher number of poles, flux in the armature core reduces which interm reduces the area of cross section of Armature core.

ie) weight of Armature core decreases.

But in DC machines, The armature is the rotating part, hence we consider the effect of frequency of flux Reversal.

The equation which relates the poles and frequency is given by

$$f = \frac{Pn}{2}$$

If we choose higher number of poles, the frequency increases which interm increases the iron losses.

But here

Eddy current loss ↑es with higher number of poles.

Hysteresis loss ↓es with choosing higher number of poles.

c) Overall diameter

If we choose higher number of poles, the armature mmf / pole will decreases.

If armature mmf / pole is reduced, the number of turns in the field winding required is reduced, which in turn reduces the height of the field winding which allow us to reduce the height of the pole.

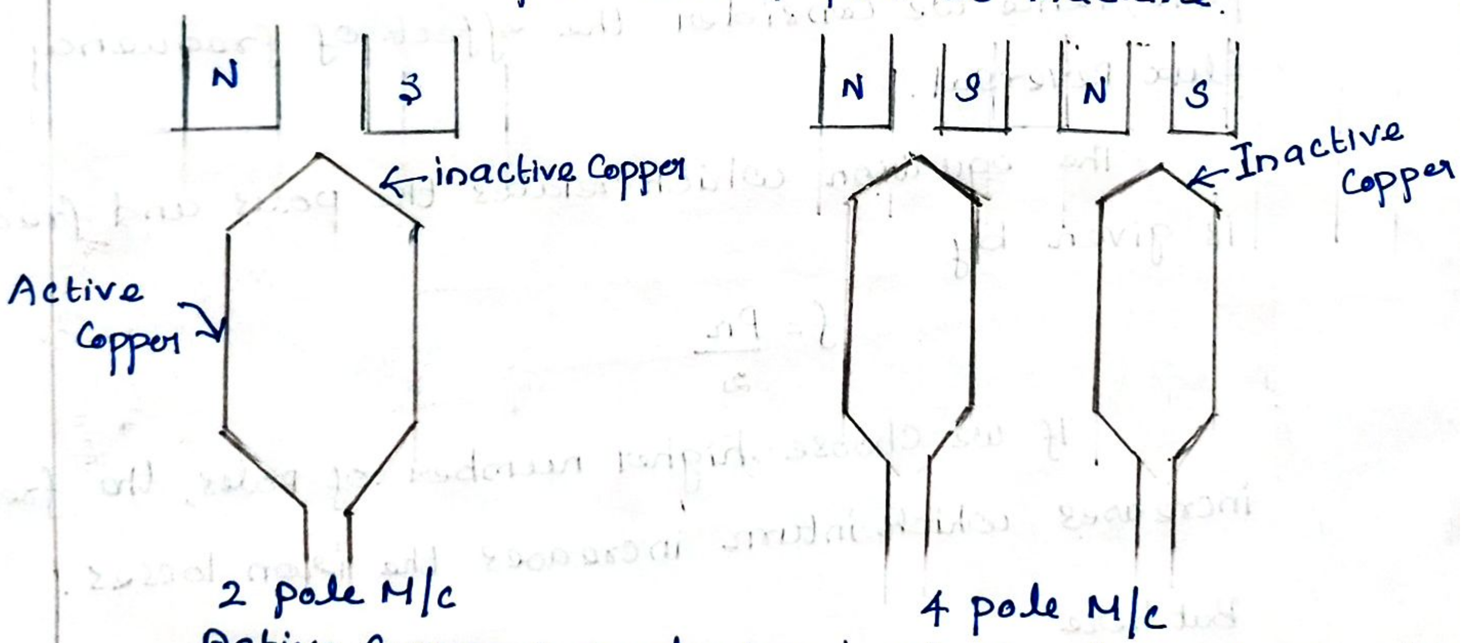
If height of the pole reduces, the Overall diameter of the machine reduces.

ie) weight of machine reduces with selecting higher no:: of poles.

iii) Weight of Copper

a) Weight of Armature Copper

Consider a 2 pole and 4 pole DC machine.



Active Copper → Conductor inside the Slot and responsible for emf production

Inactive copper → Conductor which lies outside the Slot and used for end connection

From this figure, we understood that inactive copper length decreases with increase in poles. That means the weight of copper in Armature is reduced by using higher no:· of poles.

b) weight of field copper

If we choose higher number of poles, the field mmf Pole reduces, which allow us to reduce the area of Cross Section of pole which inturn reduces the length of mean turn of field winding.

If length of mean turn of field winding reduces, then weight of field copper reduces and also the power loss in the field winding reduces.

iv) Length of commutator

Length of Commutator is determined by thickness of brush. The thickness of brush depends on ~~Ca~~ Current Carried by the brush arm. We know that 2 parallel paths meets at each brush arm. Therefore

The Current Carried by the brush arm $I_b = 2 I_z = \frac{2 I_a}{A}$

For Lap winding $(A = P)$, If we choose higher number of poles, the Current Carried by the brush arm decreases, which allow us to reduce the area ; thickness of brush.

Reduction in brush thickness which leads to reduction in length of commutator.

v) Labour charge

Labour charge increase with choosing higher number of poles

vi) Flash over

We know that No: of brushes = No: of poles

If we choose higher number of poles, then number of brush arm increases, that means Distance b/w adjacent brush arm decreases leads to the possibility of flash over.

vii) Distortion of field flux

When we select more number of poles, the armature mmf/pole decreases, that means the effect of armature flux over field flux decreases.

Choosing higher number poles reduces the effect of Armature Reaction

Selection of number of Poles

Guiding factors for selection of number of poles.

1) The frequency of flux reversals in the armature core generally lies between 25 to 50 Hz.

$$f = \frac{Pn}{2}$$

where $n \rightarrow$ speed in rps

$P \rightarrow$ No: of poles.

2) The value of current / parallel path (I_Z) is limited to about 200 A. Thus the current per brush arm (I_b) should not be more than 400 A.

3) The armature mmf should not be excessively large.

$$\text{Armature mmf / pole } AT_a = ac\tau / 2$$

$$AT_a = \frac{ac\pi D}{2P}$$

output (kw)	Armature mmf / pole
up [illegible] 100	5,000 (or) less
100 to 500	5,000 to 7,500
500 to [illegible]00	7,500 to 10,000
over 1500	upto 12,500

If more than one poles satisfies the above conditions, then select large number of poles. This results in reduction in iron and copper.

Determine the main dimensions, number of poles and the length of Air gap of a 600 kW, 500 V, 900 r.p.m DC generator. Assume average gap density as 0.6 wb/m² and ampere conductor / metre as 35000. The ratio of pole arc to pole pitch is 0.75 and the efficiency is 91%. The following are the design constraints : peripheral speed $\ngtr$ 40 m/s, frequency of flux reversals $\ngtr$ 50 Hz, current per brush arm $\ngtr$ 400 A and the armature mmf / pole $\ngtr$ 7500 A. The mmf Required for air gap is 50% of armature mmf / pole and gap contraction factor is 1.15.

Given data

$P_o = 600$ kW, $V = 500$ V, $N = 900$ rpm, DC Generator, $B_{av} = 0.6$ wb/m², $ac = 25000$, $\frac{\text{Pole arc}}{\text{pole pitch}} = 0.75$, $\eta = 91\%$

The mmf Required for air gap is 50% of armature mmf / pole, gap contraction factor is 1.15.

Design Constraints

$V_a \ngtr 40$ m/s, Frequency Reversals $\ngtr$ 50 Hz, Current / Brush arm $\ngtr$ 400 A, Armature mmf / pole $\ngtr$ 7500 A

To find

i) Main dimensions

ii) Number of poles

iii) Length of air gap.

Solution

i) Main dimensions

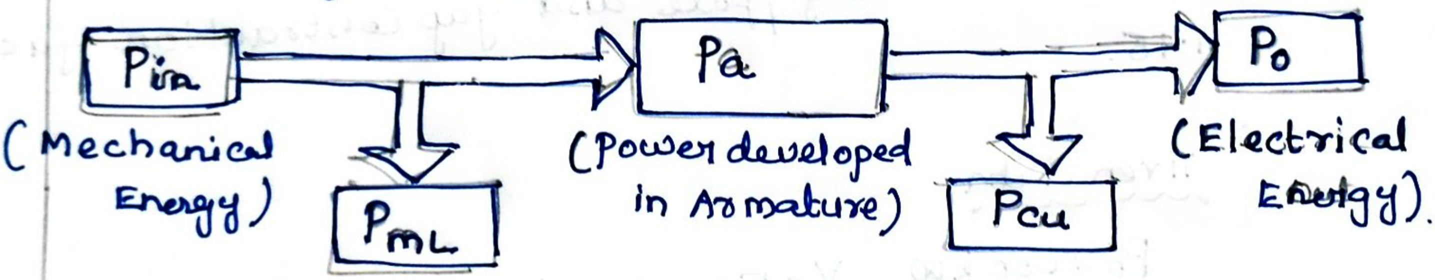
Power developed in Armature (P_a) in kW.

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

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

$$D^2 L = \frac{P_a}{\pi^2 \times \left(\frac{900}{60}\right) \times 0.6 \times 35000 \times 10^{-3}} \rightarrow (1)$$

For DC generator



Therefore $P_a = P_{in} - P_{mL}$

$$P_a = \frac{P_o}{\eta} - P_{mL}$$

$$\eta = \frac{P_o}{P_{in}}$$

$$\Downarrow$$

$$P_{in} = \frac{P_o}{\eta}.$$

For 600 kW, P_{mL} can be neglected,

then

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

$$P_a = \frac{600 \times 10^3}{0.91} = \underline{659.3407 \text{ kW}}$$

From Equation (1)

$$D^2L = \frac{659.3407}{\pi^2 \times 15 \times 0.6 \times 35000 \times 10^{-3}}$$

$$D^2L = \underline{\underline{0.2121}}, \ m^3. \quad \rightarrow (2)$$

In DC machine, seperation of D and L from D^2L Based on the ratio $\frac{L}{\tau}$

Here $\frac{L}{\tau}$ ratio in not given, so we assume the pole is square face

Therefore $\frac{L}{\tau} = \frac{\text{Pole arc}}{\text{pole pitch}}$

Given $\frac{\text{pole arc}}{\text{pole pitch}} = 0.75$, then

$$\frac{L}{\tau} = 0.75$$

$$L = 0.75\,\tau$$

$$L = 0.75 \frac{\pi D}{P} \quad \rightarrow (3)$$

ii) Determination of Poles

The guiding factors to Select poles are

a) Frequency lies b/w 25 to 50 Hz.

b) Current / parallel path not exceeds 200 A.

a) frequency lies b/w 25 to 50 Hz

$$f = \frac{Pn}{2} \qquad n = \frac{N}{60} = \frac{900}{60} = 15$$

$P=2, \quad f = \frac{2 \times 15}{2} = 15 \text{ Hz}$

$P=4, \quad f = \frac{4 \times 15}{2} = 30 \text{ Hz}$

$P=6, \quad f = \frac{6 \times 15}{2} = 45 \text{ Hz}$

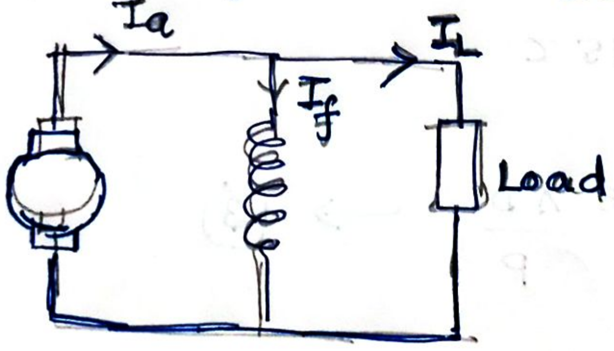
$P=8, \quad f = \frac{8 \times 15}{2} = 60 \text{ Hz}$

$P=4$ and 6, makes the frequency b/w 25 Hz to 50 Hz.

b) current / parallel path $\ngtr$ 200 A

Current / parallel path $(I_z) = \frac{I_a}{A} \ngtr 200$ A

Assume DC generator is DC shunt generator



$V = 500$ V, $P_o = 600$ kW

$$I_a = I_f + I_L$$

There is no way to find I_f. Hence I_f can be neglected

$$\therefore I_a = I_L$$

$$P_L = V_L I_L$$

$$I_L = \frac{P_L}{V_L} = \frac{600 \times 10^3}{500} = 1200 \text{ A}$$

$$I_a = I_L = \underline{\underline{1200 \text{ A}}}$$

For lap winding

$$\underline{A = P}$$

When $P = 4$, Current/parallel path $(I_z) = \frac{I_a}{A} = \frac{1200}{4}$

$$= \underline{\underline{300 \text{ A}}}$$

When $P = 6$, Current/parallel path $(I_z) = \frac{I_a}{6} = \frac{1200}{6}$

$$= \underline{\underline{200 \text{ A}}}$$

For wave winding

$$\underline{\underline{A = 2}}$$

Current/parallel path $(I_z) = \frac{I_a}{A} = \frac{1200}{2} = 600 \text{ A}$

Therefore for lap winding, when $P = 6$, current/parallel path not exceeds 200 A

$$\boxed{P = 6}$$

From Equation 3

$$L = \frac{0.75 \pi D}{P}$$

$$L = \underline{\underline{0.3927}} \, D \rightarrow 4$$

From Equation (2)

$$D^2 (0.3927) D = 0.2121$$

$$D^3 = \frac{0.2121}{0.3927}$$

$$D^3 = 0.5401$$

$$D = \underline{\underline{0.8144}}\ , m$$

From Equation (4)

$$L = 0.3927 \times 0.8144$$

$$L = \underline{\underline{0.3198}}\ , m$$

iii) Air gap length (AT_g)

$$AT_g = 8,00,000\ B_g l_g k_g$$

$$l_g = \frac{AT_g}{8,00,000\ B_g k_g} \rightarrow (5)$$

Given $AT_g = 50\%$ of armature mmf / pole $\rightarrow$ (6)

$$\text{armature mmf / pole} = \frac{I_z \cdot Z}{2P} = \frac{ac\pi D}{2P}$$

$$= \frac{35000 \times \pi \times 0.8144}{2 \times 6}$$

armature mmf / pole = $\underline{\underline{7462.3297}}$ AT.

From Equation (6)

$$AT_g = 0.5 \times 7462.3297$$

$$AT_g = \underline{\underline{3731.1649}}\ AT$$

Given $\frac{\text{pole arc}}{\text{pole pitch}} = 0.75$ and we know that

$$\text{Form factor } (k_g) = \frac{\text{pole arc}}{\text{pole pitch}} = \frac{B_{av}}{B_g}$$

$$\therefore \quad \frac{B_{av}}{B_g} = 0.75$$

$$\frac{B_{av}}{0.75} = B_g$$

$$B_g = \frac{0.6}{0.75} = \underline{\underline{0.8}}\ wb/m^2$$

From Equation (5)

$$l_g = \frac{3731.1649}{8,00,000 \times 0.8 \times 1.15}$$

$$l_g = 0.0051\ m = \underline{\underline{5.1}}\ mm$$

Check for constraints

i) $V_a \ngtr 40\ m/s$

$$V_a = \pi D n$$

$V_a = \pi \times 0.8144 \times 15$

$= \underline{38.3777}\ , m/s$

It lies within the limit

ii) Frequency of Reversal $\not> 50\ Hz$

When $P=6$, $f = 45\ Hz$

Hence it is within the limit.

iii) Armature mmf / pole not exceeds 7500 AT

From Equation 6, Armature mmf / pole

$= \underline{7462.3297}\ AT$

It lies within the limit.

Answer

i) Main dimension

$D = \underline{0.8144}\ , m \quad , \quad L = \underline{0.3198}\ , m$

ii) No of poles

$P = 6$

iii) Air gap length (l_g)

$l_g = \underline{5.1}\ mm$

Design procedure for field winding of DC Shunt machines

i) Determine the Dimensions of the pole

flux in the pole, $\phi_p = C_l \phi$

where

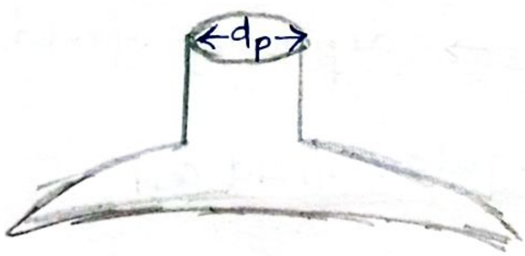
$C_l \rightarrow$ leakage coefficient

(Assume a suitable value of C_l)

Area of the pole, $A_p = \dfrac{\phi_p}{B_p}$

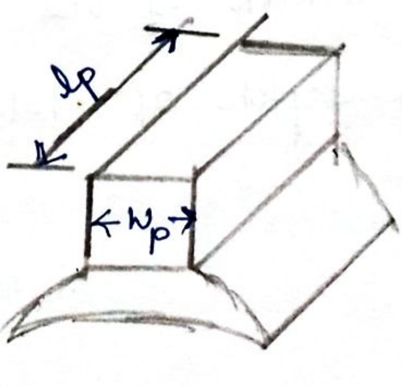
where $B_p \rightarrow$ flux density lies between 1.2 to 1.7 wb/m^2.

For Cylindrical pole



Diameter of pole $d_p = \sqrt{\dfrac{4A_p}{\pi}}$

For Rectangular pole



Length of pole, $L_p = L - (0.01 \text{ to } 0.015)$

Net iron length of pole

$$L_{pi} = 0.9 L_p$$

width of the pole, $w_p = A_p / L_{pi}$

2) Determine the mean length of field coil

A suitable value for depth of winding is assumed by knowing the diameter of the armature core.

For Cylindrical field coil

Mean length, $L_{mt} = \pi (d_p + d_f)$

where, $d_p \rightarrow$ depth of pole

$d_f \rightarrow$ depth of field winding.

For Rectangular field coil

mean length, $L_{mt} = 2L_p + 2w_p + 4d_f$

where, $L_p \rightarrow$ length of the pole

$w_p \rightarrow$ width of the pole

$d_f \rightarrow$ depth of field winding.

3) Calculate the voltage across each shunt field coil

Voltage across field coil, $E_f = \frac{(0.8 \text{ to } 0.85)V}{P}$

4) Calculate the area of cross section of field conductor.

Area of cross section of field conductor

$$a_f = \frac{\rho L_{mt} AT_{fl}}{E_f}$$

5) Calculate the diameter of field conductor and copper space factor

Usually circular shaped conductors are used for field winding

$$a_f = \frac{\pi d_{fc}^2}{4}$$

$$d_{fc}^2 = \frac{4 a_f}{\pi}$$

$$d_{fc} = \sqrt{\frac{4 a_f}{\pi}}$$

$d_{fc} \rightarrow$ diameter of field conductor

Diameter of field conductor with insulation thickness is expressed as d_{fci}

copper space factor $= 0.75\left(\dfrac{d_{fc}}{d_{fci}}\right)^2$

6) Determine the number of turns (T_f) and height of field coil (h_f). They can be determined by solving the following two equations.

$$2 L_{mt} q_f (h_f + d_f) = \frac{E_f^2 a_f}{\rho L_{mt} T_f}$$

$$T_f a_f = S_f' h_f d_f$$

7) Calculate the resistance of the field coil and field current

Resistance of field coil, $R_f = \dfrac{T_f \rho L_{mt}}{a_f}$

Field current $I_f = \dfrac{E_f}{R_f}$

8) Check the current density in field coil

$$\delta_f = \frac{I_f}{a_f}$$

The current density should not exceed ~~3.5 A/m~~ 3.5 A/mm^2. If it exceeds 3.5 A/mm^2, then increase a_f by 5% and repeat the steps 5 to 8 untill δ_f is less than 3.5 A/mm^2

9) Check for desired value of mmf

Actual value of mmf $= I_f T_f$

If the actual mmf is less than the desired value, then increasing the depth of field winding by 5% and repeat step 2 to step 7, ontill the desired mmf is achived.

10) Check for temperature rise.

$$\text{Temperature rise } (\theta_m) = \frac{\text{Field cu loss}}{\lambda_f S_f}$$

$\lambda_f = \frac{1}{c}$, where c is the cooling coefficient. $= \frac{0.14 \text{ to } 0.16}{1 + 0.1 V_a}$

$V_a \rightarrow$ Peripheral speed of Armature

$S_f \rightarrow$ Surface area of field coil.

$$\text{Fiel cu loss} = I_f^2 R_f$$

If temperature rise is within limits, then the design values are accepted.. otherwise repeat the design procedure by increasing the depth of field winding by 5%

The allowable temperature rise depends on the class of Insulation.

Design of Commutator

The Commutator is constructed by using hard drawn copper and Commutator segments can be seperated by thin mica sheet. The following steps are required to design a commutator.

i) Number of Commutator Segments

Number of Commutator segments = No:: of coils

Number of Coils (C) = $= \frac{1}{2} u S_a$

$u \rightarrow$ Coil sides / slot

$= 2, 4, 6, 8, \ldots$

$S_a \rightarrow$ Armature slots.

The minimum number of coils is obtained when voltage between Commutator segments is not exceed 15 at no load.

$\therefore$ Minimum no of coils $= \frac{EP}{15}$

where $E \rightarrow$ induced emf

$P \rightarrow$ no:: of poles.

ii) Commutator diameter (D_c)

$D_c = (0.6 \text{ to } 0.8) D$, where D is the Armature diameter.

Commutator diameter (D_c) should make the ~~pher~~ pheripheral speed b/w 15 m/s and 30 m/s.

∴ Commutator peripheral speed $V_c = \pi D_c n_s$, m/s

Also the commutator diameter must statisfies ~~the~~ the commutator segment pitch is $\geq$ 4 mm.

$$\text{Commutator segment pitch } (\beta_c) = \frac{\pi D_c}{C}$$

iii) Length of commutator (L_c)

The length of the commutator is decided by

a) Space required by the brushes.

b) Surface area required to dissipate the heat generated by losses in the commutator.

Length of commutator $L_c = n_b(w_b + C_b) + C_1 + C_2$

$n_b \rightarrow$ Number of brushes per spindle.

$w_b \rightarrow$ width of each brush

$C_b \rightarrow$ Clearance b/w brushes

= 5 mm

$C_1 \rightarrow$ clearance allowed for staggering the brushes

= 10 mm for small machines

= 30 mm for large machines.

$C_2 \rightarrow$ clearance for allowing the end play

$C_2 = 10$ to 25 mm.

if length of the Commutator is small, then surface area available for heat dissipation is less and that leads to temperature rise of Commutator which exceeds the permissible limit.

iv) Commutator losses (P_c)

Losses in the commutator are brush contact loss and brush friction loss.

$$P_c = P_{bc} + P_{bf}$$

a) Brush Contact loss (P_{bc})

P_{bc} = Voltage drop per brush arm × Current per brush

or

P_{bc} = Total Voltage drop in brushes × Armature Current

b) Brush friction loss (P_{bf})

The Brush friction loss depends upon the brush pressure, peripheral speed of the commutator and the coefficient of friction b/w brush and Commutator.

Brush friction loss P_{bf} Can be Calculated by

$$P_{bf} = \mu P_b P A_b V_c$$

where $\mu \rightarrow$ Coefficient of friction

$\doteq 0.1$ to 0.3

$P_b \rightarrow$ Brush contact pressure, N/m^2

$P \Rightarrow$ No of poles.

$A_b \Rightarrow$ total Area of Brushes, m^2

$V_c \rightarrow$ peripheral speed of Commutator, m/s

Design of Brush

The materials used for Brushes are Carbon, Carbon graphite and metal graphite.

The dimensions of the brushes are its thickness and width.

The thickness of brush is selected such that it covers 2 to 3 commutator segments. The area of each brush be taken to carry the current not more than 70 A.

Total brush contact area in a spindle $(A_b) = \frac{I_b}{\delta_b}$

$I_b \rightarrow$ current carried by each brush $= \frac{2 I_a}{A}$

$\delta_b \rightarrow$ Current density $= 0.1 \ A/mm^2$

$\therefore$ Total brush contact area $(A_b) = \frac{2 I_a}{A \delta_b} \rightarrow (1)$

Let A be the parallel path which depends on type of winding selected.

To limit the current carried by each brush to 70 A, then minimum number of brushes

Required is Calculated

$$\text{minimum number of Brushes} = \frac{\text{Current Carried by each brush}}{70}$$

∴ No of brushes should be greater than minimum no∴ of brushes.

Also the total area of brushes in a spindle can be expressed as

A_b = no∴ of brushes × Area of each brush

$$A_b = n_b \times w_b t_b \rightarrow (2)$$

From Eq (1) and (2)

$$\frac{2 I_a}{A \delta_b} = n_b w_b t_b$$

$$\boxed{w_b = \frac{2 I_a}{A \delta_b n_b t_b}}$$

$t_b \rightarrow$ thickness of brush

= (2 to 3) × width of Commutator segments

= (2 to 3) × β_c

Design a Suitable Commutator for a 350 kW, 600 rpm, 440V, 6 pole DC generator having an armature diameter of 0.75 m. The number of coils is 288. Assume Suitable values wherever necessary.

Given

$P_o = 350$ kW, $N = 600$ rpm, $V = 440$ V, $P = 6$, $D = 0.75$ m

$C = 288$.

To find

Dimensions of a Commutator.

Solution

i) Diameter of Commutator

$$D_c = (0.6 \text{ to } 0.8) D.$$

$$D_c = 0.7 \times D = 0.7 \times 0.75$$

$$D_c = 0.525 \text{ m}$$

Check this Commutator diameter D_c that makes peripheral speed of Commutator ≤ 15 mm.

$$V_c = \pi D_c n_s = \pi \times 0.525 \times \frac{600}{60}$$

$$V_c = 16.4934 \text{ m/s}$$

Here the Peripheral Speed of Commutator is greater than 15 m/s. Hence reduce the diameter of Commutator.

0.6 to 0.7 $\quad D_c \quad V_c = \pi D_c n_s$

0.65 $\quad D_c = 0.65 \times D$ $\quad V_c = 15.3153 \text{ m/s}$

$= 0.65 \times 0.75$

$= 0.4875 \text{ m}$

0.64 $\quad D_c = 0.64 \times$ $\quad V_c = 15.0796 \text{ m/s}$

$= 0.48 \text{ m}$

0.63 $\quad D_c = 0.63 \times$ $\quad V_c = 14.8440 \text{ m/s}.$

$= 0.4725 \text{ m}$

So, out of this when $D_c = 0.48$, the pheripheral Speed of Commutator is ~~cat~~ approximately equal to 15 m/s.

Also check that the selected D_c statisfies the Commutator Segment pitch (β_c) is ≥ 4mm

$$\beta_c = \frac{\pi D_c}{\text{No of Commutator Segments}}$$

$$\beta_c = \frac{\pi \times 0.48}{288} = 0.0052 = 5.2 \text{ mm}$$

Here obtained β_c is greater than 4 mm, Hence we select $\boxed{D_c = 0.48, \text{m}}$

ii) Length of Commutator

$$L_c = n_b(\omega_b + C_b) + C_1 + C_2$$

$C_b \rightarrow$ Clearance b/w brushes

$= 5\,mm$

$C_1 \rightarrow$ Clearance allowed for staggering the brushes

$= 30\,mm$ for large machines.

$C_2 \rightarrow$ Clearance for allowing the end play

$C_2 = 20\,mm$.

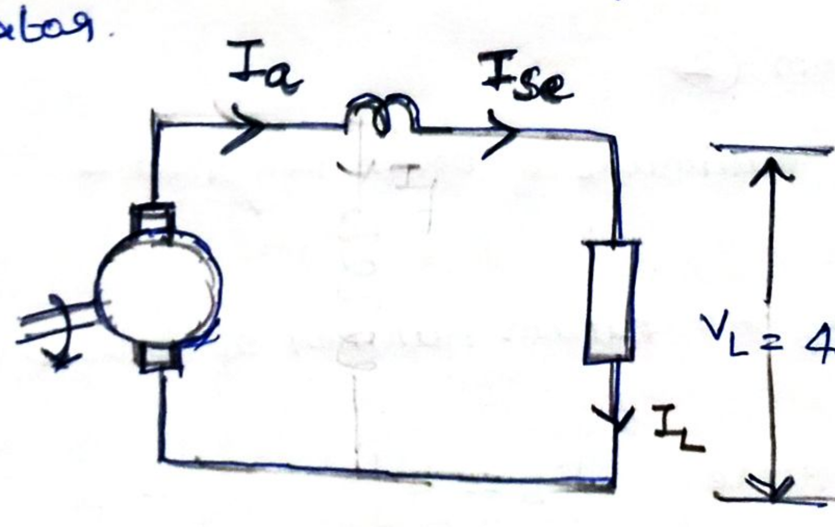
Therefore $L_c = n_b(\omega_b + (5\times10^{-3})) + (30\times10^{-3}) + (20\times10^{-3})$ $\rightarrow (1)$

Minimum number of Brush Required $\Big\} = \dfrac{\text{Current carried by Brush } (I_b)}{70}$ $\rightarrow (2)$

where

$$I_b = \frac{2I_a}{A} \rightarrow (3)$$

Let us assume the DC generator is series Generator.



$V_L = 440\,V$, $P_L = P_o = 350\,kW$

$$P_L = P_o = V_L I_L$$

$$I_L = \frac{P_o}{V_L} = \frac{350 \times 10^3}{440} = \underline{795.45}, A$$

From Figure, $I_a = I_{se} = I_L$

$$I_a = \underline{795.45}, A$$

If Lap winding is selected, then current/parallel path

$$I_z = \frac{I_a}{A} = \frac{I_a}{P} = \frac{795.45}{6} = \underline{132.575}, A$$

If wave winding is selected, then current/parallel path

$$I_z = \frac{I_a}{A} = \frac{I_a}{2} = \frac{795.45}{2} = \underline{397.725}, A$$

For Lap winding only, the current/parallel path (I_z) not exceeds 200 A, Hence lap winding is selected.

For Lap winding $\boxed{A = P = 6}$

From (3) $I_b = \frac{2 \times 795.45}{6} = \underline{265.15}, A$

From (2)

$$\text{minimum of brush Required} = \frac{265.15}{70} = 3.7879$$
$$\simeq 4$$

$n_b >$ minimum number of brushes Required

Therefore $\boxed{n_b = 6}$

$$\left.\begin{array}{l}\text{Total contact area of}\\ \text{brush in a spindle}\end{array}\right\} = \text{no. of brushes} \times \text{Area of each brush}$$

$$A_p = n_b \times w_b t_b \rightarrow (4)$$

$$A_p = \frac{I_b}{\delta_b} = \frac{2 I_a}{A \delta_b} \quad \left\{ \begin{array}{l} \delta_b = 0.1 \, A/mm^2 \\ A = P = 6 \end{array}\right.$$

$$= \frac{2 \times 795.45}{6 \times 0.1 \times 10^6}$$

$$A_p = \underline{0.0027}, m^2$$

$t_b = (2 \text{ to } 3)$ width of Commutator segments

$$t_b = (2 \text{ to } 3)\ \beta_c$$

$$= 3 \times 5.2 \times 10^{-3}$$

$$t_b = \underline{0.0156} \ m$$

From Eq (4)

$$w_b = \frac{A_p}{n_b t_b} = \frac{0.0027}{6 \times 0.0156} = \underline{0.0283}, m$$

From Eq (1)

$$L_c = 6\left(0.0283 + (5 \times 10^{-3})\right) + (30 \times 10^{-3}) + (20 \times 10^{-3})$$

$$L_c = \underline{0.2498}, m$$

Answer

$D_c = 0.48$, m

$n_b = 6$

$\omega_b = 0.0283$, m

$t_b = 0.0156$, m

$L_c = 0.2498$, m.

EE 8002 DESIGN OF ELECTRICAL APPARATUS

UNIT IV

DESIGN OF INDUCTION MACHINES

Prepared by

Dr . T. Dharma Raj

Asso.Prof /EEE

Construction of 3ϕ Induction motor

The induction motor consists of two main parts

a) Stator

b) Rotor

a) Stator

The stator is made up of a number of stampings with alternate slot and tooth. Stampings are insulated from each other. Each stamping is 0.4 to 0.5 mm thick. Number of stampings are stamped together to build the stator bore. The stator bore is then fitted in a casted (or) fabricated steel frame. The slots house the three phase winding called stator winding. It may be connected either in star or delta. The stator winding is made for a fixed number of poles.

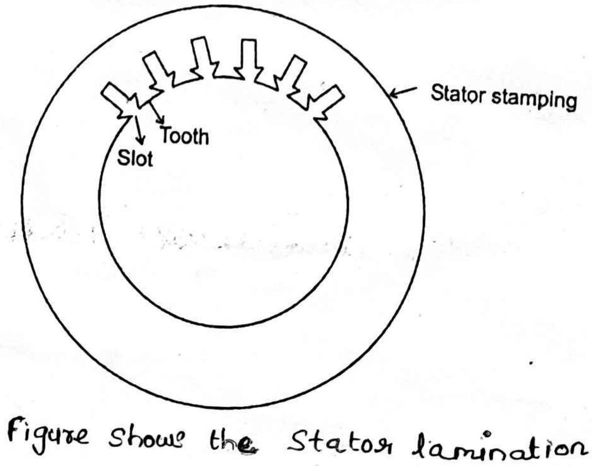


Figure shows the stator lamination

b) Rotor

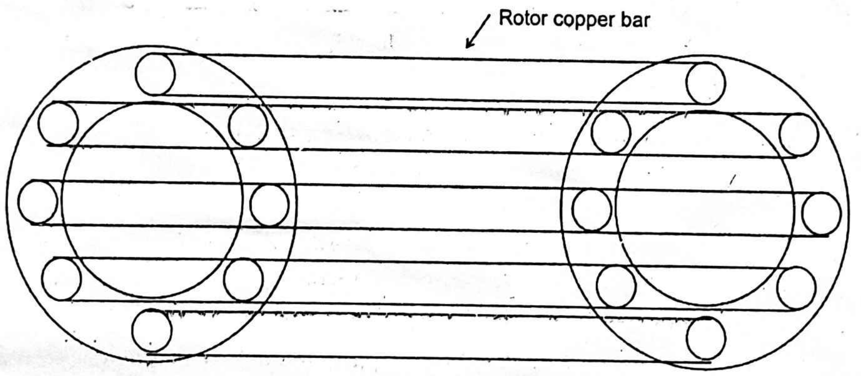
There are two types of rotors used in Induction motors. They are

i) Squirrel cage rotor

ii) Slipring or wound rotor.

i) Squirrel cage rotor

This is made up of a cylindrical laminated core with slots to carry the rotor conductors. The rotor conductors are heavy bars of copper (or) aluminium short circuited by both ends by end rings. Hence this rotor is also called a short circuited rotor. The entire rotor resistance is very small. External resistance cannot be connected in the rotor current. Such motors are extremely rugged in construction. Motors using such rotors are called squirrel cage Induction motors.



ii) Slip ring rotor

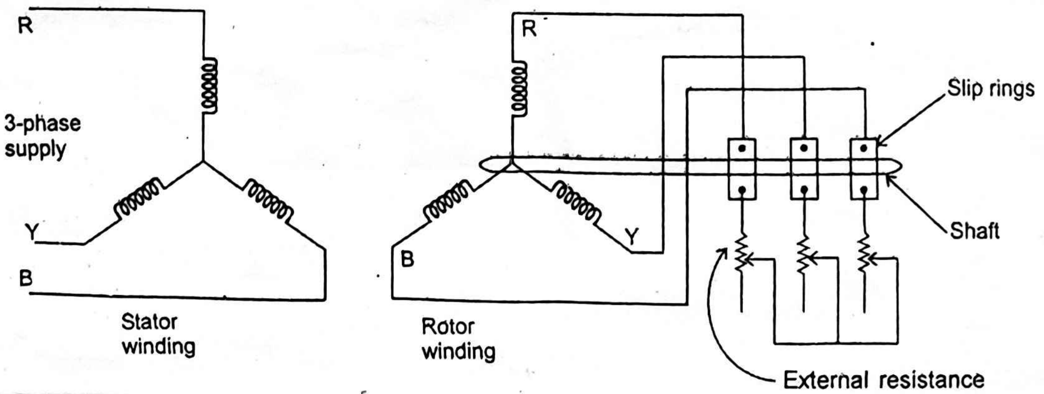


Figure shows the slip ring (or) wound rotor. In this type of rotor, rotor windings are similiar to the stator winding. The rotor winding may be star or delta connected, wound for as many number of poles as the stator. The three phases are brought out and connected to slip rings mounted on the rotor shaft. Variable external resistance can be connected in the rotor circuit, with the help of brushes and slip ring arrangements. By varying the external resistance in the rotor circuit, the motor speed and torque can be controlled. This motor using this type of rotor is called slip ring (or) wound rotor Induction motor.

Camparision of Squirrel cage and slip-ring Induction motor

S.No	Squirrel Cage Induction motor	Slip ring Induction Motor
1.	Low starting torque	Much Higher starting torque
2.	No slip rings, brushes gears etc	Extra slip rings, brush gears, etc.
3.	Comparatively higher efficiency	Comparatively lower efficiency.

Specific Electric and Magnetic loading of IM

Specific Electric loading (ac)

We know that $ac = \frac{I_Z \cdot Z}{\pi D} \rightarrow (1)$

The following factor are to be considered for selecting the specific electric loading

a) Copper loss and Temperature rise.

b) Voltage

c) Size and Cost of the machine.

d) Overload Capacity

a) Copper loss and Temperature rise

From Equation (1), the higher the value of ac is choosen, which increases the current flow through the conductor and number of conductors

Increase in current in the Conductor, which increases the temperature rise of the machine.

Increase in Conductor, increases the copper loss, which reduces the efficiency.

b) Voltage.

For high Voltage machine, thickness of Insulation around the Conductor is less. Therefore area of Cross of the Conductor is less.

If large of ac is choosen, will damage the Conductor.

, c) Size and cost of the machine.

From equation ①, Specific electric loading is inversely proportional to the inner diameter of the stator.

If higher value of ac is choosen, results the small value of Diameter of the machine is required

Therefore if diameter reduces, the size of the machine reduces, which inturn reduces the cost of the machine.

d) Overload capacity

If higher value of ac is choosen, the number of conductor used will increases, which inturn increases the leakage reactance.

If leakage reactance increases, the short circuit current decreases.

Reduction in short circuit current reduces the diameter of the circle diagram, which inturn reduces the maximum output. Hence overload capacity of the motor reduces.

From the point of view of

Copper loss and temperature rise, Voltage and Overload capacity } allows lower value of ac to choose.

Size and cost of the machine } allows higher value of ac to choose.

Because of the above factors, the specific electric loading of an Induction motor usually lies between 25000 to 40000 ampere conductor /metre.

Specific Magnetic loading (B_{av})

We know that $B_{av} = \frac{P\phi}{\pi D L}$ → ②

The following factors are to be considered while selecting the specific magnetic loading

a) Power factor

b) Iron loss

c) Overload capacity

a) Power factor

From Equation ②, If higher value of B_{av} is choosen, means flux/pole is high

To make flux/pole to high, the induction motor draws more magnetising current

$\therefore$ Increase in magnetising current results in poor power factor.

b) Iron loss

There are two types of iron losses.

Eddy current loss $\propto B_c^2 f^2$

Hysterisis loss $\propto B_c^{1.6} f$

From the above Equations, If we select higher value of Bav, increases the iron loss, which reduces the efficiency.

c) Overload Capacity

From Equation (2), If we select the higher value of Bav, flux/pole will be large.

If flux/pole increases, which inturn increases the emf induced in the winding, because

$$E_{sph} = 4.44 f \phi T_{sph} k_w \text{ , Volts.}$$

So as to maintain the constant voltage, we should decrease the turns in the winding, which reduces the leakage reactance.

If leakage reactance reduces, which results in increase in short circuit current.

If short circuit current increases, the diameter of the circle diagram increases which in turn increases the maximum output of the Induction motor.

From the point of view of

Powerfactor and Iron loss → low value of B_{av} is chosen

Overload capacity → high value of B_{av} is chosen.

Therefore the specific magnetic loading lies between 0.3 to 0.6 wb/m^2.

Output Equation of 3ϕ Induction Motor.

Input Q in kVA $= 3 \times E_{sph} \times I_{sph} \times 10^{-3}$, kVA $\rightarrow$ (1)

where $E_{sph} \rightarrow$ stator induced emf / phase

$I_{sph} \rightarrow$ stator current / phase.

We know that

$$E_{sph} = 4.44 f \phi T_{sph} k_w \text{ ; Volts}$$

where, $k_w \rightarrow$ winding factor

From eq (1)

Input Q in kVA $= 3 \times 4.44 f \phi T_{sph} k_w \times I_{sph} \times 10^{-3}$, kVA $\rightarrow$ (2)

We know that

$$\text{Synchronous Speed } N_s = \frac{120 f}{P}, \text{ rpm}$$

$$f = \frac{N_s P}{120} = \frac{N_s P}{2 \times 60}$$

$$\boxed{f = \frac{P n_s}{2}}$$

where $P \rightarrow$ number of poles

$n_s \rightarrow$ Synchronous speed in rps.

From Equation (2)

Input Q in kVA $= 3 \times 4.44 \frac{P n_s}{2} \phi T_{sph} k_w \times I_{sph} \times 10^{-3}$, kVA

Input Q in kVA $= 6.66 (P\phi) n_s T_{sph} k_w \times I_{sph} \times 10^{-3}$, kVA

$\rightarrow$ (3)

We know that

$$T_s = \frac{Z_s}{2}$$

$$T_{sph} = \frac{Z_s}{2 \times 3}$$

$$\boxed{T_{sph} = \frac{Z_s}{6}}$$

From Equation (3)

$$\text{Input } Q \text{ in kVA} = 6.66 (P\phi) n_s \frac{Z_s}{6} k_w \times I_{sph} \times 10^{-3}, \text{ kVA} \quad \rightarrow (4)$$

Let I_{sph} be the stator current per phase, if there is only one parallel path, then $\boxed{I_{sph} = I_z}$

From Equation (4)

$$\text{Input } Q \text{ in kVA} = 6.66 (P\phi) n_s \frac{Z_s}{6} k_w \times I_z \times 10^{-3}, \text{ kVA}$$

$$\text{Input } Q \text{ in kVA} = 1.11 (P\phi) n_s k_w (I_z . Z_s) \times 10^{-3}, \text{ kVA}$$

We know that $\rightarrow (5)$

$$\text{Specific magnetic loading, } (B_{av}) = \frac{P\phi}{\pi D L}$$

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

$$\text{Specific Electric loading, } (ac) = \frac{I_z . Z_s}{\pi D}$$

$$\boxed{I_z . Z_s = ac \pi D}$$

From Equation (5)

Input Q in kVA $= 1.11\,(B_{av}\pi DL)\,n_s\,k_w\,(ac\pi D)\times 10^{-3}$, kVA

$$\boxed{\text{Input Q in kVA} = 1.11\,\pi^2 D^2 L\, n_s\, B_{av}\, ac\, k_w \times 10^{-3}, \ \text{kVA}}$$

Note

The output power of Induction motor can be expressed as in kW or hp, then

$$\text{Input Q in kVA} = \frac{P_o\,(\text{in kW})}{\eta \times \cos\phi}$$

or

$$\text{Input Q in kVA} = \frac{Hp \times 0.746\ (\text{in kW})}{\eta \times \cos\phi}$$

Find the main dimensions of 20 HP, 3ϕ, 400V, 50 Hz, 2810 rpm Squirrel cage IM having η of 88% and Pf of 0.9, average flux density is 0.5 Tesla, Specific electric loading is 25000 ac/m, If the rotor pheripheral Speed is 20 m/s. Assume K_w = 0.955.

Given data

$P_o = 20\,HP = 20 \times 0.746 = 14.92\,kW$, phase = 3, $V = 400\,V$,

$f = 50\,Hz$, $N = 2810\,rpm$, $\eta = 88\%$, $Pf = 0.9$, B_{av} = 0.5 tesla = 0.5 wb/m^2, $ac = 25,000$, $V_a = 20\,m/s$,

$K_w = 0.955$.

To find

Main dimensions.

Solutions

$$\text{Input } Q \text{ in kVA} = 1.11\,\pi^2 D^2 L\, n_s B_{av}\, ac\, k_w \times 10^{-3}, \text{ kVA}$$

$$D^2L = \frac{\text{Input } Q \text{ in kVA}}{1.11\,\pi^2\, n_s B_{av}\, ac\, k_w \times 10^{-3}}$$

$$D^2L = \frac{\text{Input } Q \text{ in kVA}}{1.11\,\pi^2\, n_s \times 0.5 \times 25,000 \times 0.955 \times 10^{-3}} \rightarrow (1)$$

$$\text{Input } Q \text{ in kVA} = \frac{\text{Output power in kW}}{\eta \times \cos\phi}$$

$$= \frac{14.92}{0.88 \times 0.9} = 18.8384, \text{ kVA}$$

$n_s = \frac{N_s}{60}$, where $N_s \rightarrow$ Synchronous speed in rpm.

The Synchronous speed nearer to motor speed 2810 is 3000 rpm.

$\therefore n_s = \frac{3000}{60} = \underline{\underline{50}}$, rps

Substitute Q and n_s value in equation (1), we get

$$D^2L = \frac{18.8384}{1.11 \times \pi^2 \times 50 \times 0.5 \times 25000 \times 0.955 \times 10^{-3}}$$

$$D^2L = \underline{\underline{0.0029}}, m^3 \longrightarrow (2)$$

Given $V_a = 20$ m/s

$$\pi D n_s = 20$$

$$\pi \times D \times 50 = 20$$

$$D = \frac{20}{50 \times \pi} = \underline{\underline{0.1274}}, m$$

From (2)

$$(0.1274)^2 L = 0.0029$$

$$L = \frac{0.0029}{(0.1274)^2} = \underline{\underline{0.1787}}, m$$

Ans

$D = \underline{\underline{0.1274}}$, m

$L = \underline{\underline{0.1787}}$, m

Estimate the stator core dimensions, no of stator slots and no of stator cond/slot for a 100 kW, 3300 V, 50 Hz, 12 pole, star connected slip ring induction motor. Assume average gap density = 0.4 wb/m², ac = 25,000 A/m, $\eta = 0.9$, $\cos\phi = 0.9$, and winding factor = 0.96. Choose main dimensions to give best power factor. The slot loading should not exceed 500 A.

Given data

$P_o = 100$ kW, $V_L = E_L = 3300$ V, $f = 50$, $p = 12$, stator winding - star connected, $B_{av} = 0.4$ wb/m², ~~ac = 25,00~~

ac = 25000, $\eta = 0.9$, $Pf = \cos\phi = 0.9$, $k_w = 0.96$

Slot loading $= I_z Z = I_{sph} Z_s \leq 500$ A.

To find

Core dimensions, no. of stator slots, number of stator cond/slot

Solution

i) Core dimensions

$$\text{Input } Q \text{ in kVA} = 1.11\pi^2 D^2 L n_s B_{av} ac K_w \times 10^{-3}, \text{ kVA}$$

$$D^2L = \frac{\text{Input } Q \text{ in kVA}}{1.11 \times \pi^2 \times n_s \times B_{av} \times ac \times k_w \times 10^{-3}}$$

$$D^2L = \frac{\text{Input } Q \text{ in kVA}}{1.11 \times \pi^2 \times n_s \times 0.4 \times 25{,}000 \times 0.96 \times 10^{-3}} \rightarrow (1)$$

$$\text{Input } Q \text{ in kVA} = \frac{\text{Output power in kW}}{\eta \times \cos\phi}$$

$$= \frac{100}{0.9 \times 0.9} = \underline{\underline{123.4568}}, \text{ kVA}$$

$$n_s = \frac{N_s}{60} = \frac{120 f}{P \times 60} = \frac{120 \times 50}{12 \times 60} = \underline{\underline{8.3333}}, \text{ rps}$$

Substitute the Q and n_s value in eq (1)

$$D^2 L = \frac{123.4568}{1.11 \times \pi^2 \times 8.3333 \times 0.4 \times 25000 \times 0.96 \times 10^{-3}}$$

$$D^2 L = \underline{\underline{0.1409}}, \text{ m}^3 \rightarrow (2)$$

Given for best power power factor choose the main dimensions:

Therefore for Best power factor

$$\tau = \sqrt{0.18 L}$$

$$\tau^2 = 0.18 L$$

$$\left(\frac{\pi D}{P}\right)^2 = 0.18 L$$

$$\frac{\pi^2 D^2}{P^2} = 0.18 L$$

$$D^2 = \frac{0.18 L P^2}{\pi^2}$$

$$D^2 = \frac{0.18 L \times 12^2}{\pi^2}$$

$$D^2 = 2.6262 L \rightarrow (3)$$

From Equation (2)

$$2.6262 L \times L = 0.1409$$

$$L^2 = \frac{0.1409}{2.6262}$$

$$L = \sqrt{0.0537}$$

$$\boxed{L = 0.2316} \text{ m}$$

From Equation (3)

$$D^2 = 2.6262 \times 0.2316$$

$$D^2 = 0.6083$$

$$D = \sqrt{0.6083}$$

$$\boxed{D = 0.7799} \text{ m.}$$

ii) Number of Stator slot

$m \rightarrow$ Slots / pole / phase

m	$S_s = m \times pole \times phase$	$Y_{ss} = \frac{\pi D}{S_s}$
2	72	34 mm
3	108	22.7 mm
4	144	17 mm
5	180	13.6 mm

For high capacity motor, slot pitch allowed is between 15 mm to 25 mm.

Therefore we can select $\boxed{S_s = 108 \text{ or } 144}$

Due to the Advantage of mechanical strength, we select $\boxed{S_s = 108}$

iii) Stator turns / phase

$$E_{sph} = 4.44 f \phi T_{sph} k_w, \text{ Volts.}$$

$$T_{sph} = \frac{E_{sph}}{4.44 \times f \times \phi \times k_w}$$

$$T_{sph} = \frac{E_{sph}}{4.44 \times 50 \times \phi \times 0.96} \rightarrow (4)$$

Given Stator winding is Star Connected

$$E_L = \sqrt{3}\, E_{sph}$$

$$E_{sph} = \frac{3300}{\sqrt{3}} = \underline{\underline{1905.2559}}, \text{ Volts}$$

We know that $B_{av} = \frac{P\phi}{\pi DL}$

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

$$\phi = \frac{0.4 \times \pi \times 0.7799 \times 0.2316}{12}$$

$$\phi = \underline{\underline{0.0189}}, \text{ wb}$$

Substitute E_{sph} and ϕ value in Eq (4)

$$T_{sph} = \frac{1905.2559}{4.44 \times 50 \times 0.0189 \times 0.96}$$

$$T_{sph} = 473.0067$$

$$T_{sph} = 473$$

Stator Conductors $(Z_s) = 6 \times T_{sph}$

$$Z_s = 2838$$

Stator Conductor / Slot $= \frac{2838}{108} = 26.2778$

$$\boxed{\text{Stator Cond / Slot } (Z_s) = 26}$$

For high capacity motor, double layer winding is used, Hence Conductor / Slot should be an even Integer.

$$Z_s(\text{new}) = \text{Cond / Slot} \times \text{Slot}$$

$$Z_s(\text{new}) = 26 \times 108$$

$$\boxed{Z_s(\text{new}) = 2808}$$

$$T_{sph}(\text{new}) = \frac{Z_s(\text{new})}{6} = \frac{2808}{6}$$

$$\boxed{T_{sph}(\text{new}) = 468}$$

Check for Slot loading

$$\text{Slot loading} = I_Z . Z = I_{sph} \times Z_{ss}, \ A$$

$Z_{ss} \rightarrow$ Stator Conductor / Slot $\rightarrow$ (5)

$$\text{Input Q in kVA} = 3 \ E_{sph} \ I_{sph} \times 10^{-3}, \ \text{kVA}$$

$$I_{sph} = \frac{\text{Input Q in kVA}}{3 \times E_{sph} \times 10^{-3}}$$

$$I_{sph} = \frac{123.4568}{3 \times 1905.2559 \times 10^{-3}}$$

$$I_{sph} = \underline{\underline{21.5993}}, \ A$$

From Equation (5)

Slot loading $= 21.5993 \times 26 = \underline{561.5828}$, A

when $S_s = 108$, the slot loading exceeds the limit 500 A,

Therefore we select $\boxed{S_s = 144}$

Stator conductor / slot $= \frac{2838}{144}$

Stator conductor / slot $= 19.7083$

$\boxed{\text{Stator conductor / slot} = 20}$

Stator conductors $Z_s = \frac{\text{cond}}{\text{slot}} \times \text{slot}$

$Z_s = 20 \times 144$

$\boxed{Z_s = 2880}$

Stator turns / phase $T_{sph} = \frac{Z_s}{6} = \frac{2880}{6}$

$\boxed{T_{sph} = 480}$

Check for slot loading

Slot loading $= I_{sph} \cdot Z_{ss}$

Slot loading = $21.5993 \times 20 = \underline{431.9860}$, A

When $S_s = 144$, the slot loading lies within the limit 500 A.

Answers

$D = 0.7799$, m

$L = 0.2316$, m

$S_s = 144$

Conductor / slot = 20

Total stator conductors = 2880

Stator turns / phase = 480

Determine the main dimensions, no: of ventillating ducts, no: of stator slots and the no: of turns / phase, area of cross section of stator conductors of a 3.7 kw, 400V, 3 ϕ, 4 pole and 50 Hz squirrel cage Induction motor to be started by a star-delta starter. Assume average flux density in the gap = 0.45 wb/m², power factor = 0.84. Machine rated at 3.7 kw, 4 pole are soll at a least price and therefore choose the main dimensions. Assume winding factor = 0.955, stacking factor = 0.9, current density = 5 A/mm², efficiency = 85%, ac = 23,000 ampere conductor / meter.

Given data

$P_o = 3.7$ kw, $E_L = V_L = 400V$, $p = 6$, phase = 3, $f = 50$ Hz, star-delta starter, $B_{av} = 0.45$ wb/m², $Pf = 0.84$, $k_w = 0.955$, $S_f = 0.9$, $\delta = 5$ A/mm², efficiency = 85% = 0.85, ac = 23,000

To find

i) main dimensions ii) no: of ventillating ducts, iii) No: of stator slots iv) no: of stator turns / phase v) area of cross section of stator conductors.

Solution

i) Main Dimensions

Input Q in kVA = $1.11 D^2 L n_s B_{av}\, ac\, k_w \times 10^{-3}$, kVA

$$D^2L = \frac{\text{Input } Q \text{ in kVA}}{1.11\,\pi^2\, n_s\, B_{av}\, ac\, k_w \times 10^{-3}}$$

$$D^2L = \frac{\text{Input } Q \text{ in kVA}}{1.11\,\pi^2\, n_s \times 0.45 \times 23{,}000 \times 0.955 \times 10^{-3}} \rightarrow (1)$$

$$\text{Input } Q \text{ in kVA} = \frac{\text{Output power in kW}}{\eta \times \cos\phi}$$

$$= \frac{3.7}{0.85 \times 0.84} = \underline{\underline{5.1821}}\ \text{kVA}$$

$$n_s = \frac{N_s}{60} = \frac{120 \times f}{P \times 60} = \frac{120 \times 50}{4 \times 60} = \underline{\underline{25}}\ \text{rps}$$

Substitute Q and n_s value in eq (1)

$$D^2L = \frac{5.1821}{1.11 \times \pi^2 \times 25 \times 0.45 \times 23{,}000 \times 0.955 \times 10^{-3}}$$

$$D^2L = \underline{\underline{0.0019}}\ \text{m}^3 \rightarrow (2)$$

Given choose main dimension for Cheap design

$\frac{L}{\tau} = 1.5$ to 2, Let us assume $\frac{L}{\tau} = 1.5$

$$\therefore\quad L = 1.5\,\tau$$

$$L = 1.5\left(\frac{\pi D}{P}\right)$$

$$L = 1.5\left(\frac{\pi D}{4}\right)$$

$$L = 1.5 \times 0.7854 \times D$$

$$\boxed{L = 1.1781\,D} \longrightarrow (3)$$

From Eq (2)

$$D^2 \times 1.1781\,D = 0.0019$$

$$D^3 = \frac{0.0019}{1.1781} = 0.0016$$

$$\boxed{D = 0.1173}\,,\ m$$

From Eq (3)

$$L = 1.1781 \times 0.1173$$

$$\boxed{L = 0.1382}\,,\ m.$$

ii) Number of ventillating ducts

when $L > 0.1\,m$ or 100 mm, ventillating ducts are provided to cool the motor.

Given $S_f = 0.9$

$$\therefore S_f = \frac{L_i}{L}$$

$$L_i = S_f \times L = 0.9 \times 0.1382$$

$$= \underline{0.1244}\ m$$

If $L_i = 0.1244\,m$, It is possible to use 2 ducts with 10 mm wide.

$$\boxed{\text{Ventillating Ducts} = 2 \text{ of } 10\,mm \text{ wide}}$$

iii) No: of Stator Slots

$m \rightarrow$ Slots / pole / phase.

m	S_s $S_s = m \times \text{pole} \times \text{phase}$	Y_{ss} $= \pi D / S_s$
2	24	15.24 mm
3	36	10.21 mm
4	48	7.79 mm
5	60	6.158 mm

For low capacity machine, the stator slot pitch Y_{ss} is less than 15 mm

So we select $\boxed{S_s = 36}$

iv) No: of turns / phase

$$E_{sph} = 4.44 f \phi T_{sph} k_w \text{ , Volts}$$

$$T_{sph} = \frac{E_{sph}}{4.44 f \phi k_w}$$

$$T_{sph} = \frac{E_{sph}}{4.44 \times 50 \times \phi \times 0.955} \rightarrow (4)$$

Given, Motor is started by star-Delta Starter (ie) running time the stator winding is Delta connected.

$$E_L = E_{sph} = 400\,V.$$

We know that $B_{av} = \frac{P\phi}{\pi D L}$

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

$$\phi = \frac{0.45 \times \pi \times 0.1173 \times 0.1382}{4}$$

$$\phi = \underline{0.0057}\ wb$$

Substitute E_{sph} and ϕ value in eq (4)

$$T_{sph} = \frac{400}{4.44 \times 50 \times 0.0057 \times 0.955}$$

$$T_{sph} = 331.006 \simeq 331.$$

Stator Conductors $(Z_s) = 6 \times T_{sph}$
$= 1986$

Stator Conductors / slot $= \frac{1986}{36} = 55.1668$
$\simeq 55.$

$$\boxed{\text{Stator Conductor / slot} = 55}$$

Stator Conductors Z_s (new) = Cond/Slot × Slot

$$\boxed{Z_{s(new)} = 55 \times 36 = 1980}$$

Stator turns/phase ($T_{sph(new)}$) $= \frac{Z_s}{6} = \frac{1980}{6}$

$$\boxed{T_{sph(new)} = 330}$$

v) Area of Cross section of stator Conductors

Current density $\delta = \frac{I_{sph}}{a_s}$

$$a_s = \frac{I_{sph}}{\delta} = \frac{I_{sph}}{5} \rightarrow (5)$$

We know that

$$\text{Input Q in kVA} = 3 E_{sph} I_{sph} \times 10^{-3}, \text{ kVA}$$

$$I_{sph} = \frac{\text{Input Q in kVA}}{3 \times E_{sph} \times 10^{-3}}$$

$$= \frac{5.1821}{3 \times 400 \times 10^{-3}}$$

$$I_{sph} = 4.3184 \text{ A}$$

From Equation (5)

$$\boxed{a_s = 0.8637}\text{, mm}^2$$

Answers

$D = 0.1173$ m

$L = 0.1382$ m

$n_d = 2$

$S_s = 36$

$T_{sph} = 330$

$Z_{se} = 1980$

Stator conductor / slot = 55

Area of Stator Conductor, $a_s = 0.8637$, mm^2.

A 15 kW, 440V, 4 pole, 50 Hz, 3φ Induction motor is built with a Stator bore = 0.25m and core length of 0.16m. The Specific electric loading is 23,000 amp.cond/m. Using the data of this machine, determine the core dimensions, no. of Stator Slot and no. of Stator Conductors for a 11 kW, 460V, 6 pole, 50 Hz motor. Assume a full load efficiency of 84% and powerfactor of 0.88 for each machine. The winding factor is 0.955.

Given data

Motor 1.	Motor 2
$P_o = 15\ kW$	$P_o = 11\ kW$
$V = 440\ V$	$V = 460\ V$
$P = 4$	$P = 6$
$f = 50\ Hz$	$f = 50\ Hz$
$D = 0.25\ m$	$\eta = 84\% = 0.84$
$L = 0.16\ m$	$Pf = 0.8$
$ac = 23000$	$k_w = 0.955$
$\eta = 84\% = 0.84$	
$Pf = 0.8$	
$k_w = 0.955$	

To find

main dimensions, no.s of stator slots and no of stator conductors for a 11 kW motor.

Solution

The output Equation of 3ϕ Induction motor is Input Q in kVA $= 1.11\pi^2 D^2 L n_s B_{av} ac\, k_w \times 10^{-3}$, kVA

$$D^2L = \frac{\text{Input } Q \text{ in kVA}}{1.11\pi^2 n_s B_{av}\, ac\, k_w \times 10^{-3}}$$

$$D^2L = \frac{\text{Input } Q \text{ in kVA}}{1.11\pi^2 n_s B_{av} \times 23{,}000 \times 0.955 \times 10^{-3}} \rightarrow (1)$$

$$\text{Input } Q \text{ in kVA} = \frac{\text{output power in kW}}{\eta \times \cos\phi}$$

$$= \frac{11}{0.84 \times 0.82}$$

Input Q in kVA $= \underline{15.9628}$, kVA

$$n_s = \frac{N_s}{60} = \frac{120f}{P \times 60} = \frac{120 \times 50}{6 \times 60}$$

$n_s = \underline{16.6667}$, rps

To find B_{av}, use the data of 15 kW Induction motor

Input Q in kVA $= 1.11\,\pi^2 D^2 L\, n_s\, B_{av}\, ac\, k_w \times 10^{-3}$, kVA

$$B_{av} = \frac{\text{Input Q in kVA}}{1.11\,\pi^2 D^2 L\, n_s\, ac.\, k_w \times 10^{-3}}$$

$$B_{av} = \frac{\text{Input Q in kVA}}{1.11\,\pi^2 \times (0.25)^2 \times (0.16) \times n_s \times 23{,}000 \times 0.955 \times 10^{-3}} \quad \longrightarrow (2)$$

$$\text{Input Q in kVA} = \frac{\text{output power in kW}}{\eta \times \cos\phi}$$

$$\text{Input Q in kVA} = \frac{15}{0.84 \times 0.82}$$

Input Q in kVA $= \underline{21.777}$, kVA

$$n_s = \frac{N_s}{60} = \frac{120 f}{P \times 60} = \frac{120 \times 50}{4 \times 60} = \underline{\underline{25}},\ \text{rps}$$

From Eq (2)

$$B_{av} = \frac{21.777}{1.11 \times \pi^2 \times (0.25)^2 \times 0.16 \times 25 \times 23{,}000 \times 0.955 \times 10^{-3}}$$

$B_{av} = \underline{0.3620}$, Wb/m^2

Sub $B_{av} = 0.3620$ wb/m^2, $n_s = 16.6667$ rps, and Input Q in kVA = 15.9628 in eq ①, we get

$$D^2L = \frac{15.9628}{1.11\,\pi^2 \times 16.6667 \times 0.3620 \times 23{,}000 \times 0.955 \times 10^{-3}}$$

$$D^2L = \underline{\underline{0.0110}}\,, m^3 \longrightarrow ⑧$$

As per given data, the seperation of D and L from D^2L is based on the ratio $\frac{L}{\tau}$

∴ To find $\frac{L}{\tau}$ ratio, use the data of 15 kW IM

$$\frac{L}{\tau} = \frac{L}{(\pi D/P)} = \frac{0.16}{((\pi \times 0.25)/4)} = \underline{\underline{0.8149}}$$

$$\frac{L}{\tau} = 0.8149$$

For 11 kW, Induction motor

$$\frac{L}{\tau} = 0.8149, \text{ then } L = 0.8149\,\tau$$

$$L = 0.8149\,\frac{\pi D}{P}$$

$$L = 0.8149 \times \frac{3.14\,D}{6}$$

$$L = 0.4265\,D \longrightarrow ④$$

From Equation (3)

$$D^2 \times 0.4265 D = 0.0110$$

$$D^3 = \frac{0.011}{0.4265} = \underline{\underline{0.0258}}$$

$$D = \sqrt[3]{0.0258} = \underline{\underline{0.2955}},\ m$$

From Equation (4)

$$L = 0.4265 \times 0.2955$$

$$L = \underline{\underline{0.1260}},\ m$$

No of Stator slots $\boxed{m = \text{slots} / \text{pole} / \text{phase}}$

m	$S_s = m \times \text{pole} \times \text{phase}$ $= m \times 6 \times 3$	$Y_{ss} = \frac{\pi D}{S_s}$
2	36	25.74 mm
3	54	17.16 mm
4	72	12.87 mm

When $S_s = 54$, the slot pitch lies b/w the range 15 mm to 25 mm, Hence we select $S_s = 54$

$$\boxed{S_s = 54}$$

Stator Conductors

$$E_{sph} = 4.44 f \phi T_{sph} k_w \text{, Volts}$$

$$T_{sph} = \frac{E_{sph}}{4.44 f \phi k_w}$$

$$T_{sph} = \frac{E_{sph}}{4.44 \times 50 \times \phi \times 0.955} \rightarrow (5)$$

Let us assume that stator winding is Delta connected

$$E_{sph} = E_L = 460 \text{ V}$$

We know that $B_{av} = \frac{P\phi}{\pi D L}$

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

$$\phi = \frac{0.3620 \times \pi \times 0.2955 \times 0.126}{6}$$

$$\phi = \underline{\underline{0.0071}} \text{, wb}$$

Sub E_{sph} and ϕ values in Eq (5), we get

$$T_{sph} = \frac{460}{4.44 \times 50 \times 0.0071 \times 0.955}$$

$$T_{sph} = 305.5928 = 306$$

We know that

$$T_{sph} = \frac{Z_s}{6}$$

$T_s = \frac{Z_s}{2}$

$T_{sph} = \frac{Z_s}{2 \times 3}$

Stator Conductors $(Z_s) = 6 \times T_{sph}$

$= 6 \times 306$

$= 1836$

Stator Conductor / slot $= 1836/54$

$= 34$

Answer

$D = \underline{0.2955}$, m

$L = \underline{0.1260}$, m

Stator slots $(S_s) = 54$

Stator turns/phase $(T_{sph}) = 306$

Stator conductors $(Z_s) = 1836$

Stator Conductor / slot $= 34$.

Design of Squirrel Cage Rotor

It involes the following

i) Diameter and length of Rotor

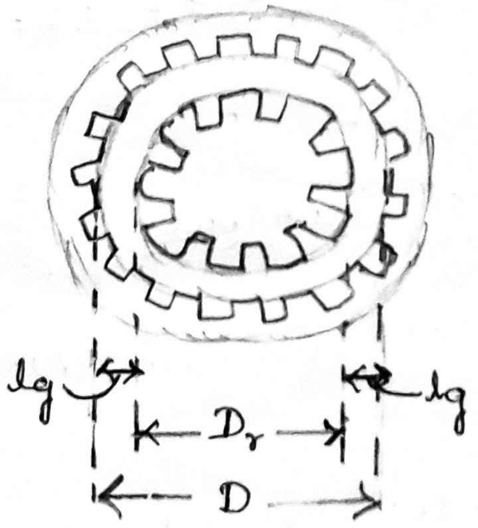
ii) Number of Rotor Slots

iii) Number of Rotor bars

iv) Rotor bar current and area of rotor conductors

v) End ring current and area of end rings.

i) Diameter and length of Rotor



$$D = D_r + l_g + l_g$$

$$\boxed{D_r = D - 2l_g}$$

where $l_g = 0.2 + 2\sqrt{DL}$, mm

D and L are in m

Length of rotor = length of stator

$$\boxed{L_r = L}$$

ii) Number of Rotor Slots

With certain combination of stator and rotor slots machine may be

a) refuse to start (cogging)

b) run at $1/7^{th}$ speed of synchronous speed (crawling)

c) produce noise and vibration.

To avoid this, $(S_s - S_r)$ should not be equal to

$S_s - S_r \neq 0, \pm 1, \pm 2, \pm P, \pm 2P, \pm 3P, \pm (P \pm 1), \pm (P \pm 2)$.

iii) Number of rotor bars

Number of rotor bars = No. of rotor slots.

iv) Rotor bar current and area of Rotor bar

Rotor bar Current

Let us assume that Rotor mmf is 85% of stator mmf.

$$\frac{\text{Rotor bars}}{2} \times I_b = 0.85 \times 3 \times T_{sph} \times I_{sph}$$

$$\frac{S_r}{2} \times I_b = 0.85 \times 3 \times T_{sph} \times I_{sph}$$

$$\boxed{I_b = \frac{0.85 \times 6 \times T_{sph} \times I_{sph}}{S_r}}$$

Area of Rotor bar

Area of Rotor bar is proportional to the Current flows through the ba

$$\delta_b = \frac{I_b}{a_b}$$

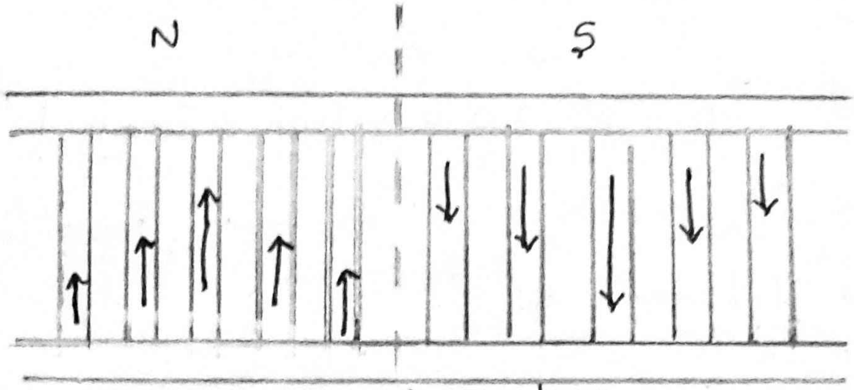
$$\boxed{a_b = \frac{I_b}{\delta_b}}, \ mm^2.$$

v) End ring current and Area of end ring

Let us consider the bars under ~~N and S~~ alternate North and South poles. The bars under North pole allows the current in upward direction and bars under South pole allows the current in downward direction.

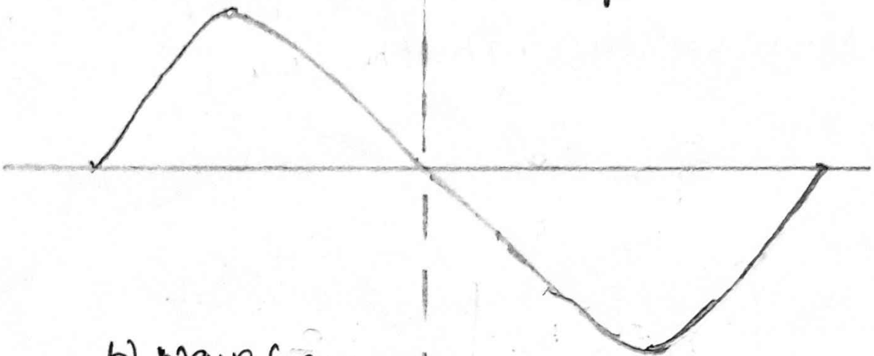
If the flux and emf distribution is sinusoidal, then the bar current and end ring current is also sinusoidal.

Normally, the resistance of end rings is ~~neglib~~ negligible as compared to the resistance of bars.

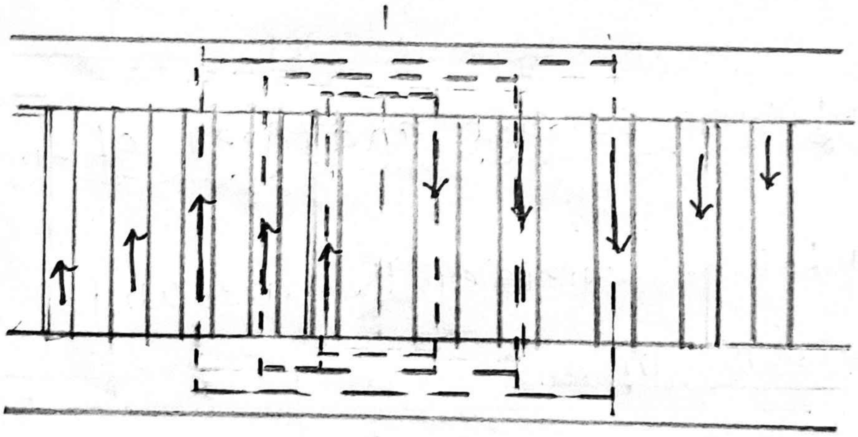


a) Current in Copper bar

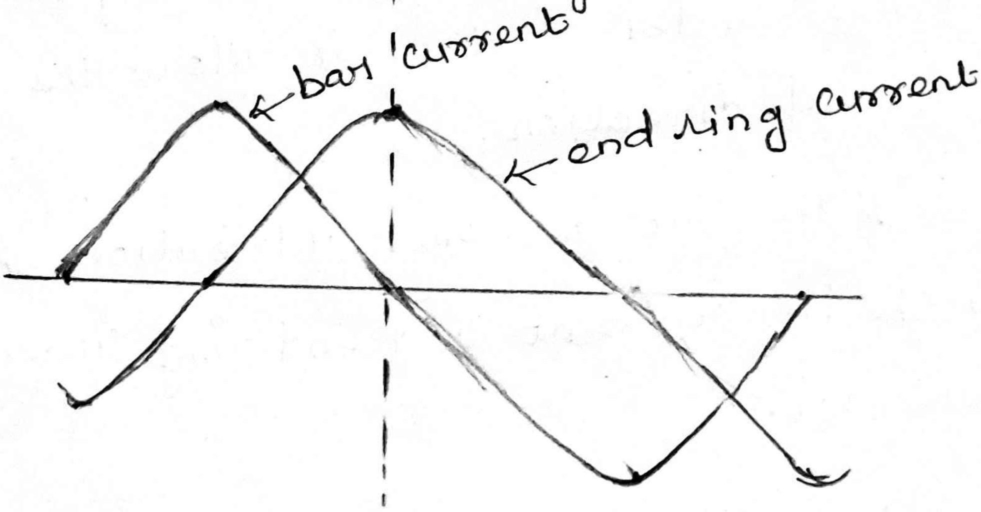
← Interpolar axis



b) Waveform of emf Induced in bars.



c) Current in end ring



d) Waveform of end ring and bar current

Let us consider the bars under one pole pitch and assume that current in all bars are maximum. Therefore maximum value of the current in end ring is given by

$$I_{e(max)} = \frac{\text{Bars under pole}}{2} \times I_{b(max)}.$$

$$I_{e(max)} = \frac{S_r}{2p} \times I_{b(max)} \rightarrow ①$$

Practically all bar currents are not maximum at same time. Therefore we take the average value of bar current

$$\therefore I_{e(max)} = \frac{S_r}{2p} I_{b(avg)} \rightarrow ①$$

where

$$I_{b(avg)} = \frac{2}{\pi} I_{b(max)}$$

Equation ① becomes

$$I_{e(max)} = \frac{S_r}{2p} \times \frac{2}{\pi} I_{b(max)}.$$

The R.m.s value of end ring current is given by

$$\sqrt{2} I_e = \frac{S_r}{2p} \times \frac{2}{\pi} \sqrt{2} I_b$$

$$\boxed{I_e = \frac{S_r I_b}{\pi p}}$$

We know that

$$I_{Rms} = \frac{I_{max}}{\sqrt{2}}$$

$$\boxed{I_{max} = \sqrt{2} . I}$$

Area of the end ring

$$\delta_e = \frac{I_e}{a_e}$$

$$\boxed{a_e = \frac{I_e}{\delta_e}}$$, where $\delta_e \rightarrow$ current density

A 11 kW, 3 ϕ, 6 pole, 50 Hz, 220 V, star connected Induction motor has 54 stator slot, each slot containing 9 conductors. Calculate the values of bar and end ring currents, the number of rotor bar is 64. The machine has $\eta = 0.86$ and $\cos\phi = 0.85$, the rotor mmf may be assumed as 85% stator mmf. Also find the area of bar and end ring section, if the current density is 5 A/mm^2.

Given data

$P_o = 11$ kW, $P = 6$, 3 phase Y connected Induction motor, $S_s = 54$, $f = 50$, $V_L = 220$ V $= E_L$, Cond/slot $= 9$

$S_r = 64$, $\eta = 0.86$, $\cos\phi = 0.85$, rotor mmf $= 85\% = 0.85$ of stator mmf, $\delta_e = \delta_b = 5$ A/mm^2.

To find

Area of bar and end ring section.

Solution

i) Area of bar

$$\delta_b = \frac{I_b}{a_b}$$

$$a_b = \frac{I_b}{\delta_b}$$

$$a_b = \frac{I_b}{5} \rightarrow (1)$$

Given rotor mmf = 0.85 x stator mmf

$$\frac{\text{rotor conductors}}{2} \times I_b = 0.85 \times 3 \times T_{sph} \times I_{sph}.$$

rotor conductors = rotor slots

$$\frac{S_r}{2} \times I_b = 0.85 \times 3 \times T_{sph} \times I_{sph}$$

$$\frac{64}{2} \times I_b = 0.85 \times 3 \times T_{sph} \times I_{sph} \rightarrow (2)$$

Given stator conductor/slot = 9

$$\text{Stator conductors } Z_s = \frac{\text{Conductor}}{\text{slot}} \times \text{stator slots}$$

$$Z_s = 9 \times 54 = 486$$

$$\text{Stator Turns/phase } T_{sph} = \frac{Z_s}{6} = \frac{486}{6} = 81$$

$$\boxed{T_{sph} = 81}$$

We know that

$$\text{Input Q in kVA} = 3 \times E_{sph} \times I_{sph} \times 10^{-3}, \text{ kVA}$$

$$I_{sph} = \frac{\text{Input Q in kVA}}{3 \times E_{sph} \times 10^{-3}} \rightarrow (3)$$

$$\text{Input Q in kVA} = \frac{\text{Output power in kW}}{\eta \times \cos\phi}$$

$$= \frac{11}{0.86 \times 0.85}$$

$$\text{Input Q in kVA} = \underline{\underline{15.0479}}, \text{ kVA}$$

Given stator winding is star connected, therefore

$$E_{sph} = \frac{E_L}{\sqrt{3}},$$

$$E_{sph} = \frac{220}{\sqrt{3}} = \underline{\underline{155.5635}}, \text{ Volt}$$

From Equation (3)

$$I_{sph} = \frac{15.0479}{3 \times 155.5635 \times 10^{-3}}$$

$$I_{sph} = \underline{\underline{32.2439}}, \text{ A}$$

Substitute T_{sph} and I_{sph} value in equation (2)

$$\frac{64}{2} \times I_b = 0.85 \times 3 \times 81 \times 32.2439$$

$$I_b = \frac{0.85 \times 3 \times 81 \times 32.2439 \times 2}{64}$$

$$I_b = \underline{\underline{208.1240}}, \text{ A}$$

From Equation ①

$$a_b = \frac{208.1240}{5}$$

$$a_b = \underline{41.6248}, mm^2.$$

ii) Area of end ring

$$\delta_e = \frac{I_e}{a_e}$$

$$a_e = \frac{I_e}{\delta_e} \rightarrow ④$$

$$I_e = \frac{S_r I_b}{\pi P}$$

$$I_e = \frac{64 \times 208.1240}{\pi \times 6}$$

$$I_e = \underline{706.6446}, A$$

From Equation ④

$$a_e = \frac{706.6446}{5}$$

$$a_e = \underline{141.3289}, mm^2.$$

A 90 kW, 500V, 50Hz, 3ϕ, 8 pole, Induction motor has a star connected stator winding accomadated in 53 slots with 6 conductor/slot. If the slip ring voltage on open circuit is to be about 400V. Find the suitable rotor slots, number of rotor conductors per slot, approximate full load current per phase in rotor. Assume $\eta = 0.9$, $\cos\phi = 0.86$, $\delta = 5 \, A/mm^2$, Also find the area of rotor conductors.

Given data

$P_o = 90 \, kW$, $V_L = E_L = 500 \, V$, $f = 50 \, Hz$, 3 phase, star connected stator winding, $p = 8$, $S_s = 53$, Stator conductor/slot $(Z_{ss}) = 6$, $E_{rL} = 400 \, V$.
$\eta = 0.9$, $\cos\phi = 0.86$, $\delta = 5 \, A/mm^2$.

To find

i) Rotor slots, ii) Number of rotor conductors per slots iii) area of rotor conductors.

Solution

i) Rotor slots

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

$S_s - S_r$ should not be equal to $0, \pm 1, \pm 2, \pm 8, \pm 16, \pm 18, \pm 7, \pm 9, \pm 6, \pm 10$

$S_s - S_r$ should be equal to $\pm 3, \pm \cancel{4}, \pm 5, \pm 11, \pm 12, \pm 13, \pm 14, \pm 15 \pm 17 \ldots$

q	$S_r = q \times \text{pole} \times \text{phase}$	$S_s - S_r$
2	48	$63 - 48 = 15$ ✓
3	72	$63 - 72 = 9$ ×
4	96	$63 - \cancel{120}\ 96 = \cancel{57}\ 33$ ✓
5	120	$63 - 120 = 57$ ✓

When $S_r = 48$, the difference b/w S_s and S_r is minimum, so we select $\boxed{S_r = 48}$

ii) Rotor conductors

$$E_{sph} = 4.44 f \phi T_{sph} k_{ws}.$$

$$E_{rph} = 4.44 f \phi T_{rph} k_{wr}$$

$$\frac{E_{sph}}{E_{rph}} = \frac{T_{sph}}{T_{rph}}$$

$$T_{rph} = \frac{T_{sph} E_{rph}}{E_{sph}} \longrightarrow (1)$$

Given Stator Conductor / slot = 6, and $S_s = 53$

$\therefore$ Stator Conductors $Z_s = \frac{\text{Stator conductor}}{\text{Slot}} \times \text{Slot}$

$$Z_s = 6 \times 53 = 318$$

$$T_{sph} = \frac{Z_s}{6} = \frac{318}{6} = 63$$

We know that for slip ring rotor, the rotor winding is star connected

$$E_{rph} = \frac{E_{rL}}{\sqrt{3}} = \frac{400}{\sqrt{3}} = \underline{\underline{230.9401}}, \checkmark$$

and also given stator winding is star connected

$$E_{sph} = \frac{E_{sL}}{\sqrt{3}} = \frac{500}{\sqrt{3}} = \underline{\underline{288.6751}}, \checkmark$$

From Equation (1)

$$T_{rph} = \frac{63 \times 230.9401}{288.6751} = 50.4 \simeq 50$$

$$\boxed{T_{rph} = 50}$$

$$Z_{rph} = 6 \times 50 = 300$$

~~Rototor~~ Rotor Conductor / slot $(Z_{rs}) = \frac{300}{48} = \underline{\underline{6.25}}$

$$\boxed{\text{Rotor conductor / slot } (Z_{rs}) = 6}$$

(Because for high Capacity motor conductor/slot should be a Even Integer).

$$Z_r\ (new) = \text{Rotor Conductor/Slot} \times \text{Rotor slot}$$

$$= 6 \times 48$$

$$\boxed{Z_r(new) = 288}$$

$$T_{rph}(new) = \frac{Z_r(new)}{6} = 48$$

$$\boxed{T_{rph}(new) = 48}$$

iii) area of rotor Conductors

$$\delta_r = \frac{I_{rph}}{a_r}$$

($\delta_r \rightarrow$ current density in rotor)

$$a_r = \frac{I_{rph}}{\delta_r} \rightarrow (2)$$

To find I_{rph}, assume rotor mmf is 85% of stator mmf

$$T_{rph}\, I_{rph} = 0.85 \times T_{sph} \times I_{sph}$$

$$I_{rph} = \frac{0.85 \times T_{sph} \times I_{sph}}{T_{rph}}$$

$$I_{rph} = \frac{0.85 \times 63 \times I_{sph}}{48} \rightarrow (3)$$

We know that

$$\text{Input Q in kVA} = 3 \times E_{sph} \times I_{sph} \times 10^{-3}, \text{ kVA}$$

$$I_{sph} = \frac{\text{Input Q in kVA}}{3 \times E_{sph} \times 10^{-3}}$$

$$I_{sph} = \frac{\text{Input Q in kVA}}{3 \times 288.6751 \times 10^{-3}} \rightarrow (4)$$

$$\text{Input Q in kVA} = \frac{\text{Output power in kW}}{\eta \times \cos\phi}$$

$$= \frac{90}{0.9 \times 0.86}$$

$$\text{Input Q in kVA} = \underline{116.2791}, \text{ kVA}$$

From Equation (4)

$$I_{sph} = \frac{116.2791}{3 \times 288.6751 \times 10^{-3}}$$

$$\boxed{I_{sph} = \underline{134.2675}, \text{ A}}$$

From Equation (3)

$$I_{rph} = \frac{0.85 \times 63 \times 134.2675}{48}$$

$$\boxed{I_{rph} = 149.7922,\ A}$$

From Equation (2)

$$a_r = \frac{149.7922}{5} \qquad \left(\text{given } \delta = 5\ A/mm^2\right)$$

$$\boxed{a_r = 29.9584,\ mm^2}$$

Answers

Rotor slot $S_r = 48$

Rotor Conductor/slot = 6

Rotor Conductors = 288

Rotor turns/phase = 48

Rotor current/phase = 149.7922, A

Area of Rotor Conductors = 29.9584, mm^2

Circle Diagram:

It is an graphical method to determine the performance of an Induction motor

To construct an circle diagram, the following data's are needed.

i) No load test:

→ gives the information about rated voltage (V_o) and no load current (I_o) and no load power (W_o)

ii) Blocked rotor test data:

→ gives the information about blocked rotor voltage (V_b), Blocked rotor current (I_b) and Blocked rotor power (W_b)

iii) Stator Resistance test data:

→ gives the information about stator resistance/phase.

convert the above data into per phase values.

From the above datas, calculate the ϕ_o, ϕ_b, I_{bn}, W_{bn}.

where, $\phi_o = \cos^{-1}\left(\frac{W_o}{\sqrt{3}\, V_o I_o}\right)$

$$\phi_b = \cos^{-1}\left(\frac{W_b}{\sqrt{3}\, V_b I_b}\right)$$

$I_{bn} \rightarrow$ current drawn by the blocked rotor motor at rated voltage.

$$I_{bn} = I_b \times \left(\frac{V_0}{V_b}\right)$$

$W_{bn} \rightarrow$ power taken by blocked rotor motor at rated voltage.

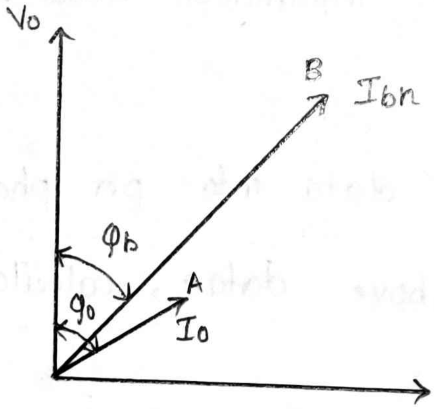
$$W_{bn} = W_b \times \left(\frac{V_0}{V_b}\right)^2.$$

Procedure to construct circle diagram:

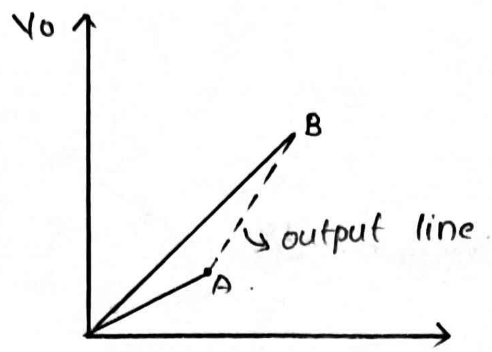
1). Take rated voltage V_0 as the reference phasor.

2) Choose a suitable current scale and convert I_0 and I_{bn} in cm.

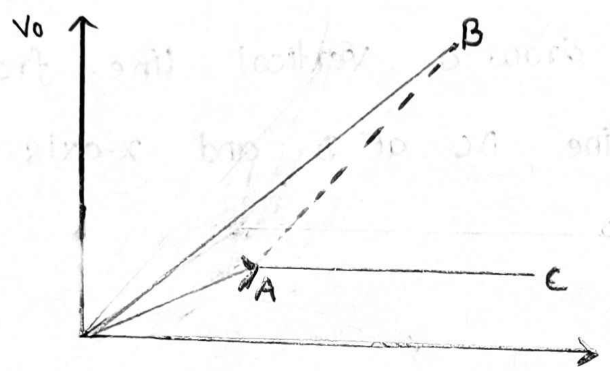
3). Draw the vector I_0 lags V_0 by an angle ϕ_0 and I_{bn} lags V_0 by an angle ϕ_b.



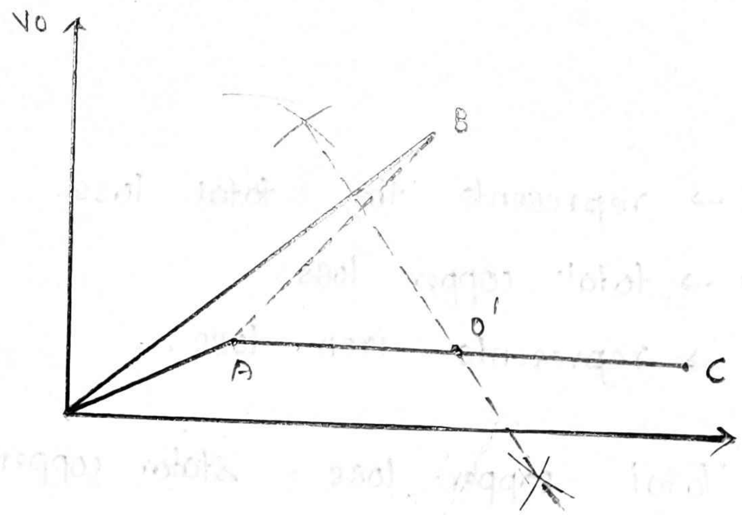
4) Join the points A and B, the line AB represent the output line.



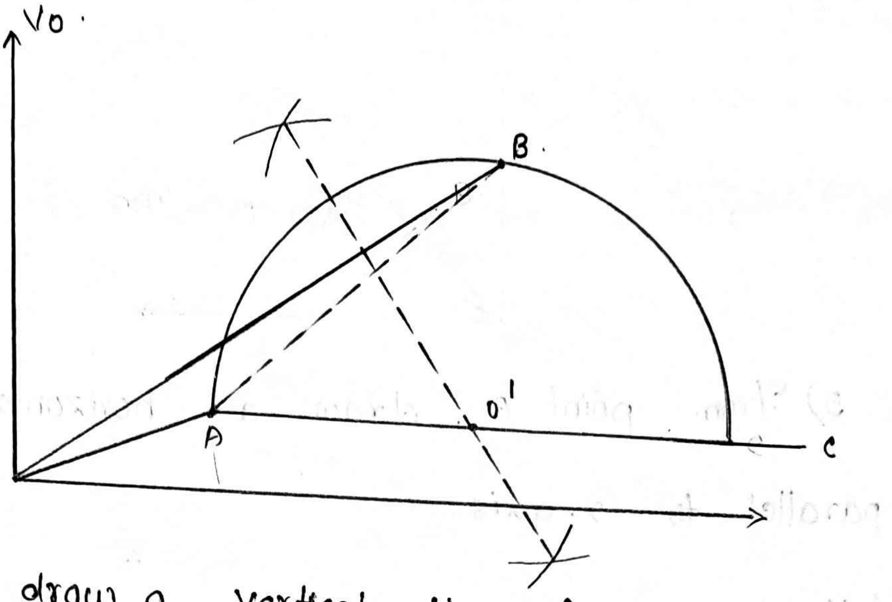
5) From point A, draw a horizontal line AC parallel to x-axis.



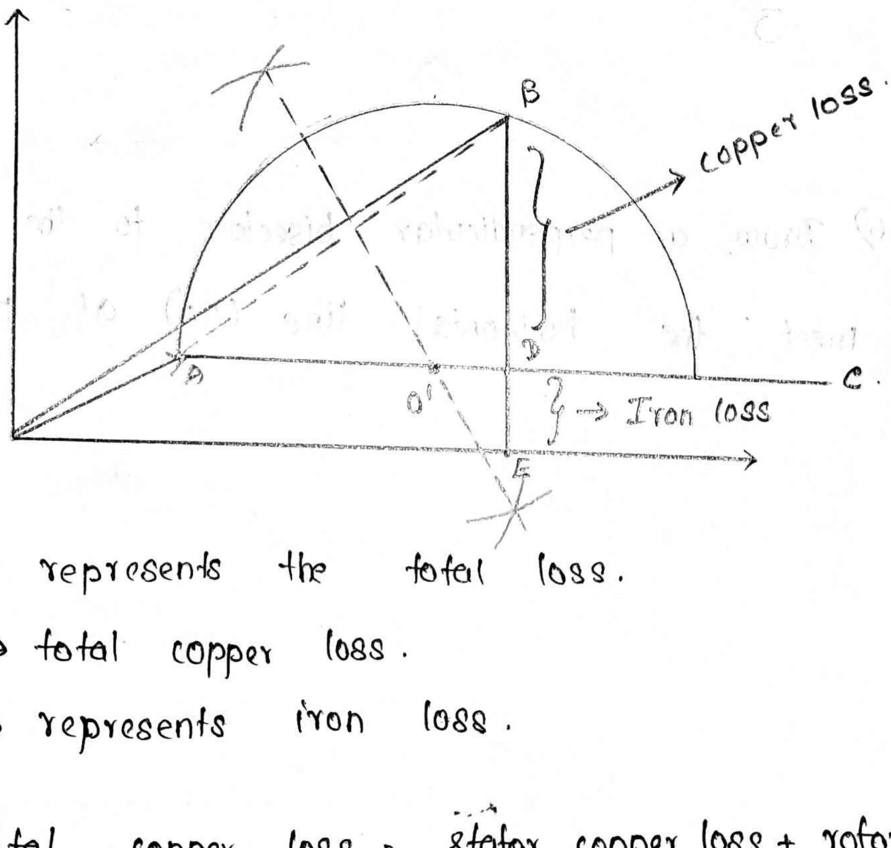
6) Draw a perpendicular bisector to the output line, that meet the horizontal line (AC) at point o'.



7) Draw a semi circle, with o' as a centre and o'A as radius.



8) From B, draw a vertical line from point B, it meets the line AC at D and x-axis at E.



BE → represents the total loss.

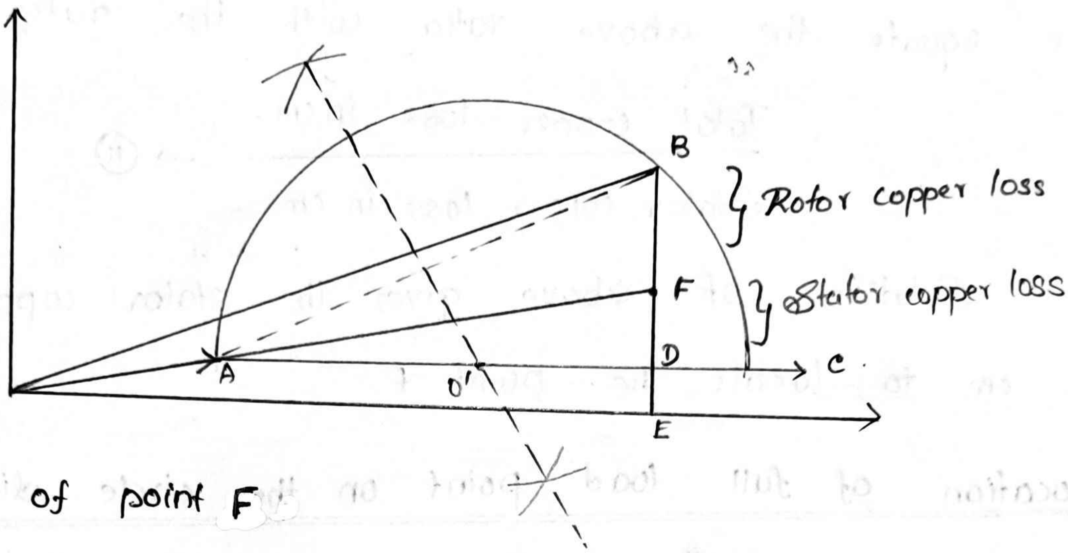
BD → total copper loss.

DE → represents iron loss.

Total copper loss = stator copper loss + rotor copper loss.

To seperate the stator copper loss and rotor copper loss, we should draw the torque line.

9) The vector AF is the torque line which seperates the stator and rotor copper loss.



Location of point F

Draw the torque line based on the ratio

$$\frac{\text{Stator copper loss}}{\text{Rotor copper loss}}$$, If this ratio is not given.

In case of cage rotor,

$$\frac{\text{Stator copper loss}}{\text{Rotor copper loss}} = \frac{3 I_1^2 R_1}{W_{bn} - 3 I_1^2 R_1}$$

In case of slip ring rotor,

$$\frac{\text{Stator copper loss}}{\text{Rotor copper loss}} = \frac{3 I_1^2 R_1}{3 I_2^2 R_2} = \frac{I_1^2}{I_2^2} \cdot \frac{R_1}{R_2} = k^2 \cdot \frac{R_1}{R_2}.$$

After determining this ratio, convert the ratio to

$$\frac{\text{Total copper loss}}{\text{Stator copper loss}} \rightarrow (1)$$

From the circle diagram, the total copper loss is represented by BC and is given in cm. So we equate the above ratio with the ratio

$$\frac{\text{Total copper loss in cm.}}{\text{Stator copper loss in cm}} \rightarrow (11)$$

Solution of above gives the stator copper loss in cm to locate the point F.

Location of full load point on the circle diagram.

Case (i) :- If full load current is not given,

From point B, draw a vertical line BG.

$$\text{Length of } BG = \frac{\text{Rated output}}{\text{power scale.}}$$

Where, $\text{power scale} = \dfrac{W_{bn}}{\text{Length of } BE}$.

From point G, draw a parallel line to the output line. This parallel line meet the semicircle at point P. This point is called full load point.

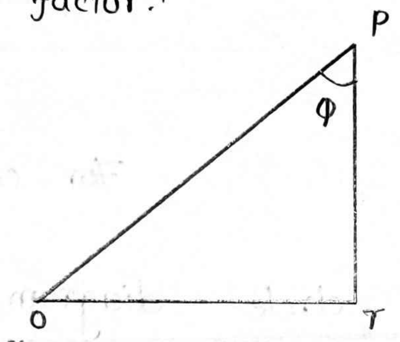
Case (ii) :- If full load is ~~not~~ given.

Convert the I_{fL} in ampere to cm and draw an arc on semicircle by taking O as centre with I_{fL} as radius. The meeting point P , output line, torque line, horizontal meets line. and x axis at points Q, R, S and T respectively. and to meet x-axis at point T

Performance analysis:

1) Line current = Length of OP x current scale.

2) Power factor:



$$\cos\varphi = \frac{PT}{OT}$$

3) Input power = Length of PT x power scale.

4) Output power = PQ x power scale.

5) Efficiency $\eta = \frac{PQ}{PT} \times 100\%$.

6) Rotor copper loss = Length of QP x power scale.

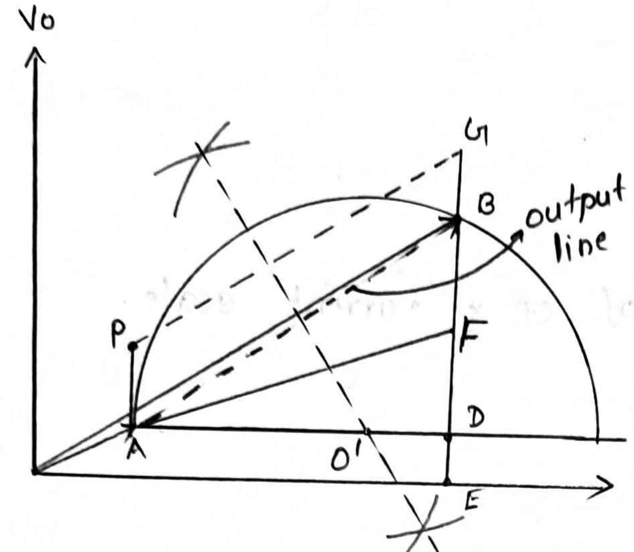
7) Rotor input = Length of PR x power scale.

8) Rotor output = Length of PQ x power scale.

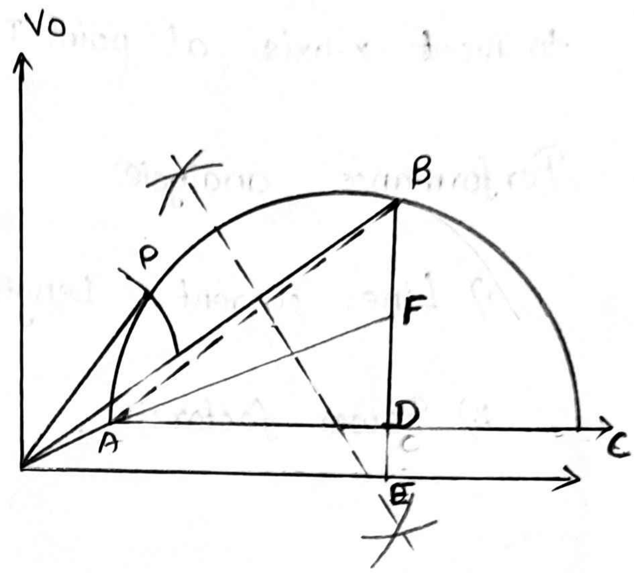
9) Slip = $\frac{\text{Rotor copper loss}}{\text{Rotor input}} = \frac{QR}{PR}$.

10) Rotor efficiency = $\frac{PQ}{PR} \times 100$.

point of arch on the semicircle at point p is called full load point.

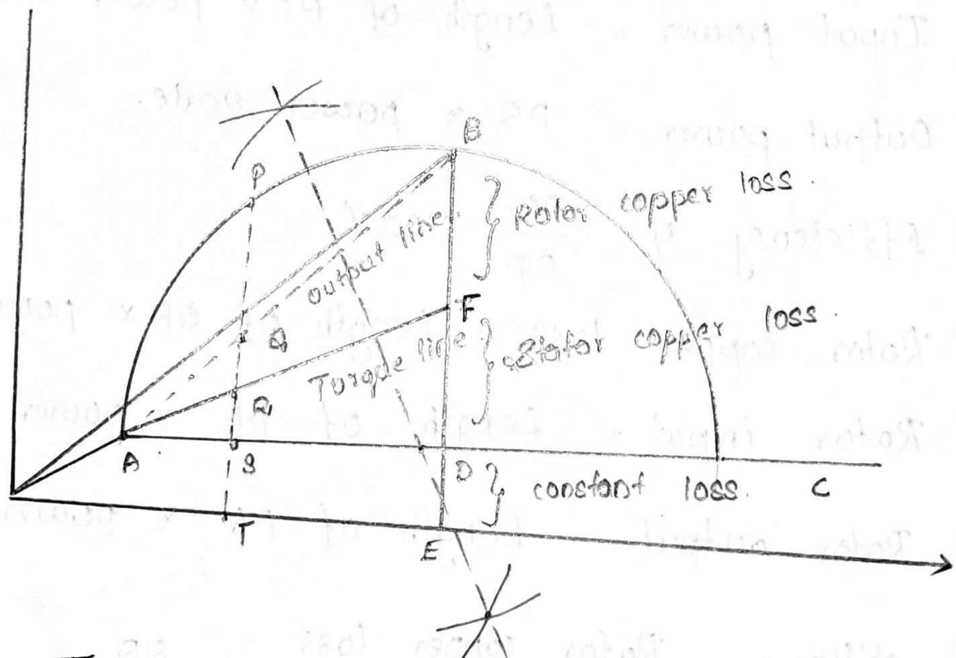


For case (i)



For case (ii)

Performance analysis of circle diagram:



To analyse the performance from circle diagram draw a vertical line from full load

ii) Maximum Input, Maximum output and Maximum Torque.

Maximum Input

Locate a point H on the mid of the semicircle. From point H, draw a vertical line meets the x axis at Point I

Maximum Input = length of HI × Power scale.

Maximum output

Draw a line $O'P_m$ ⊥r to the output line. From the point P_m draw a vertical line so as to meet the output line at N.

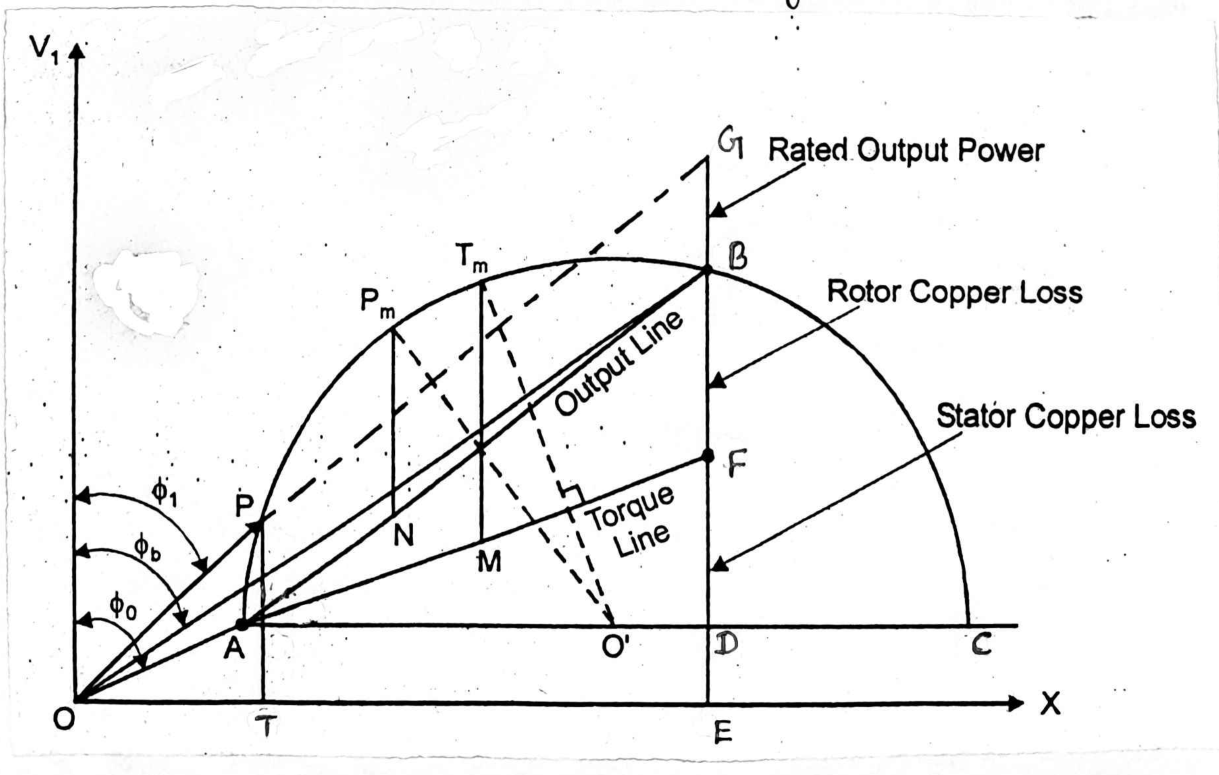
Maximum output = length NP_m × Power Scale.

Maximum Torque.

Draw a line $O'T_m$ ⊥r to the torque line. From the point T_m, draw a vertical line so as to meet the torque line at the point M.

Maximum Torque = length MT_m × Power Scale

= ______ Syn. watts.



EE 8002 DESIGN OF ELECTRICAL APPARATUS

UNIT V

DESIGN OF SYNCHRONOUS MACHINES

Prepared by

Dr . T. Dharma Raj
Asso.Prof /EEE

Synchronous Generator

A Synchronous machine Consists of two major parts.

i) armature and ii) field system.

Based on the arrangement of the above parts, it is classified into two types.

i) Revolving armature and

ii) Revolving field system.

Revolving armature system is similiar to DC machines This type of Construction is used only for low power synchronous machines and is unsuitable for medium and high power machines.

Revolving field System has the following advantages.

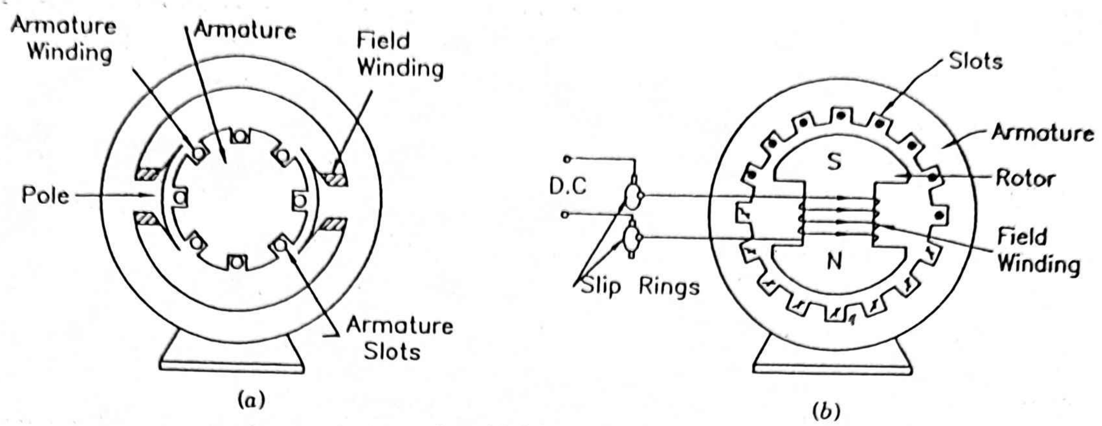
i) it permits the use of a Stationary armature on which the windings can be easily braced and insulated for high voltage.

2) The use of slip rings Carrying large currents at high voltages is avoided in the stationary armature

The Revolving field System Synchronous machines are classified into two types.

1) Non Salient pole (or) Cylindrical pole Machines.

2) Salient pole Machines.



Salient pole machines have projecting poles with concentrated field windings shown in figure (b). The Salient pole construction is used for generators driven by hydraulic turbines (water turbines). Since these turbines at relatively low speeds and it needs a large number of poles to produce the desired frequency.

$$\left(N = \frac{120f}{P}\right)$$

Cylindrical pole machines have their field winding distributed in slots is shown in figure (a).

The cylindrical rotor construction is used for turbo-alternators which are driven by high speed steam or gas turbines.

Comparision of Salient pole and non salient pole Machines

Salient pole	non Salient pole.
i) Large diameter and short axial length	Small diameter and long axial length
ii) Water turbines act as prime movers	steam turbines act as prime movers
iii) Has projected poles	Has no projected poles
iv) Needs damper wdgs	Does not need damper windings.

Prime movers for Synchronous Machines.

i) Salient pole → Water turbines act as primemover, hence it is known as ~~Whate~~ water wheel generators or hydro generators. The type of turbine to be used depends upon the water head available. The use of hydraulic turbines at various heads is listed below.

Water heads 400m and above - Pelton wheel

Water heads upto 380 m - Francis turbine

Water heads upto 50 m - kaplan turbine.

ii) non Salient pole → Steam turbines act as primer mover ~~hence~~ hence it is called turbo alternators.

Run away Speed

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

The following are the runaway speeds permissible for Hydro generators

i) pelton wheel – 1·8 times rated speed

ii) Francis turbine – 2 to 2·2 times rated speed

iii) kaplan turbine – 2·5 to 2·8 times rated speed.

Thus the salient pole (or) Hydro generators are designed to withstand mechanical stresses encountered at run-away speeds.

The maximum peripheral speed for which salient pole machines are designed is about 140 m/s. while for turbo alternators (non salient pole) are designed with maximum peripheral speed of about 175 m/s.

1) Main Dimensions

D and L are the main dimensions of salient pole machines, where D is the inner diameter of the stator and L is the length of the stator.

2) Output Equations

The output Q in kVA = $3 E_{sph} I_{sph} \times 10^{-3}$ kVA → ①

where $E_{sph} = 4.44 f \phi T_{sph} k_{ws}$ Volts.

from equation ①

Output Q in kVA $= 3 \times 4.44 f \phi T_{sph} k_{ws} I_{sph} \times 10^{-3}$ kVA → ②

In synchronous generator, the frequency is proportional to the speed of the prime mover, that is given by the expression

$$N = \frac{120 f}{P} = \frac{2 \times 60 f}{P}$$

$$f = \frac{NP}{2 \times 60} = \frac{Pn}{2}$$

From equation ②

Output Q in kVA $= 3 \times 4.44 \frac{Pn}{2} \phi T_{sph} k_{ws} I_{sph} \times 10^{-3}$ kVA → ③

We know that $B_{av} = \frac{P\phi}{\pi DL}$, $P\phi = B_{av} \pi DL$

Output Q in kVA $= 3 \times 4.44 \frac{n}{2} B_{av} \pi DL T_{sph} k_{ws} I_{sph} \times 10^{-3}$ kVA

Output Q in kVA $= 6.66 n B_{av} \pi DL k_{ws} T_{sph} I_{sph} \times 10^{-3}$ kVA → ④

$$T_{sph} = \frac{Z_s}{6}$$

For n number of parallel paths

$$T_{sph} = \frac{Z_s}{6A}$$

$I_z = I_{sph}$

For n number of $\parallel^{ell}$ paths

$I_z = \frac{I_{sph}}{A}$; $I_{sph} = A I_z$

From Equation (4)

Output Q in kVA $= 6.66\, n\, B_{av}\, \pi D L\, k_{ws} \frac{Z_s}{6} . I_z \times 10^{-3}$ kVA

Output Q in kVA $= 1.11\, n\, B_{av}\, \pi D L\, k_{ws}\, Z_s . I_z \times 10^{-3}$ kVA

We know that $ac = \frac{I_z . Z_s}{\pi D}$

$I_z . Z_s = ac\, \pi D$

Output Q in kVA $= 1.11\, n\, B_{av}\, \pi D L\, k_{ws}\, ac\, \pi D \times 10^{-3}$ kVA

$= 1.11\, \pi^2 D^2 L\, n\, B_{av}\, ac\, k_{ws} \times 10^{-3}$ kVA

$$\boxed{\text{The Output Q in kVA} = 1.11\, \pi^2 D^2 L\, n\, B_{av}\, ac\, k_{ws} \times 10^{-3} \text{ kVA}}$$

3) Choice of specific electric and magnetic loading

a) Choice of specific Electric Loading

The specific electric loading is defined as the ratio of total armature ampere conductors to the armature periphery at air gap

$$ac = \frac{I_z \cdot Z_s}{\pi D} \rightarrow (1)$$

The following factors are considered for the choice of specific loading

i) Copper loss and temperature rise

ii) Voltage

iii) Synchronous reactance

iv) Stray load loss

i) Copper loss and temperature rise.

From Equation $ac = \frac{I_z \cdot Z_s}{\pi D}$, the higher the value of ac which increases the I_z and Z_s. Therefore increase in current, increases the temperature rise and increase in area of conductors, increases the copper loss which resulting low efficiency.

Therefore low value of ac is selected, to reduce the copper loss and temperature rise.

ii) Voltage.

For high voltage machines, the conductor area is less, because large space is required for insulation. Therefore the low value of ac is used for high voltage machines.

The higher value of ac can be used for low machines, because the space required for insulation is small.

iii) Synchronous Reactance.

From the definition $ac = \frac{I_z \cdot Z_s}{\pi D}$, a high value of ac leads to high value of leakage reactance (due to increase in Z_s) results a high value of synchronous reactance.

Therefore a machine designed with a high value of ac will have high X_s results

i) poor inherent voltage Regulation

ii) low current under short circuit conditions

iii) low value of steady state stablity limit and small synchronizing power and consequently leads to instablity ($P_{max} = \frac{3 E_{ph} V_{ph}}{X_s}$)

iv) Stray load loss

The stray load loss increases steeply with an increase in ac.

Therefore the typical values of ac used in synchronous machines

Salient pole machines - 20,000 to 40,000 A/m

Turbo-generators - 50,000 to 75,000 A/m.

b) Specific magnetic loading (B_{av})

It is defined as the ratio of total flux around the air gap to the area of the armature periphery at the air gap

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

The following factors are to be considered for the choice of specific magnetic loading

i) Iron loss

ii) Voltage

iii) Transient short circuit current

iv) Stablity

v) parallel operation

i) Iron Loss

A high value of B_{av} leads to a high value of flux density in the stator core and teeth. This increases the iron loss, because the flux density is proportional to iron loss.

Therefore a low value of B_{av} is selected to reduce the Iron loss.

ii) Voltage

From the definition of flux density, $B_t = \frac{\phi_t}{A_t}$

For high voltage, the space occupied by the insulation is greater and smaller space is left for teeth. Therefore decrease in the area of the teeth, increases the value of flux density in teeth and core.

Therefore to avoid excessive values of flux density, a low value of gap density is used for high voltage machines.

iii) Transient Short Circuit Current.

From the Emf Equation $E_s = 4.44 f \phi T_s k_{ws}$ volts

By substituting the f and pϕ value in above equation, we get

$$E_s = 4.44 \frac{n}{2} B_{av} \pi D L T_s k_{ws} \text{ volts}$$

$$E_s \propto B_{av}$$

Higher the value of B_{av}, increases the E_s which ~~into~~ inturn increases the short circuit current $\left[I_s = \frac{E_s}{X_s} \right]$

Therefore to limit the initial electromagnetic force under short circuits condition, a low value of gap density should be used.

iv) Stablity

The maximum power delivered by the synchronous machine is given by

$$P_{max} = \frac{3 E_{ph} V_{ph}}{X_{sph}}.$$

From the above equation, the maximum power is inversly proportional to its synchronous reactance.

If a high value of gap density is used, the flux per pole is large and therefore a smaller number of turns are required for the armature winding. This results in reduction in the value of synchronous reactance, which inturn increases the synchronising power.

Therefore the use of high gap density improves the steady state stablity limit.

v) Parallel operation.

For load sharing, the synchronous generators are connected in parallel with other synchronous generators. The statisfactory parallel operaton depends on the synchronising power $P_{max} = \frac{3 E_{ph} V_{ph}}{X_{sph}}$.

If a high value of Bav is used, results in reduction of synchronous reactance which in turn increases the synchronising power. Therefore the machine designed with high value of gap density have the satisfied parallel operation.

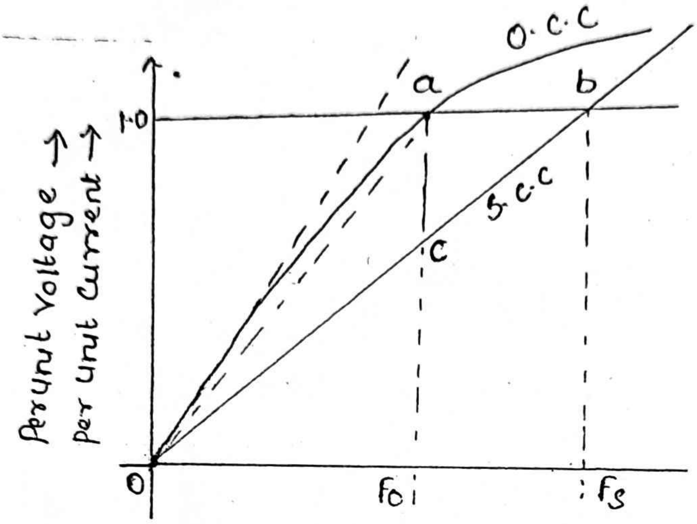
Therefore the typical values of Bav used in synchronous machines are

Salient pole machines - 0.52 to 0.65 wb/m^2

Turbo generators - 0.54 to 0.65 wb/m^2.

4) Short Circuit ratio

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



From the per unit diagram

$$SCR = \frac{OF_o}{OF_s} = \frac{cF_o}{bF_s} = \frac{cF_o}{aF_o} = \frac{1}{aF_o/cF_o}$$

$$= \frac{1}{\dfrac{\text{per unit voltage on open circuit}}{\text{Corresponding per unit current on short circuit}}}$$

$SCR = \frac{1}{X_d}$, Thus the Short circuit Ratio ~~is the~~ is the reciprocal of Synchronous reactance X_d.

The following are the typical values of SCR used in Synchronous Machines

Salient pole machines → 1.0 to 1.5

Turbo generators → 0.5 to 0.7.

Effects of SCR on machine performance

(i) Voltage Regulation

From the definition of SCR,

$$SCR = \frac{1}{\dfrac{\text{Per unit voltage on open circuit}}{\text{Corresponding per unit current on short circuit}}} \rightarrow (1)$$

$$SCR = \frac{1}{X_d} \rightarrow (2)$$

From eq (1), A low value of SCR, results a greater changes in voltage under fluctation of load. Therefore the voltage regulation of the machine is poor.

ii) Stablity

The maximum power delivered by the synchronous machine is given by

$$P_{max} = \frac{3 E_{ph} V_{ph}}{X_{sph}} \rightarrow (3)$$

From equation (2), the low of SCR , high value of synchronous reactance.

From Equatio (3), the high value of X_{sph} reduces the synchronising power.

Therefore the low value of SCR lower stablity limit.

iii) parallel operation

The Synchronising power required to keep the parallel operated machines is given by

$$P_{max} = \frac{3 E_{ph} V_{ph}}{X_{sph}}$$

A low of value of SCR increases the Sychronous reactance X_{sph} from equation ②.

This increased X_{sph} decreases the Synchronising power. There fore the low value of SCR gives un statisfactory parallel operation.

iv) Short circuit Current.

From equation ②, a low value of SCR means that the Synchronous reactance has a large value

The short circuit current is given by

$I_s = \frac{E_s}{X_{s1}}$, larger the value of X_s results in smaller the value of short circuit Current.

Therefore the small value of SCR limits the Short circuit Current.

iv) Self Excitation

Synchronous generator Connected with long transmission lines should not be designed with small SCR, because this small value of SCR lead to large voltages on open circuit produced by self excitation owing to large capacitive currents drawn by transmission lines.

---

5) Length of air gap.

The length of air gap greatly influences the performance of the synchronous machines. The reluctance of the airgap is given by

$$S = \frac{l_g}{\mu_0 A}$$

Increase in airgap length increases the reluctance produced by the armature mmf and reduces the effects of armature reaction. This results in a small value of Synchronous reactance and high value of SCR.

Thus the machine with a large air gap has

i) a small value of Regulation

ii) a higher value of stablity limit

iii) a higher synchronizing power which makes the machine less sensitive to load variations.

But increase in airgap length, needs a larger field mmf, resulting in increase of cost of the machine.

Stator design of Salient pole Machines

i) Main dimensions

The output Q in kVA = $1.11 \pi^2 D^2 L n B_{av} ac K_w \times 10^{-3}$ kVA

$$D^2L = \frac{Q \text{ in kVA}}{1.11 \pi^2 n B_{av} ac K_w \times 10^{-3}}$$

$$D^2L = \_\_\_\_ \; m^3$$

ii) Seperation of D and L from D^2L

In salient pole machines, the selection of D depends upon

a) the type of pole used

b) the permissible peripheral speed.

a) Type of pole used

i) Round poles → $\frac{L}{\tau} = 0.6$ to 0.7

ii) Rectangular poles → $\frac{L}{\tau} = 1$ to 5

b) The permissible peripheral speed

i) Bolted construction → 50 m/s

ii) Dove tailed and T head construction → 80 m/s.

The rotor should be designed to withstand centrifugal forces produced under runaway speeds.

iii) Stator design

a) Stator slot

i) $Y_s \leq 25mm$ for low voltage machines

$Y_s \leq 40mm$ for 6kV or low voltage machines

$Y_s \leq 60mm$ for machines upto 15 kV

ii) slots/pole/phase is usually between 2 to 4

b) Stator Conductors

$$E_{s_{ph}} = 4.44 f \phi T_{s_{ph}} k_{ws} \text{ Volts} \rightarrow (1)$$

$$T_{sph} = \frac{E_{sph}}{4.44 f \phi k_{ws}} \rightarrow (2),$$

where

$T_s \rightarrow$ stator turns/phase

$E_s \rightarrow$ stator vge/phase.

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

$$\boxed{Z_s = 6 T_{sph}}$$

For n number of parallel paths, the equation

(1) $\Rightarrow$

$$E_{sph} = 4.44 f \phi \frac{T_{sph}}{A} k_{ws} \text{ Volts}$$

$$T_{sph} = \frac{E_{sph} \times A}{4.44 f \phi k_{ws}}$$

$$\boxed{Z_s = 6 T_{sph}}$$

Check Cond/slot should be a integer or not, if it is not a integer means makes it a integer value.

$$Z_s(new) = Cond/slot \times slot$$

$$T_{s\,ph}(new) = \frac{Z_s(new)}{6}.$$

iv) Air gap length

$$AT_{fo} = AT_a \times SCR$$

where $AT_a = \frac{2.7 \times T_{sph} \times I_{sph} \times k_{ws}}{p}$

Let us assume that mmf required for the airgap is 80% of no load field mmf (AT_{fo})

$$8,00,000\, k_g l_g B_g = 80\% \text{ of } AT_{fo}$$

$$l_g = \frac{0.8 \times AT_{fo}}{8,00,000\, k_g B_g}$$

where B_g is calculated, by using the formula $k_f = \frac{\text{Pole arc}}{\text{pole pitch}} = \frac{B_{av}}{B_g}$.

(or)

$$l_g = \frac{0.8 \times AT_a \times SCR}{8,00,000\, k_g B_g}$$

Where $k_g \rightarrow$ gap contraction factor

$B_g \rightarrow$ maximum flux density

Determine the dimensions for a 1000 kVA, 50 Hz, 3ϕ 375 rpm alternator. The average airgap is 0·55 wb/m². and the ampere conductor per meter are 28000. Use rectangular poles and assume a suitable value for ratio core length to pole pitch in order that bolted pole construction is used, for which maximum permissible speed is 50 m/s. The runaway speed is 1·8 times the synchronous speed.

Given data

$Q = 1000$ kVA, $f = 50$ Hz, 3ϕ, $N = 375$ rpm,

$B_{av} = 0.55$ wb/m², $ac = 28000$, Rectangular pole,

V_a not exceed 50 m/s. The runaway speed is 1·8 times the synchronous speed.

To find

Main dimension.

Solution

The output Equation of synchronous machine is given by

$$\text{Output } Q \text{ in kVA} = 1.11\,\pi^2 D^2 L\, n\, B_{av}\, ac\, k_{ws} \times 10^{-3}, \text{ kVA}$$

$$D^2 L = \frac{\text{Output } Q \text{ in kVA}}{1.11\,\pi^2 n\, B_{av}\, ac\, k_{ws} \times 10^{-3}}$$

$$D^2L = \frac{1000}{1.11\,\pi^2 \times \left(\frac{375}{60}\right) \times 28{,}000 \times 0.55 \times 0.955 \times 10^{-3}}$$

$$D^2L = \underline{0.9931}\ m^3 \longrightarrow (1)$$

Given Rectangular poles.

For Rectangular poles $\frac{L}{\tau} = 1$ to 5

i) When $\frac{L}{\tau} = 1$

$$L = \tau$$

$$L = \frac{\pi D}{P} \longrightarrow (2)$$

We know that $N = \frac{120f}{P}$

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

$$P = \frac{120 \times 50}{375} = 16$$

From Equation (2)

$$L = \frac{\pi D}{16}$$

$$L = \underline{0.1963}\ D \rightarrow (3)$$

From Equation (1)

$$D^2 \times 0.1963\ D = 0.9931$$

$$D^3 = \frac{0.9931}{0.1963}$$

$D^3 = 5.0591$

$$\boxed{D = 1.7167,\ m}$$

From equation (B)

$L = 0.1963 \times 1.7167$

$$\boxed{L = 0.3370,\ m}$$

Check for peripheral speed and runaway peripheral speed

Peripheral speed $V_a = \pi D n$

$= \pi \times 1.7167 \times \left(\frac{375}{60}\right)$

$= \underline{33.7073}\ m/s$

$n = \frac{N}{60}$
$= \frac{375}{60}$

Runaway peripheral speed $= 1.8 \times V_a$

$= 1.8 \times 33.7073$

Runaway peripheral speed $= \underline{60.6732}\ m/s$

The Runaway peripheral speed exceeds the maximum perimissible speed 50 m/s. Then select $\frac{L}{\tau} = 2$

$L = 2\tau$

$L = \frac{2\pi D}{P}$

$$L = \frac{2\pi D}{P}$$

$$L = 0.3927\,D \rightarrow (4)$$

From Equation (1)

$$D^2 \times 0.3927D = 0.9931$$

$$D^3 = \frac{0.9931}{0.3927} = 2.5289$$

$$\boxed{D = 1.3624,\ m}$$

From Equation (4)

$$L = 0.3927 \times 1.3624$$

$$\boxed{L = 0.535,\ m}$$

Check for peripheral speed and runaway peripheral speed

Peripheral speed $V_a = \pi D n$

$$= \pi \times 1.3624 \times \left(\frac{375}{60}\right)$$

$$= \underline{26.7507}\ m/s$$

Run away peripheral speed $= 1.8 \times V_a$

$$= \underline{48.1513},\ m/s$$

The runaway peripheral speed is within the permissible speed 50 m/s.

Answers

$D = \underline{1.3624}$, m

$L = \underline{0.535}$, m

Find the main dimensions of a 2500 kVA, 187·5 rpm, 50 Hz, 3 phase, 3 kV, Salient pole Synchronous generator. The generator is to vertical, water wheel type. The Specific magnetic loading is 0·6 wb/m^2 and the Specific electric loading is 34000 A/m. use circular poles with ratio of core length to pole pitch = 0·65. Specify the type of pole Construction used if the runaway Speed is about 2 times the normal Speed.

Given data

Q_r = 2500 kVA, N = 187·5 rpm, 50 Hz, 3ϕ, ~~3 kV~~
V_L = 3 kV = 3000 Volt, Salient type gnr., B_{av} = 0·6 wb/m^2, ac = 34000 A/m, Circular poles, $\frac{L}{\tau}$ = 0·65.
Runaway Speed = 2 times the Normal Speed.

To find

Main dimensions.

Solution

The output Equation of Synchronous machine is

$$\text{Output } Q_r \text{ in kVA} = 1{\cdot}11\,\pi^2 D^2 L n\, B_{av}\, ac\, k_{ws} \times 10^{-3}, \text{ kVA}$$

$$D^2L = \frac{\text{Output } Q_r \text{ in kVA}}{1{\cdot}11\,\pi^2\, B_{av}\, ac\, k_{ws} \times 10^{-3}}$$

$$D^2L = \frac{2500}{1.11 \times \pi^2 \times \frac{187.5}{60} \times 0.06 \times 34000 \times 0.955 \times 10^{-3}}$$

$$D^2L = \underline{\underline{3.7483}}, m^3 \rightarrow (1)$$

Given circular poles and $\frac{L}{\tau} = 0.65$

$\therefore L = 0.65 \tau$

$L = 0.65 \times \frac{\pi D}{P}$

$L = \frac{0.65 \times \pi D}{32}$

$L = 0.0638 D \rightarrow (2)$

$N = \frac{120 f}{P}$

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

$P = \frac{120 \times 50}{187.5}$

$\boxed{P = 32}$

From Equation (1)

$D^2 (0.0638) = 3.7483$

$D^2 = \frac{3.7483}{0.0638}$

$D^2 = 58.7508$

$\boxed{D = 3.8875, m}$

From Equation (2)

$L = 0.0638 \times 3.8875$

$\boxed{L = 0.2480, m}$

Check for peripheral Speed and runaway peripheral Speed

$$\text{peripheral Speed } V_a = \pi D n$$

$$= \pi \times 3.8875 \times \left(\frac{187.5}{60}\right)$$

$$= \underline{38.1654}, m/s$$

$$\text{Runaway peripherial} = 2 \times V_a \quad \text{(Given)}$$

$$= 2 \times 38.1654$$

$$= 76.3309, m/s$$

For this Runaway peripherial speed, Dove tailed type of pole construction is used.

Answers

$D = \underline{3.8875}, m$

$L = \underline{0.2480}, m$

Pole Conconstruction is Dove tailed

Find the main dimensions of a 100 MVA, 11 kV, 50 Hz, 150 rpm, 3ϕ, water wheel generator. The average gap density is 0.65 wb/m² and ampere conductor per meter are 40,000. The peripheral speed should not exceed 65 m/s at normal running speed inorder to limit the runaway peripheral speed.

Given data

$$= 100 \times 10^3 \text{ KVA}$$

$Q = 100$ MVA, $V = 11$ kV, $f = 50$ Hz, $N = 150$ rpm, 3ϕ,

$B_{av} = 0.65$ wb/m², $ac = 40{,}000$, V_a not exceed 65 m/s.. Run away speed = normal running speed

To find

Main dimensions.

Solution

The output Equation of Synchronous machine is

$$\text{Output } Q \text{ in kVA} = 1.11 \pi^2 D^2 L n B_{av}\, ac \times k_{ws} \times 10^{-3} \text{ kVA}$$

$$D^2L = \frac{\text{Output } Q \text{ in kVA}}{1.11 \pi^2 n B_{av}\, ac\, k_{ws} \times 10^{-3}}$$

$$D^2L = \frac{100 \times 10^3}{1.11 \times \pi^2 \times \left(\frac{150}{60}\right) \times 0.65 \times 40{,}000 \times 0.955 \times 10^{-3}}$$

$$D^2L = 147.0485 \text{ m}^3 \rightarrow (1)$$

$\frac{L}{\tau}$ is choosen based on type of pole used in Construction. Here type of pole construction is not Specified. Hence we Check for circular pole and Rectangular poles.

a, For circular poles, $\frac{L}{\tau} = 0.6$ to 0.7

i) when $\frac{L}{\tau} = 0.6$

$$L = 0.6\tau$$

$$L = 0.6 \frac{\pi D}{P}$$

$$L = 0.6 \times \frac{\pi D}{40}$$

$$L = \underline{0.0471}\ D$$

$$N = \frac{120f}{P}$$

$$P = \frac{120f}{N}$$

$$P = \frac{120 \times 50}{150}$$

$$P = 40$$

From Equation ①

$$D^2 \times 0.0471 D = 147.0485$$

$$D = \underline{14.6155}, m$$

$$L = \underline{0.6884}, m$$

peripheral speed $V_a = \pi D n$

$$V_a = \pi \times 14.6155 \times \left(\frac{150}{60}\right)$$

$$= \underline{114.7899}\ m/s$$

This peripheral speed exceeds the limit.

ii) when $\frac{L}{\tau} = 0.7$

$$L = 0.7\tau$$

$$L = 0.7 \frac{\pi D}{P}$$

$$L = 0.7 \frac{\pi D}{40}$$

$$L = 0.0550\, D$$

From Equation (1)

$$D^2 \times 0.0550\, D = 147.0485$$

$$D = \underline{\underline{13.8811}}, \; m$$

$$L = \underline{\underline{0.7635}}, \; m.$$

Peripheral Speed $V_a = \pi D n$

$$V_a = \pi \times 13.8811 \times \left(\frac{150}{60}\right)$$

$$= \underline{\underline{109.0219}}, \; m/s.$$

This peripheral speed also exceeds the limit. Therefore we try it for Rectangular poles.

b, For Rectangular Poles, $\frac{L}{\tau} = 1$ to 5

i) When $\frac{L}{\tau} = 1$

$$L = \tau$$

$$L = \frac{\pi D}{P}$$

$$L = \frac{\pi D}{40}$$

$$L = 0.0785\, D$$

From Equation (1)

$$D^2 \times 0.0785D = 147.0485$$

$$D = \underline{12.3251}, m$$

$$L = \underline{0.9675}, m$$

Peripheral Speed $V_a = \pi D n$

$$V_a = \pi \times 12.3251 \times \left(\frac{150}{60}\right)$$

$$V_a = \underline{96.8011}, m/s$$

This peripheral speed exceeds the limit

ii) $\frac{L}{\tau} = 2$

$$L = 2\tau$$

$$L = \frac{2\pi D}{P}$$

$$L = \frac{2\pi D}{40}$$

$$L = 0.1571\ D$$

From Equation (1)

$$D^2 \times 0.1571\ D = 147.0485$$

$$D = \underline{9.7824}, m$$

$$L = \underline{1.5368}, m$$

Pasi

Peripheral speed $V_a = \pi D n$

$$= \pi \times 9.7824 \times \left(\frac{150}{60}\right)$$

$$= \underline{76.8308} \text{ m/s}$$

This peripheral speed exceeds the limit.

ii) $\frac{L}{\tau} = 3$

$$L = 3\tau$$

$$L = 3 \frac{\pi D}{P}$$

$$L = \frac{3 \times \pi D}{40}$$

$$L = 0.2356\, D$$

From Equation ①

$$D^2 \times 0.2356 D = 147.0485$$

$$D = \underline{8.5457}, \text{ m}$$

$$L = \underline{2.0134} \text{ m}$$

Peripheral speed $V_a = \pi D n$

$$= \pi \times 8.5457 \times \left(\frac{150}{60}\right)$$

$$= \underline{67.1178} \text{ m/s}$$

This peripheral speed also exceeds the limit.

iv) $\frac{L}{\tau} = 4$

$$L = 4\tau$$

$$L = 4 \frac{\pi D}{P}$$

$L = 0.3142\ D$

From Equation (1)

$$D^2 \times 0.3142 D = 147.0485$$

$$D = \underline{7.7643}\ ,\ m$$

$$L = \underline{2.4396}\ ,\ m$$

Peripheral Speed $V_a = \pi D n$

$$= \pi \times 7.7643 \times \left(\frac{150}{60}\right)$$

$$= \underline{60.9807}\ ,\ m/s$$

This peripheral speed lies within the limit. Therefore we choose

$$D = \underline{7.7643}\ ,\ m$$

$L = \underline{2.4396}\ ,\ m$ and type of pole used is Rectangular pole with T head or Dove tailed construction.

Design of Rotor of Salient pole Machine

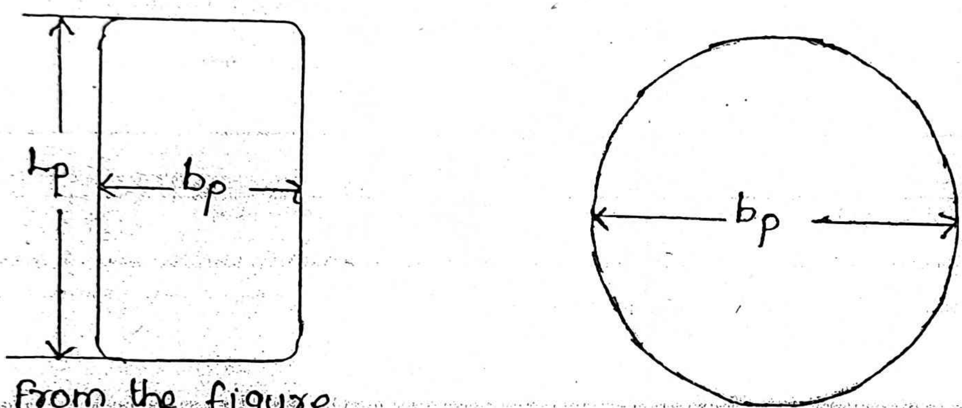
a) Design of Salient pole

i) Area of Cross section of pole

Area of Cross-Section of pole body $A_p = \frac{\phi_p}{B_p}$

Flux in the pole body ϕ_p = leakage Coefficient x useful flux/pole,

$$\phi_p = C_l \times \phi$$



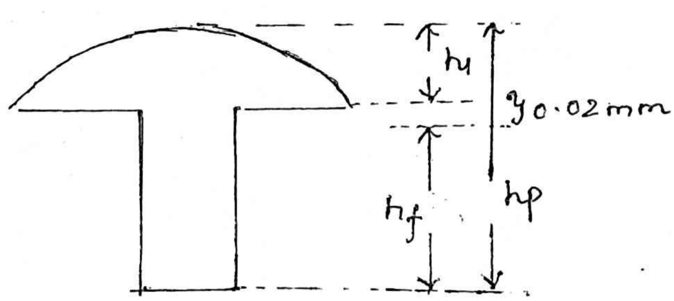
From the figure

$A_p = 0.98\, L_p b_p$ for rectangular poles.

$A_p = \left(\frac{\pi}{4}\right) b_p^2$ for Circular poles.

L_p is taken equal to gross ~~Stacking~~ Stator Core length L.

ii) Height of pole.



where $h_1 \rightarrow$ height of pole shoe

$h_2 \rightarrow$ height taken by flanges usually about 20 mm

$h_f \rightarrow$ height of field wdg

Height of the pole = $h_1 + 0.02 + h_f$

Height of the pole shoe (h_1) is determined from pole profile drawing

Estimation of height of the field wdg.

MMF / metre height of field winding = $10^4 \sqrt{S_f d_f q_f}$

$$\frac{AT_{fl}}{h_f} = 10^4 \sqrt{S_f d_f q_f}$$

Height of the field wdg $h_f = \dfrac{AT_{fl}}{10^4 \sqrt{S_f d_f q_f}}$

where $AT_{fl} \rightarrow$ full load field mmf

$S_f \rightarrow$ Copper space factor,

$q_f \rightarrow$ loss per unit surface, W/m^2

$d_f \rightarrow$ depth of the field wdg

$q_f = \lambda \theta = \frac{1}{c} \theta$.

where c is the cooling coefficients for rotating coils

$$c = \frac{0.08 \text{ to } 0.12}{1 + 0.1 V_a}$$

$$q_f = \left(\frac{1 + 0.1 V_a}{0.08 \text{ to } 0.12} \right) \theta \ W/m^2$$

An approximate estimation of full load field mmf can be made by the method given below.

No load field mmf AT_{fo} = SCR × AT_a

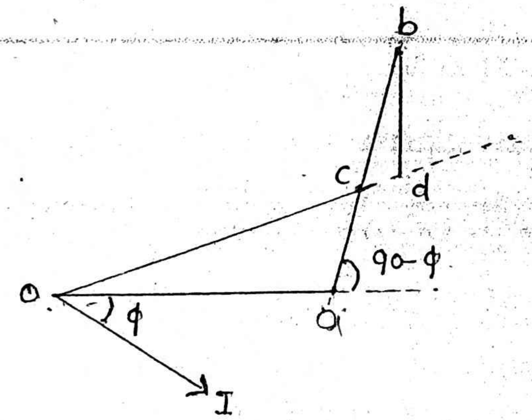
where AT_a (armature mmf/pole) = $\frac{2.7 T_s I_s k_{ws}}{P}$

i) Draw oa = AT_{fo}

ii) Draw ab = AT_a at angle $(90-\phi)$ to oa,

iii) Cut off ac such that $\frac{ac}{ab} = K$, where k_r is called the cross reaction coefficient which depends upon the ratio pole arc to pole pitch

iv) Join oc and extend it. Drop a perpendicular from b on oc extended, cutting it at d.



From the phasor diagram

od = field mmf at full load (AT_{fd}) with power factor $\cos\phi$ (lagging).

b) Design of field winding.

The following procedures are followed to design the field winding

i. The field winding should be designed for a voltage from 15 to 20 percent less than the exciter voltage.

$$\text{Voltage across the field coil}(E_f) = \frac{(0.8 \text{ to } 0.85) V_e}{P} \rightarrow (1)$$

2. Determine the height of field winding from the equation $h_p = h_y + 0.02 + h_f$

$$h_f = h_p - h_y - 0.02; \; m \rightarrow (2)$$

3. Assume suitable depth of the field winding from below table

Pole pitch (mm)	winding depth (mm)
0.1	25
0.2	35
0.4	45

4) Voltage across the field coil

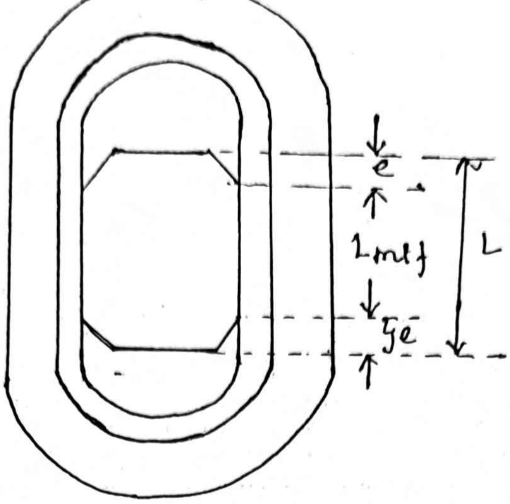
$$E_f = I_f R_f = \frac{I_f T_f \rho L_{mtf}}{a_f}$$

$$a_f = \frac{I_f T_f \rho L_{mtf}}{E_f} = \frac{AT_{fl} \rho L_{mtf}}{E_f} \rightarrow (3)$$

where $I_f T_f = AT_{fl}$ is the full load field mmf.

Lmtf → Length of mean turn of field winding.

This can be determined from the below figure



$$L_{mtf} = 2L_m + \pi(b_p + 0.01 + d_f)$$

$L_m = 0.9L$ and $e = 0.05L$

5, Determine the field current I_f by assuming the current density δ_f is 3 to 4 A/mm²

$$I_f = \delta_f \times a_f \rightarrow (4)$$

6, Determine the field turns T_f from AT_{fl}

$$AT_{fl} = I_f T_f$$

$$T_f = \frac{AT_{fl}}{I_f} \rightarrow (5)$$

7, Check the winding space, whether it is possible to accommodate the field turns or not. In case the winding space available is less, increase the depth and if the space is more, decrease the depth till the winding fits in

viii) The resistance of the winding is calculated by

$$R_f = \frac{T_f \rho L_{mtf}}{a_f} \rightarrow (5)$$

Copper loss in each field coil at 75°C, $Q_f = I_f^2 R_f$

$$Q_f = \frac{I_f^2 T_f \rho L_{mtf}}{a_f} \rightarrow (6)$$

This loss is to be dissipated by the field coil and therefore we must check that the temperature rise is within the limits

Dissipating surface of the coil is $(S) = 2 L_{mtf}(h_f + d_f) \rightarrow 7$

Cooling coefficient to rotating field coils $(C_f) = \frac{0.08 \text{ to } 0.12}{1 + 0.1 V_a}$

$\therefore$ Temperature rise $\theta = \frac{Q_f C_f}{S} \rightarrow 8$

If the temperature rise of the coil exceeds the limits, increase the depth of field winding. The increase of depth of field winding increases the heat dissipating surface of the coil from equation (7). and decrease the temperature rise from equation (8)

c) Design of damper winding

The design of damper winding depends upon the purpose for which it is provided.

In Synchronous generators, It is provided to supress the negative sequence field and to damp the oscillations when the machine starts hunting

In Synchronous motor, its function is to provide starting torque and to develop damping power when the machine starts hunting.

The design of damper winding to suppress the inverse rotating field follows the below procedures.

The amplitude of fundamental of mmf AT_1 of one phas of a polyphase winding is obtained by the equation

$$AT_1 = \frac{4}{\pi} AT_m k_{w1} \rightarrow (1)$$

$$\text{Where } AT_m = q Z_{ss} \frac{I_{sph}}{\sqrt{2}} \rightarrow (2)$$

$q \Rightarrow$ Slots / pole / phase

$Z_{ss} \Rightarrow$ Stator Conductors / Slot

$I_s \Rightarrow$ Stator Current / phase.

$$Z_{ss} = \frac{Z_s}{S} = \frac{Z_s}{q \times pole \times phases} = \frac{Z_s}{3qp}$$

from ②

$$AT_m = q \cdot \frac{Z_s}{3qP} \times \frac{I_{sph}}{\sqrt{2}}$$

$$AT_m = q \cdot \frac{6T_{sph}}{3qP} \times \frac{I_{sph}}{\sqrt{2}}$$

$$= \frac{2T_{sph}}{P} \times \frac{I_{sph}}{\sqrt{2}}$$

$$AT_m = \sqrt{2}\,\frac{T_{sph} \cdot I_{sph}}{P}$$

from Equation ①

$$AT_1 = \frac{4}{\pi}\,\frac{\sqrt{2}\,T_{sph} I_{sph} k_{w_1}}{P} \rightarrow ③$$

This pulsating mmf is resolved into two rotating mmfs, one called the synchronous mmf and the other Inverse mmf each having half the magnitude as above. If the damper winding is to suppress the inverse rotating field, it must develop an equal mmf as that of the Inverse field.

$$\text{mmf of damper winding} = \frac{4\sqrt{2}}{2\pi}\,\frac{T_{sph} I_{sph}}{P}\,k_{w_1} \rightarrow ④$$

$$\text{Ampere conductor / pole} = \frac{I_{sph} Z_s}{P} = \frac{ac\pi D}{P} = ac\,\tau \rightarrow ⑤$$

Also

$$\text{Amper conductor / pole} = \frac{I_{sph} Z_s}{P} = \frac{6T_{sph} I_{sph}}{p} \rightarrow ⑥$$

Equating the equations (5) and (6)

$$ac\tau = \frac{6 I_{sph} T_{sph}}{P}$$

$$\frac{T_{sph} I_{sph}}{P} = \frac{ac\tau}{6}$$

Equation (4) $\Rightarrow$

mmf for damper winding $= \frac{4\sqrt{2}}{2\pi} \times \frac{ac\tau}{6} k_{w1}$

$$= 0.15\ ac\tau$$

Let Ad be the total area of damper bar/pole and δ_d be the current density in the bars

Mmf for damper winding $= A_d \delta_d = 0.15\ ac\tau$

$$A_d = \frac{0.15\ ac\tau}{\delta_d}$$

In practice, the area provided for damper winding is greater than the area required. Therefore

$$A_d = \frac{0.2\ ac\tau}{\delta_d}$$

The current density in the damper bars is usually taken as 3 to 4 A/mm^2.

In order to reduce the current induced in damper windings by tooth ripples, the damper winding pitch is about 20% less than stator slot pitch

$$\frac{\text{pole arc}}{\text{no. of bars/pole}} = 0.8 \times Y_{ss}$$

$$\text{No. of damper bars/pole } (N_d) = \frac{\text{Pole arc}}{0.8 \times Y_{ss}}$$

Cross section of each damper bar (a_d) :

$$a_d = \frac{\text{total area of bars / pole}}{\text{number of damper bars/pole}} = \frac{A_d}{N_d}.$$

The length of each damper bar L_d is given by

$$L_d = 1.1 L \text{ for small machines}$$

$$= L + 0.1 m \text{ for large machines.}$$

The diameter of each damper bar d_d is given by

$$a_d = \frac{\pi}{4} d_d^2 \text{ for circular bar}$$

$$d_d = \sqrt{\frac{a_d}{\pi/4}}$$

A 1250 kVA, 3ϕ, 60 Hz, 6600V, salient pole alternator has the following data.

Air gap diameter = 1.6m, length of Core = 0.45m, No of poles = 20, armature ampere conductors per meter = 28,000, ratio of pole arc to pole pitch = 0.68. Stator slot pitch = 28 mm, current density in damper bars = 3 A/mm^2. Design a suitable damper winding for the machine.

Given data

$Q = 1250$ kVA, 3ϕ, $60\,Hz$ (f), $E_L = 6600V$, Salient pole

$D = 1.6m$, $L = 0.45\,m$, $P = 20$, $ac = 28,000$, $\frac{\text{Pole arc}}{\text{Pole pitch}} = 0.68$

$Y_{ss} = 28\,mm$, $\delta = 3\ A/mm^2$

To find

Design of damper winding.

Solution

i) Area of the damper bar / pole

$$A_d = \frac{0.2\ ac\ \tau}{\delta}$$

$$A_d = \frac{0.2 \times ac \times (\pi D/P)}{\delta}$$

$$A_d = \frac{0.2 \times 28,000 \times \left(\frac{\pi \times 1.6}{20}\right)}{3}$$

$$\boxed{A_d = 469.1445 \text{ , } mm^2}$$

ii) No. of damper bar/pole

No. of damper bar/pole = $\dfrac{\text{Pole arc}}{0.8 \times Y_{ss}}$ → ①

Given, $\dfrac{\text{pole arc}}{\text{pole pitch}} = 0.68$

Pole arc $= 0.68 \times$ pole pitch

$= 0.68 \times \dfrac{\pi D}{P}$

$= 0.68 \times \dfrac{\pi \times 1.6}{20}$

Pole arc $= 0.1709$, m

Y_{ss} → Stator slot pitch $= 28$ mm $= 28 \times 10^{-3}$ m

From Equation ①

No. of damper bar/pole $= \dfrac{0.1709}{0.8 \times 28 \times 10^{-3}}$

$= 7.6296$

$\boxed{\text{No. of damper bar/pole} \simeq 8}$

ii) Area of each damper bar

$a_d = \dfrac{A_d}{n_d}$

$a_d = \dfrac{469.1445}{8}$

$$\boxed{a_d = 58.6431 \ mm^2}$$

iv) Length of damper bar

For large machine, $L_d = L + 0.1$, m

$$L_d = 0.45 + 0.1$$

$$\boxed{L_d = 0.55, \ m}$$

v) Diameter of damper bar

$$a_d = \frac{\pi d_d^2}{4}$$

$$d_d^2 = \frac{4 a_d}{\pi}$$

$$d_d^2 = \frac{4 \times 58.6431}{\pi}$$

$$d_d^2 = 74.6667$$

$$\boxed{d_d = 8.6410, \ mm}$$

Design of turbo alternators

a) Main dimensions.

The output Q in kVA = $1.11 \pi^2 D^2 L n B_{av} ac\, k_w \times 10^{-3}$

$$D^2 L = \frac{Q \text{ in kVA}}{1.11 \pi^2 n B_{av}\, ac\, k_w \times 10^{-3}} \rightarrow ①$$

where $k_w = k_c \times k_d$

$k_c \rightarrow$ pitch factor $= \cos\left(\frac{\alpha}{2}\right)$

where α is the angle by which coils are short Chorded.

$k_d \rightarrow$ distribution factor $= \dfrac{\sin\left(\frac{m\beta}{2}\right)}{m \sin\left(\frac{\beta}{2}\right)}$

$m\beta$ = phase spread

$\beta \rightarrow$ slot angle $= \dfrac{180°}{n}$

$n \rightarrow$ slot/pole.

$m \rightarrow$ slot/pole/phase.

After substituting the values in equation ①

we get $D^2 L =$ ____ m^3.

In turbo generators D is limited by peripheral speed. ~~The~~ For Normal designs a peripheral speed of about 120 m/s is used. The maximum peripheral speed is .

b) Stator design.

i) Stator slot

i) The slot pitch is normally about 25 to 60 mm but in the case of large turbo alternators it may even be 75 to 90 mm.

ii) number of slot/pole/phase is usually b/w 2 to 4. but in the case of large turbo-alternators 8 or 9 slots per pole per phas may be used.

ii) Stator Conductors.

$$E_{sph} = 4.44 f \phi T_{s_{ph}} k_{ws} \text{ volts} \rightarrow (1)$$

$$T_{sph} = \frac{E_{sph}}{4.44 f \phi k_{ws}} \rightarrow (2)$$

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

$$\boxed{Z_s = 6 T_{sph}}$$

For n number of parallel paths, the equation (1) is modified as

$$E_s = 4.44 f \phi \frac{T_{sph}}{A} k_{ws} \text{ Volts}$$

$$T_{sph} = \frac{E_{sph} \times A}{4.44 f \phi k_{ws}}$$

$$Z_s = 6 T_{sph}$$

Check Cond/slot should be a integer or not. If it is not a integer means makes it a integer value

$$Z_{s(new)} = \text{Cond/slot} \times \text{Slot}$$

$$T_{s(new)ph} = \frac{Z_{s(new)}}{6.}$$

c) Length of air gap

$$AT_{fo} = AT_a \times SCR$$

where armature mmf/pole $(AT_a) = \frac{2.7\, T_s\, I_s\, k_{ws}}{P}$

or

armature mmf/pole $(AT_a) = \frac{ac\tau}{2.}$

[We seen that ampere conductor per pole $= \frac{I_z Z_s}{P} = ac\tau$

$\therefore$ ampere turns per pole $= \frac{ac\tau}{2}$]

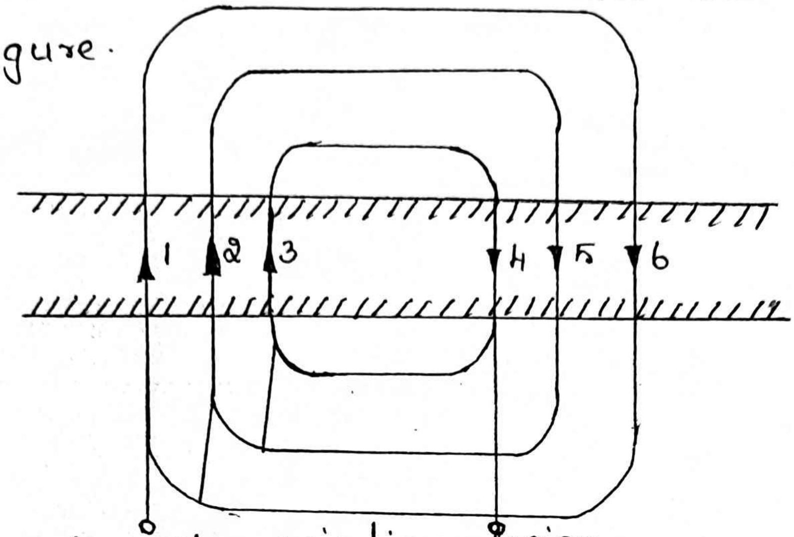
Let us assume that mmf required for the airgap is 80% of no load field mmf

$$8{,}00{,}000\, B_g l_g k_g = 0.8 \times \frac{ac\tau}{2} \times SCR$$

$$l_g = \frac{0.8 \times ac\tau \times SCR}{8{,}00{,}000\, B_g k_g \times 2}$$

d) Rotor design

The rotor winding is not concentrated but is distributed in slots. Concentric multi turn coils are used as shown in below figure.



procedure for rotor winding design.

i) Full load field mmf can be taken as twice the armature mmf

$$AT_{fl} = 2\,AT_a \quad \rightarrow (1)$$

$$\text{where } AT_a = \frac{2.7\, T_s\, I_s\, k_{ws}}{P} \quad \text{or} \quad \frac{ac\,\tau}{2}$$

ii) The field winding should be designed for a voltage from 15 to 20 percent less than the exciter voltage.

$$\text{Voltage across the field coil } (E_f) = \frac{(0.8 \text{ to } 0.85)\, V_e}{P} \quad \rightarrow (2)$$

iii) Determine the length of mean turn of field winding

$$L_{mtf} = 2L + 2.3\tau + 0.24$$

$\tau \rightarrow$ effective span of coils.

iv) Voltage across each field coil $E_f = I_f\, R_f$

$$E_f = \frac{I_f T_f \rho L_{mtf}}{a_f} = \frac{AT_{fl} \rho L_{mtf}}{a_f}$$

$$a_f = \frac{AT_{fl} \rho L_{mtf}}{E_f}$$

a_f = area of field conductor, mm^2

L_{mtf} = length of mean turn, m;

ρ = resistivity, Ω/m and mm^2.