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ASPIRE TO EXCEL

ISO 21001

ELECTRICAL MACHINE DESIGN

EE T64 ELECTRICAL MACHINE DESIGN

Objective: The objective of the course is to understand the design considerations of static and rotating electrical machines. The course refreshes the construction details of transformers DC and AC machines. Therefrom discusses the various design aspects of both DC and AC rotating electricalmachines.

Outcome: The students will be able to design various electrical machines like DC machines, transformers, induction motors and alternators according to the industrial requirements.

UNIT I: FUNDAMENTALS OF DESIGN
Rating and dimensions Temperature rise heating and cooling curves rating of electricmachines – insulation requirements-insulation materials MMF for air-gap-Net iron length - MMF for Iron – MMF for teeth-Real and Apparent flux densities - Leakage flux

UNIT II: DESIGN OF DC MACHINES
Magnetic circuit calculations-Output equation-Main Dimensions-Choice of specific electric and magnetic loadings-Selectionof Number of Poles Armature design-Design of shuntfield coil- Design of commutator and brushes.

UNIT III: DESIGN OF TRANSFORMERS
OutputEquations of Single phase and three phase transformer-Main Dimensions- KVA output for single and three phase transformers-Window space factor-Overall dimensions-Determination of number of turns and length of mean turns of windings-Resistance of windings- No load current calculation.

UNIT IV: DESIGN OF THREE PHASE INDUCTION MOTOR
Outputequation of Induction motor-Main dimensions-Length of air gap- Design of squirrel cage rotor-Rules for selecting rotor slots of squirrel cage machines-Design of rotorbars & slots-Design of end rings-Design of wound rotor

UNIT V: DESIGN OF SYNCHRONOUS MACHINES AND COMPUTER AIDED DESIGN
Outputequations-choice of loadings-Design of salient pole machines-Design of stator-Design of rotor-Design of damper winding-Design of turbo alternators-introduction to CAD- Benefits- Flowchart methods.

UNIT 1
FUNDAMENTALS OF DESIGN

Principles of Electrical Machine Design

Introduction:- Design may be defined as a Creative Physical realization of theoretical concepts.

Engineering design is application of science, technology and invention to produce machines to perform specified tasks with optimum economy and Efficiency.

The major considerations to evolve a good design are:

(i) lower cost
(ii) Durability
(iii) Lower weight
(iv) Reduced Size
(v) Better operating performance

It is impossible to design a machine which is cheap and is also durable at the same time. This is because a machine which is to have a long life span must use high quality materials and advanced manufacturing technique which obviously make it costly. However, a compromise between cost and durability can be had. A good design is one where the machine has reasonable operating life (between 20 to 30 years) and has a low initial cost.

A electrical designer must be familiar with the.

a) National and International standards

* Indian standard (IS)
* Bureau of Indian standard (BIS), India.
* British Standard (BS), England.
* International Electrotechnical Commission (IEC)
* NEMA (The National Electrical Manufacturers Association),

b. Specifications (deals with machine ratings, Performance requirem etc, of the consumer)

c. Cost of material and labour

d. Manufacturing constraints etc.

Factors for consideration in electrical machine design:-

The basic components of all electromagnetic apparatu are the field and armature windings supported by dielectric & insulation, cooling system and mechanical parts. Therefore, the factors for consideration in the design are,

1. Magnetic circuit (Flux path):- It provides the path for the magn flux using minimum MMF. The core losses should be less.

2. Electric circuit (windings):- It consists of stator and rotor windings. The copper losses should be less.

3. Dielectric circuit (insulation):- The dielectric circuit consists of insulation required to isolate one conductor from another and also the windings from the core.

4. Thermal circuit:- cooling system or ventilation. The thermal circuit is concerned with mode & media for dissipation of heat produced inside the machine on account of losses.

5. Mechanical Parts:- Should be robust. The important mechanic parts of a machine are its frame, bearings and shaft.

Limitations in Design:-

Apart from availability of suitable materials, facilities available for manufacture of required machine parts and facilities required for transportation, The following considerations impose limitation on design :

1. **Saturation**:- Higher flux density reduces the volume of iron but drives the iron to operate beyond knee of the magnetization curve or in the region of saturation. Saturation of iron poses a limitation on account of increased core loss and excessive excitation required to establish a desired value of flux. It also introduces harmonics resulting in higher cost for the field system.

2. **Current density**. Higher current density reduces the volume of copper but increases the losses and temperature.

3. **Temperature rise**:- The life of insulating material is operated beyond the maximum allowable temperature, its life is drastically reduced. Proper cooling & ventilation techniques are required to keep the temperature rise with in the safe limits.

4. **Insulation**:- The insulating materials used in a machine should be able to withstand the electrical, mechanical and thermal stresses which are produced in the machine.
The type of insulation is decided by the maximum operating temperature of the machine parts.
The size of insulation is decided by the both maximum voltage stresses and mechanical stresses produced.

5. **Mechanical Parts**:- The design of mechanical parts is important in high speed machines. In large machines, the size of the shaft is decided by considering the critical speed which depends on the deflection of the shaft.
Bearings are subjected to the action of rotor weight, external load

unbalanced rotor forces & unbalanced magnetic pull.

6. Commutation: The problem of commutation is important in the case of commutator machines as commutation conditions limit the maximum output that can be taken from a machine.

7. Powerfactor & Efficiency: High efficiency and high p.f. Poses a limitation on account of higher capital cost on the other hand (A low value of efficiency & p.f. results in a high maintenance cost).

8. Consumer & standard specifications: Apart from the above factors, consumer, manufacturer or standard specifications ~~limited~~ may poses a limitation.

General Design Procedure:-

1) Based on the given specification of the machine, choose proper materials - conducting, insulating and magnetic. For the proper choice of these materials, the designer should be conversant with the properties, availability and cost of the materials.

2) Basic design parameters such as specific magnetic loading (Bav), specific electric loading (q). etc is then assumed suitably, keeping in view the advantage and disadvantages of higher values of specific loadings.

4) Design procedure is initiated for various circuits of the machine. Performance of the machine under noload and load conditions is predetermined from the calculation the values of total losses & the cooling system adopted.

3) Design procedure is initiated for the calculation of various dimensions of magnetic and electric circuits, using various design equations developed.

5) Calculated performance of the machine is compared with the limiting performance values or customer's requirement. If the performance is not satisfactory, the designer has to modify the basic assumptions of design parameters so as to bring the final design closer to the objective.

Electrical Engineering Materials:

It is broadly classified as

1) conducting materials
2) Magnetic materials
3) Insulating materials.

Conducting materials:

1. High conductivity materials :- used for all types of windings.
2. High Resistivity materials :- used for making heating devices

Properties of High conductivity materials:

1. Highest conductivity or least resistivity.
2. Low value of temperature co-efficient of resistance.
3. High resistance to corrosion
4. Adequate mechanical strength and high tensile strength.
5. High melting point.
6. Good weldability and solderability so that the joints are reliable
7. Highly malleable and ductile
8. Durable and cheap by cost.

Some of the Properties of copper and aluminium are

Sl. No	Characteristics.	Copper	Aluminium
1	Resistivity at 20°C	$0.0172 \times 10^{-6}\ \Omega m$	$0.0287 \times 10^{-6}\ \Omega m$
2	Conductivity at 20°C	58.14×10^{6} S/m	37.2×10^{6} S/m
3.	Density at 20°C	$8933\ kg/m^3$	$2689.9\ kg/m^3$
4.	Melting Point	1083°C	660°C
5.	Tensile strength	25 to 40 kg/mm^2	10 to 18 kg/mm^2
6.	Co-efficient of Linear Expansion (0 - 100°)	16.8×10^{-6} per °C	23.5×10^{-6} per °C
7.	Cost	high	comparatively less
8.	Thermal conductivity	350 W/m·°C	200 W/m·°C
9.	Mechanical Property	high Malleable & ductile	not highly malleable and ductile.
10	Jointing	canbe easily soldered	cannot be soldered easily.

For the same resistance and length, cross sectional area of aluminium is 61% larger than that of the copper conductor and almost 50% lighter than copper.

Magnetic Materials:

All magnetic materials possess magnetic properties of materials are characterized by their relative permeability.

Magnetic materials can be classified as

1) Ferromagnetic Materials: Relative permeability of these material much greater than unity.

2) Paramagnetic materials: Relative permeability is slightly greater than unity.

3) Diamagnetic materials: Relative permeability is slightly less than unity.

only Ferromagnetic materials have properties that are well suitable for Electrical machines.

Ferromagnetic properties are confined almost entirely to iron, nickel and cobalt and their alloys.

Further the Ferromagnetic materials can be classified as

1). Hard magnetic materials: (Permanent magnetic materials)

Materials with broad hysteresis loop. (Hysteresis loss is more) are called hard magnetic materials.
eg:- carbon steel, tungsten steel, cobalt steel, alnico, hard ferrite etc. (gradually rising magnetisation curve)

2) Soft magnetic materials. Have small size hysteresis loop and a steep magnetization curve. These are classified as

(a) solid core
(b) Electrical sheet & strip
(c) Special purpose alloys

a) Solid core:
eg:- Cast iron, cast steel, rolled steel, Forged steel etc..
Generally used for Yokes, Poles of DC machines, rotors of turbo alternators etc.

b) Sheet & strips
Silicon steel (iron + 0.3 to 4.5% silicon) in the lamination form. Addition of silicon in proper percentage eliminates ageing & reduce core loss. low silicon content steel or dynamo grade steel is used in rotating electrical machines and are operated at high flux densities.
High content silicon steel (4 to 5% silicon) or transformer grade steel (or high resistance steel) is used in Transformers.
Further sheet steel may be hot rolled silicon steel and Cold rolled Grain oriented (CRGO) silicon steel.

CRGO is costlier and superior to hot rolled. CRGO steel is generally used in transformer. CRGO silicon steel has much better magnetic properties as compared to hot rolled silicon steel.

(c) Special purpose alloys:

Nickel iron alloys have high permeability and addition of molybdenum or chromium leads to improved magnetic materials. Nickel with iron in different proportion leads

(i) High nickel permalloy (iron + molybdenum + copper or chromium) used in current transformers, magnetic amplifiers

(ii) Low nickel permalloy (iron + silicon + chromium or manganese) used in transformers, induction coils, chokes etc.

(iii). Perminvar (iron + nickel + cobalt): Use is limited by high cost & difficulties in its manufacture.

iv) Permendur (iron + cobalt + vanadium) used for microp

v) Mumetal (copper + iron)

vi) Permalloys it can be divided into High nickel & low nickel.

Properties of magnetic materials:

1. Low reluctance or should be high permeable
2. High saturation induction (to minimise weight & volume of iron parts)
3. High electrical resistivity & hence eddy current loss is less
4. Narrow hysteresis loop or low coercivity so that hysteresis loss is less & efficiency is high.
5. A high curie point. (Above curie point or temperature the material loses the magnetic property)
6. Should have a high value of energy product.

Super conducting materials: Materials, whose resistivity sharply decreases to practically zero value when the temperature is brought down below 'transition' temperature. (Critical temp) (Characteristic temp) are called super conductors.

The resistance of super conductors will be practically zero. Hence with such conductors copper losses will be extremely low. As such, machines with these conductors can be designed with very high value of current density, reducing drastically the size of the machine.

	Elements	Transition temp °K	Compounds	T.T (°K)
metals	Titanium	0.49	Nb_2Zr	10.8
	Zinc	0.82	V_3Si	17.1
	Aluminium	1.175	Nb_2Al	18.0
	Tin	0.72	NB_3SN	18.1
	Mercury	4.16		
	vanadium	5.13		
	lead	7.18		
	Nobidium	8.7		

The metals which are very good conductors at room temperature ie. silver, copper etc. do not exhibit super conducting properties. Many metals & alloys which are normally bad conductors at room temperature have super conducting properties at transition temperature.

Super conductors under cryogenic conditions can be used for the production of strong magnetic field.

Applications:

1) Transformers. windings
2) Turbo alternators (large) etc., (rotor windings)

Insulating Materials:-

Insulating materials are used to provide an electrical insulation between parts at different potentials. They are essentially non metalic, are organic or inorganic, uniform or heterogeneous in composition, natural or synthetic.

Natural organic :- paper, cloth, paraffin wax and Natural resion.

Inorganic :- glass, ceramics, & Mica.

Man made Products :- Resins. insulating films etc.

* Properties of Insulating Materials.

An ideal insulating material should posses the following properties.

1) High dielectric Stregth. Should withstand high temperature.
2) High resistivity or specific resistance.
3) Good thermal conductivity.
4) Should not undergo thermal oxidation and deteriorate at high temperature
5) Should not consume power or should have a low dielectric loss angle (δ).
6) withstand stresses due to centrifugal forces. (rotating m/c's) electrodynamic or mechanical forces (as in transformers).
7) Should withstand vibrations, abrasion, bending.
8) Should not absorb moisture.
9) Should be flexible & cheap.
10) Solid materials should have a high melting or softening point.
11) Liquid insulator should not evaporate or volatilize

Insulating materials can be classified as Solid, Liquid and Gas and Vacuum.

a) Solid insulating materials: used for Field, armature, Transformer windings etc.

1) Fibrous or inorganic animal or plant origin, natural or Synthetic.
Paper, wood, cardboard, Cotton, jute, Silk etc.
rayon, nylon, terelane, asbestos, fibere glass etc.

2) plastic or resins. Natural resins - lac, amber, Shellac (கோல்) etc.
Synthetic resins - Phenol formaldehyde, melamine, Polysters, (கோந்து) epoxy, silicon resins, bakelite, Teflon, PVC etc.

3) Rubber: Natural rubber, synthetic rubber - butadiene, Silicone rubber, hypalon etc.

4) mineral: Mica, marble, slate talc, chloride etc.

5) Ceramic: porcelain, steatite (மாக்கல்), alumina etc.

6) Glass: Soda lime glass, Silica glass, lead glass, borosilicate (cover with tar) glass

7) Non resinous: Mineral waxes, asphalt, bitumen, (தார்) Chlorinated naphthalene, enamel etc.

b) Liquid insulating Materials: used in Transformers, Circuit breakers, reactors, rheostats, cables, Capacitors etc & for impregnation.

1) Mineral oil. (Petroleum byproduct)
2) Synthetic oil. askarels, Pyranols etc.
3) varnish, French Polish, lacquer (coat) epoxy resins etc.

c) Gaseous insulating materials:

1) Air used in switches, air condensers, Transmission & distribution lines etc.
2) Nitrogen use in capacitors, HV gas Pressure cables etc.
3) Hydrogen though not used as a dielectric, generally used as coolant
4) Inert gases neon, argon, mercury & Sodium vapors generally used for neon sign lamps.
5) Halogens like fluorine, used under high pressure cables.

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Classification of Insulating materials based on thermal Consideration

Classification of insulating materials for electrical machinery and apparatus in relation to their thermal stability are given in Indian Standard Publication No 1271-1958.

The classification covers seven classes of insulating materials generally used in machinery & Electrical apparatus.

Insulation class	Maximum Operating Temperature in °C	Typical Materials.
Y	90° C	Cotton, Silk, Paper, wood, cellulose, fiber etc. without impregnation or oil immersed
A	105° C	The materials of class Y impregnated with natural resins, cellulose, esters, insulating oils, etc. & also laminated wood, varnished paper etc.
E	120° C	Synthetic resin enamels of vinyl acetate or nylon tapes, Cotton & Paper laminates with formaldehyde bonding etc.
B	130° C	Mica, glass fiber, asbestos etc. with suitable bonding substances, built up mica, glass fiber and asbestos laminated.
F	155° C	The materials of class B with more thermal resistance bonding materials.
H	180° C	Glass fiber & asbestos materials & built up mica with appropriate silicone resins
C	above 180° C	Mica, ceramics, glass, quartz, & asbestos with binders or resins of super thermal stability

The maximum operating temperature is the temperature of the insulation can reach during operation and is the sum of Standardized ambient temperature ie 40°c Permissible temperature rise & allowance tolerance for hot spot in winding.

For eg:- The max. temperature of Class B insulation is (ambient temperature 40°c + allowable temp rise 80°c + hot spot tolerance 10°c) = 130°c.

Insulation is the weakest element against heat and is a critical factor in deciding the life of electrical equipment. The maximum operating temperature prescribed for different class of insulation are for a healthy life time of 20,000 hrs. The height temperature permitted for the machine parts is usually about 200°C at the maximum. Exceeding the maximum operating temperature will affect the life of the insulation. The present day trend is to design the machine using Class F insulation for Class B temperature rise.

Modern Trends in Design.

* The design of Electrical Machines is both a science and an art
* The design consists of the solution of many complex & diverse engineering problems with many solutions as the number of equations is less than the number of unknowns
* The cooling & ventilation for the machine is also required.
* The materials for its magnetic system, insulating materials, & conductor materials.
* The machine designer starts with a number of known parameters like basic electromagnetic & constructional data and performs a series of mathematical operations that may or may not involve logical decisions to arrive at one or more than one acceptable solutions.

* The overall design process, right from the specification requirement to the determination of machine dimensions & other items of information required for manufactures of both static & rotating machines.

The Three major design problems are

1) Electromagnetic design 2) mechanical design 3) Thermal design

* The other aspect of the modern day design of Electrical machines is designing a number of machines, all of which form part of a single system - For eg:- Generators, transformer & motors form a part of an electromechanical Energy network. Such system are interconnected & react upon each other

The design of all the machine have to be completed concurrently since the design of one machine depends upon that of the others. The Problem thus is that of optimization of the system

* Sometimes it is desired to design a series of machines having different ratings to fit into a single frame size. In this case the finished designs of machines must be produced in groups, where all designs within a group are interdependent.

* Therefore, the optimal solution involve iterations values of variables are changed to satisfy both performance and cost constraints.

* The evolution of design to meet the specified optimum criteria is a matter of long & tedious iterations & this fact has to application of fast digital computers to the design of electrical machine

* The computer aided design has the advantage of eliminating tedious & time consuming hand calculations thereby releasing the designer from numerical hard work. This accelerates the design process enormously

* Also the use of computer make possible more trial designs and enables sophisticated calculations to be made without intolerable tedium & excessive time. It makes possible the checking of data at every stage reduces empiricism

Modern Machine manufacturing Techniques

1. The modern electrical machines are characterized by a very wide range of power outputs. The power range varies from a fraction of a watt to several hundreds of megawatt in a single unit. Thus the ratio of power output of the smallest machine to that of the largest machine is $1:10^{10}$

The type of construction adopted depends upon the power output of the machine & also on its rotational speed.

1) Small size machines :- ~~Few kW to 5000 kW~~ power o/p upto about 750W
2) Medium size machines :- few kW to 250kW
3) large size machines :- 250kW to 5000 kW.
4) larger size machines :- on special orders from customers to meet specific demand high hundreds of mega watt.

* low speed machines (below 250 rpm) → large diameter → small axial length
* High speed machines (3000 rpm & over) → small diameter → long core length
* Commercial available large machines speed in the range of (400 - 1500 rpm).
* medium size machine speed - (2000 to 2500 rpm)

2. The second important feature of modern electrical machine manufacture is the trend to build machine which are smaller in size & involve the use of lesser material & at the ~~smaller~~ same time have the same efficiency & overload capacity.

* Development & refinement in techniques relating to construction & arrangement of conductors & some other parts of the machine & results in reduction in stray load losses
* vast development in the cooling & ventilation system of machines

3. The manufacture of modern machines is the use of magnetic materials which have a high permeability, a low iron loss & high mechanical strength. Higher flux density results in reduction in the size of the machine & promote the extension of power O/P.

4. Significant improvement in the insulating materials and newer materials are increasingly being used in the present day m/cs. These materials are able to withstand much higher temperatures. The use of better class of insulating materials allows the machine sizes to be used for the same output power ratings.

5. Modern machine building is marked with use of higher electro-magnetic loadings for active parts & increased mechanical loadings for construction materials.

6. In order to expedite (quick) the process of machine manufacture at reduced cost different improved & refined manufacturing techniques are used for individual machine parts.

7. Modern Electrical machines have a wide field of applications. They are used in varied environments and under different operating conditions.

The design of the machine & its manufacture should be such that it operates satisfactorily under the desired environmental conditions.

UNIT 2
DESIGN OF DC MACHINES

Design of DC. Machines

Output equation:

The output of a machine can be expressed in terms of its main dimensions, specific magnetic & Electric loadings and speed. The equations which relates the power output to D, L, Bav, ac and n. of the machine is known as output equation

The Emf eqn of a DC Machine

$$E = \frac{\phi Z N}{60} \frac{P}{a} = \frac{\phi Z n P}{a} \rightarrow (1) \qquad n = \frac{N}{60}.$$

Current through each Conductor = $I_z = \frac{I_a}{a}$ or $I_a = a I_z \rightarrow (2)$

a = no. of parallel paths.

Specific magnetic loading $B_{av} = \frac{P\phi}{\pi D L} = P\phi = \pi D L B_{av} \rightarrow (3)$

Specific Electric loading $ac = \frac{I_z Z}{\pi D} = I_z Z = \pi D\, ac \rightarrow (4)$

Power developed in armature

$$P_a = E I_a \times 10^{-3} \text{ in kW} \rightarrow (5)$$

On Substiting E & I in eqn (5). we get-

$$P_a = \frac{\phi Z n P}{\cancel{a}} \times \cancel{a} I_z \times 10^{-3} \rightarrow (6)$$

On substituting for $P\phi$ & $I_z Z$ from eqn 3 & 4 in eqn (6) we get $P_a = P\phi \times I_z Z \times n \times 10^{-3}$

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

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

$$P_a = C_o D^2 L n \rightarrow (7)$$

where $C_o = \pi^2 B_{av}\, ac \times 10^{-3} \rightarrow (8)$

The equation $\boxed{P_a = C_0 D^2 L n}$ → output equation

$$\boxed{C_0 = \pi^2 B_{av}\, ac \times 10^{-3}}$$ → output Co-efficient

The term D^2L in the o/p eqn is proportional to volume of active part. C_0 → constant then we can say the power output is directly proportional to the product of volume of active part and speed.

ie $P_a \propto$ Volume of active part × speed,

If C_0 is varied then the Power output is directly proportional to the four quantities and they are

ie, $P_a \propto B_{av} \times ac \times$ volume of active part × speed.

Maximum gap density $B_g = \frac{B_{av}}{K_f} \simeq \frac{B_{av}}{\psi}$.

∴ C_0 in terms of B_g is given by

$$\boxed{C_0 = \pi^2 \psi B_g\, ac \times 10^{-3}}.$$

Power developed by the armature P_a is different from the rated power output P. of the machine. The relationship between the two are

$P_a = P/\eta$ for generator

$P_a = P$ for motors.

Selection of Number of Poles.

The number of poles used in DC machine has an important bearing upon the magnetic & Electric circuits.

In case of ac m/c, number of poles is fixed by the supply frequency and the speed of the machine.

But incase of DC machine any number of poles can be used. However there is always a very small range of no. of poles that give a design which is sound from the commercial point of view.

The selection of number of poles depends on

1) Frequency 2) Length of commutator 3) Weight of iron parts
4) labour charges 5) weight of copper 6) Flash over & distortion of field form.

* The number of poles are choosen such that the frequency lies between 25 to 50Hz. With large number of poles the flux carried by the yoke reduces.
* Hence for a given flux with large no. of poles, area of cross section of yoke can be reduced. Which results in reduction of iron parts.
* Also by increasing the no. of poles, the weight of iron in the armature core can be decreased
* The overall diameter of the machine decreases as the no. of poles is increased
* The weight of copper in armature & field winding decreases with increase in no. of poles. Length of commutator reduces and so the overall length of the machine reduces. With the increase in no. of poles labour charges will increase.
* The use of large no. of poles results in increased danger of flash over between adjacent brush arms. With increases in no. of poles there is reduction in distortion of field form under load conditions.

Sha Bhav

Advantages of large no. of poles

* Weight of armature core & yoke reduced
* cost of armature & field conductors reduced
* Reduction in overall length & diameter of m/c
* length of commutator reduced
* Distortion of field form under load conditions are reduced

Disadvantages of large no. of poles.

* increase in frequency of flux reversal
* increase in labour charges
* Possibility of flashover b/w brush arms is more.

Selection of no. of slots :

The following factors to be considered for selection of number of slots are

* Slot width
* cooling of armature conductor.
* Flux pulsations
* commutation
* cost.

Airgap of DC Machine :-

* ~~Small~~ large gap is provided between the rotor & stator to avoid friction b/w the stationary & rotating parts
* larger value of air gap results in lesser noise, better cooling, reduced pole, reduced circulating currents
* less distortion of field form.
* large air gap results in higher field mmf which reduces armature reaction.

(1) Find the main Dimensions of a 200 kW, 250 V, 6 Pole, 1000 rpm, generator. The maximum value of flux density in the gap is 0.87 wb/m² and the ampere conductors per metre of armature periphery are 31000. The ratio of pole arc to pole pitch is 0.67 and the efficiency is 91%. Assume the ratio of length of core to pole pitch = 0.75.

Given :-

$P = 200$ kW . $N = 1000$ rpm $\psi = 0.67$ $D = ?$

$V = 250$ V $B_g = 0.87$ wb/m² $L/\tau = 0.75$ $L = ?$

$P = 6$ $ac = 31000$ AC/m $\eta = 0.91$

Soln :-

Power developed in armature $P_a = \frac{P}{\eta} = \frac{200}{0.91} = 219.78$ kW

Output co-efficient $C_0 = \pi^2 B_{av}\, ac \times 10^{-3} = \pi^2 \psi B_g\, ac \times 10^{-3}$

$B_{av} = \psi B_g$, $C_0 = \pi^2 \times 0.67 \times 0.87 \times 31000 \times 10^{-3}$

$C_0 = 178.34$ kW/m³-rps

Also Power developed in armature $P_a = C_0 D^2 L n$

$D^2 L = \frac{P_a}{C_0 n} = \frac{219.78}{178.34 \times \left(\frac{1000}{60}\right)} = 0.0739$

$L/\tau = 0.75$, $L = 0.75\tau = 0.75 \frac{\pi D}{P} = \frac{0.75 \times \pi}{6} D = 0.392 D$

$D^2 L = 0.0739$

$D^2(0.392 D) = 0.0739$

$D^3 = 0.188$, $\boxed{D = 0.57\text{m}}$ $L = 0.392 D$

0.392×0.57

$\boxed{L = 0.22\text{m}}$

2) Find the main dimensions and no. of poles of 37 kW, 230V, 1400 rpm shunt motor so that a square pole face is obtained. The average gap density is 0.5 wb/m² & ac = 22000. The ratio of pole arc to pole pitch is 0.7. and the full load efficiency is 90%.

Given $P = 37$ kW $\quad N = 1400$ rpm $\quad ac = 22{,}000$ AC/m
$V = 230$V $\quad B_{av} = 0.5$ wb/m² $\quad \psi = 0.7 \quad \eta = 90\%$

Soln:

If $P = 2$ then $f = \frac{PN}{120} = \frac{2 \times 1400}{120} = 23.33$ Hz

If $P = 4$ then $f = \frac{4 \times 1400}{120} = 46.67$ Hz.

Power input $\quad P_i = VI \times 10^{-3}$ kW

$$P_i = \frac{P}{\eta} = \frac{37}{0.9} = \underline{41.11 \text{ kW}}$$

$\therefore$ load current $I = \frac{P}{\eta \times V \times 10^{-3}} = \frac{37}{0.9 \times 230 \times 10^{-3}} = 178.74$A

Armature current $I_a = I = \underline{178.74\text{A}}$

The I_a is less than 200 A. current per parallel path will not exceed the upper limit of 200 A. When $P = 4$, $f = 46$ Hz which lies in the range of 25 to 50 Hz. Hence $P = 4$ is best choice.

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

$$C_o = \pi^2 \times 0.5 \times 22000 \times 10^{-3} = 108.57 \text{ kW/m}^3\text{-rps}$$

$P = 37$ kW, $\quad P_a = P = 37$ kW. (DC motor).

$$D^2 L = \frac{P_a}{C_o n} = \frac{37}{108.57\,(1400/60)} = 0.0146 \text{ m}^3$$

$\psi = 0.7$. For Square pole face Length of armature is equal to pole arc

$$\therefore \frac{\text{Pole arc}}{\text{Pole pitch}} = \frac{\text{length}}{\text{Pole pitch}} = \frac{L}{\tau} = 0.7$$

$$L = 0.7\tau = 0.7 \times \frac{\pi D}{P} = \frac{0.7 \times \pi}{4} \times D = 0.5498 D$$

$$L = 0.5498 D$$

$$D^2 L = 0.0146$$

$$D^2 (0.5498 D) = 0.0146$$

$$D^3 = \frac{0.0146}{0.5498}, \quad D = 0.2983\,m$$

$$\boxed{D = 0.3\,m}$$

$$L = 0.5498 D$$

$$L = 0.5498 \times 0.3$$

$$\boxed{L = 0.165\,m}$$

Design of DC Machines

Choice of Specific Magnetic Loading

It depends on the following

* Flux density in teeth
* Frequency of flux reversal
* Size of machines.

Large values of flux density in teeth results in increased field mmf. Higher values of field mmf increases the iron loss, copper loss and cost of copper. The Bav is choosen such that the flux density at the root of the teeth does not exceed 2.2 wb/m².

If the frequency of flux Reversals is high then iron losses in armature core & teeth would be high. Therefore we shouldnot use a high value of flux density in the air gap of machines which have a high frequency.

It is possible to use increased values of flux density as the size of the machine increases. As the diameter D of the machine increases, the width of the tooth also increases, permitting an increased value of gap flux density without causing saturation in the machine.

The value of Bav varies between 0.55 to 1.55 wb/m² and the corresponding values of Bav are 0.4 to 0.8 wb/m².

Choice of Specific Electric loading

It depends on the following

* Temperature rise
* Speed of machine
* Voltage
* Size of machine
* Armature reaction &
* commutation.

A higher value of (ac) results in a high temperature rise of windings. The temperature rise depends on the type of enclosure and cooling techniques employed in the machine.

If the Speed of the machine is high, the ventilation of the machine is better and therefore, greater losses can be dissipated. Thus a higher value of 'ac' can be used for machine having high speed.

In high voltage machines, large space is required for insulation and therefore there is less space for conductors. This means that in HV machines, the space left for conductors is less and therefore we should use a small value of 'ac'. In large machines it is easier to find space for accommodating conductors. Hence specific electric loading can be increased with increase in linear dimension.

With high value of 'ac' armature reaction will be severe. To counter this the field mmf is increased and so the cost of the machine goes high.

High value of 'ac' worsens the Commutation Condition in machines. From the point of view of commutation a small value of 'ac' is desirable.

The value of 'ac' usually lies between 15000 to 50,000 amp cond/mt.

Advantages of higher specific Electric & magnetic Loadings:

(1) Size and volume of the machine is reduced.
(2) weight of the machine is reduced
(3) over all cost of the machine reduced.

Disadvantages of higher specific Electric loading

(1) armature copper loss is increased
(2) commutation becomes inferior
(3) Commutation reactance voltage is increased.
(4) Field copper loss increases due to higher exciting current
(5) overall temperature rise increases.

Disadvantages of higher specific magnetic loading:

(1) iron losses increased
(2) Field copper losses increase
(3) higher magnitude of no-load current
(4) tooth flux density increases
(5) noise in machine increases
(6) Possibility of magnetic saturation in iron parts increases

Pole proportions:

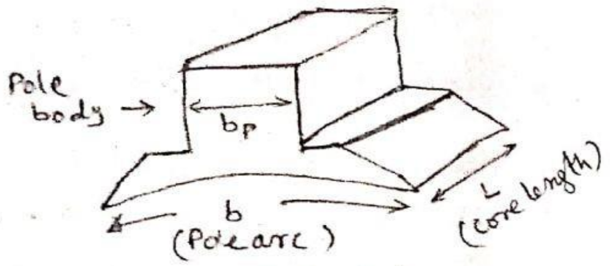


Fig Field Pole.

In square section the width of the pole body is equal to the length of the machine.

Some manufactures prefer a square pole face.

For square pole face, the pole arc (b) is equal to the length of the machine.

Some manufacturers prefer rectangular pole sections.

$\therefore$ $L = b_p$, for square pole section

$L = b$, for square pole face.

Usually the ratio of pole ~~arc~~ arc to pole pitch or the ratio L/τ is specified

$\psi = b/\tau = 0.64$ to 0.72 and

$L/\tau = 0.45$ to 1.1

Length of airgap:

Higher value of airgap results in

* Lesser noise.
* Better cooling
* Reduced pole face losses.
* Reduced circulating current
* Less distortion in field form.
* Higher field MMF which reduces armature reaction.

In general mmf required for air gap

$$AT_g = 8,00,000\ B_g K_g l_g \rightarrow (1)$$

where $K_g = 1.15$ = gap contraction factor.

In DC machines the mmf required for airgap is normally taken as 0.5 to 0.7 times the armature mmf per pole.

$$\text{Armature mmf per pole} = \frac{I_z\left(\frac{Z}{2}\right)}{P} = \frac{I_z Z}{2P} = \frac{ac\,\pi D}{2P}$$

$$AT_a = \frac{ac\,\tau}{2} \rightarrow (2)$$

$$\left(\because\ ac = \frac{I_z Z}{\pi D}\ \&\ \tau = \frac{\pi D}{P}\right)$$

$\therefore$ mmf required for airgap in DC machine $AT_g = (0.5 \text{ to } 0.7) \times \frac{ac\,\tau}{2} \rightarrow (3)$

On equating eqn (1) & (3) we get

$$800\,000\ B_g K_g l_g = (0.5 \text{ to } 0.7)\frac{ac\,\tau}{2}$$

$$\text{Airgap length } l_g = \frac{(0.5 \text{ to } 0.7)\,ac\,\tau}{1,600,000\ B_g K_g} \rightarrow (4).$$

The usually values of airgap lies between 0.01 to 0.015 times of pole pitch.

Armature core design

* Armature core
* Armature winding.

The design of armature core involves the design of 1) main dimensions D & L,
2) Number of slots
3) Slot dimensions,
4) Depth of core.

Number of armature slots

The factors tobe considered for selection of no.of armature slots are

* Slot width
* Cooling of armature conductors
* flux pulsations
* commutation
* cost.

If $\psi = \dfrac{\text{Pole arc}}{\text{Pole pitch}}$

Slots in the region between the tips of two adjacent poles

$(1-\psi) \times$ Slot per pole. ≥ 3

taking $\psi = 0.67$ (typical value)

No. of slots per pole $= \dfrac{3}{1-\psi} = \dfrac{3}{1-0.67} > 9.12$

Therefore, from the point of view of commutation the number of slots per pole should at least be equal to 9 for better commutation.

Choice of number of Slots

1. Slot Pitch: lies between 25 to 35 mm.
   Small machine 20 to 30 mm.

2. Slot loading: It should not exceed 15 000 Amp cond.

3. Flux Pulsation: The no. of slots per pole pair should be an odd integer in order to minimise pulsation loss.

4. Commutation: in order to prevent sparking the no. of slots per pole usually lies between 9 to 16.
   Small m/c – 8.

5. Suitability for winding :- Type of winding
   Simplex lap – No. of slots – multiple of pole pair
   Simplex wave – No. of slots – not a multiple of pole pair
   to avoid dummy coils.

Slot dimensions :-

Slot width × Slot depth.

$$\text{Slot area} = \frac{\text{Conductor area}}{\text{Slot space factor}}.$$

Slot space factor lies in the range of 0.25 to 0.4 & value depends on the thickness of insulation

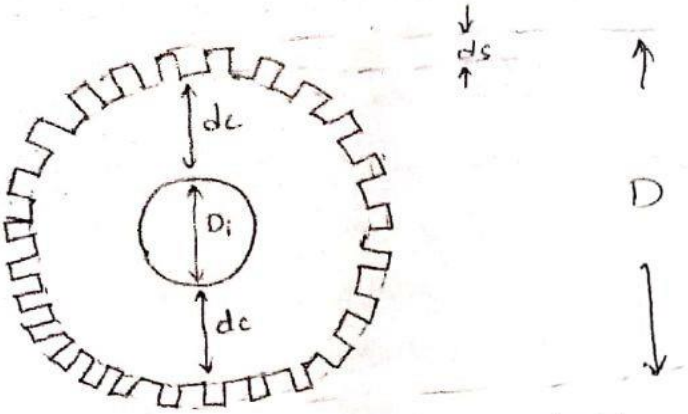
Slot depth table

Diameter of armature in mt.	Slot depth in mm
0.15	22
0.20	27
0.25	32
0.30	37
0.40	42
0.50	45

Factors considered for Slot dimensions.

* Flux density
* Flux pulsations
* Eddy current loss in conductors
* Reactance voltage
* Fabrication difficulties

Depth of armature core



$D \rightarrow$ Diameter of armature

$D_i \rightarrow$ inner diameter of armature

$d_s \rightarrow$ depth of slot

$d_c \rightarrow$ depth of core

fig: Cross section of armature.

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

$\therefore$ Depth of core $d_c = \frac{1}{2}(D - D_i - 2d_s) \rightarrow (1).$

let L_i = Net iron length of armature

ϕ = Flux per pole

A_c = area of armature core

$A_c = L_i d_c \rightarrow (2)$

Flux in armature core $\phi_c = \phi/2 \rightarrow (3)$

Flux density in core $= B_c = \phi_c / A_c \rightarrow (4)$

on equation (2) & (4) we get

$$L_i d_c = \frac{\phi_c}{B_c}$$

$$\therefore d_c = \frac{\phi_c}{L_i B_c} \rightarrow (5)$$

But $\phi_c = \frac{\phi}{2}$ $\therefore$ Depth of core $\boxed{d_c = \frac{1}{2}\frac{\phi}{L_i B_c}} \rightarrow (6)$

Armature winding design:

It involves.

* selection of type of winding → lap winding / wave winding.
* estimation of no. of armature coils
* turns per coil
* conductors per slot
* total no. of armature conductors.
* Dimensions of conductor.

Area of cross section of armature conductors are determined by current & current density.

For large M/C - $\delta_a = 4.5\ A/mm^2$

Small M/C - $\delta_a = 5\ A/mm^2$

High speed fan ventilated M/C $\delta_a = 6$ to $7\ A/mm^2$.

δ_a lies - 4 to $7\ A/mm^2$.

Power developed in armature. $P_a = E I_a \times 10^{-3}$

armature current $I_a = \dfrac{P_a}{E \times 10^{-3}}$

Current through an armature conductor $I_z = \dfrac{I_a}{a}$

a = No. of Parallel Paths.

Area of cross section of armature conductor $a_a = \dfrac{I_z}{\delta_a}$

Magnetic Circuit

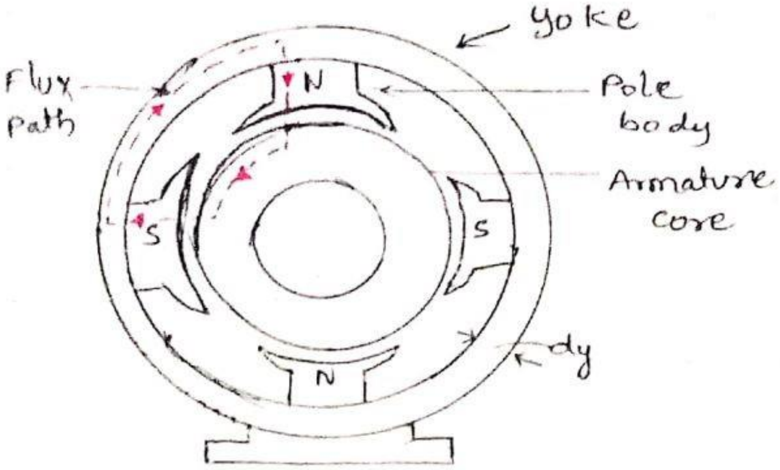


fig (1) Magnetic circuit of 4 Pole dc machine

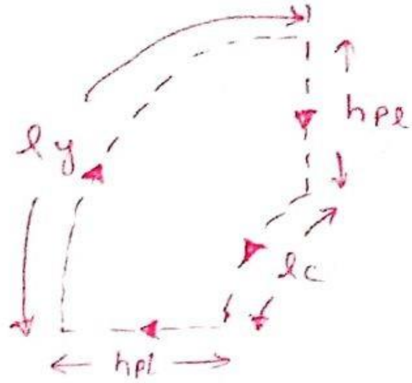


Fig (2) one complete magnetic path in a 4 Pole dc machine.

The path of magnetic flux is called magnetic circuit of dc machine comprises yoke, poles, airgap, armature teeth and armature core.

The flux produced by field coils emerges from north pole and cross the airgap to enter the armature teeth. Then it flows through armature core and again cross the airgap to enter south pole. The circuit close through the yoke of the machine.

In DC machine the number of magnetic circuits is equal to number of poles. The various magnetic circuits are interlinked and form a symmetrical arrangement

Working flux density in various parts of dc machine

Yoke	–	1.3 – 1.6 wb/m²
Pole	–	1.2 – 1.7 T
Airgap	–	0.4 – 1.6 T
Armature teeth	–	1.5 – 2.2 T
Armature core	–	1.0 – 1.5 T

mmf require for airgap - $AT_g = 8,00,000\, B_g K_g l_g$

mmf for teeth - $AT_t = at_t \times d_s$

mmf for core - $AT_c = at_c \times l_c$

mmf for pole - $AT_p = at_p \times h_{pl}$

mmf for yoke - $AT_y = at_y \times l_y$.

The values of at_t, at_c, at_p and at_y are determined by B-H curve.

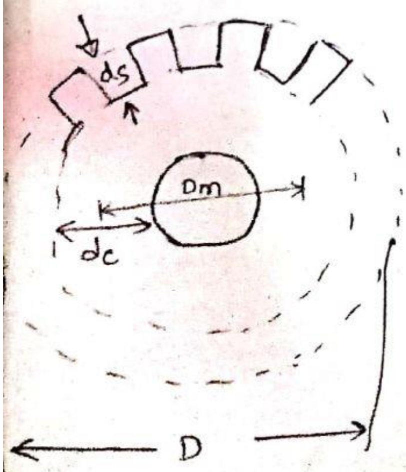
at_c = mmf/mt corresponding to flux density in core

at_p = mmf/mt " " in pole body

at_y = mmf/mt " " in yoke.

at_t = mmf/mt " " in tooth at one third height from narrow end

length of flux path in core $l_c = \dfrac{\pi D_m}{P} = \dfrac{\pi (D - 2d_s - d_c)}{P}$



Cross section of armature core

D_m = mean diameter of armature

D_{my} = mean diameter of yoke

length of flux path in yoke $l_y = \dfrac{\pi D_{my}}{P}$

$$l_y = \frac{\pi (D + 2l_g + 2h_{pl} + d_y)}{2P}$$

Total mmf/pole at no load and normal voltage

$$AT_{fo} = AT_g + AT_t + AT_c + AT_p + AT_y$$

Design of Field System

The design of poles involves the determination of area of cross section of poles, their hiegth, and design of field winding.

1) Shunt field winding :- (large no. of turns (thin conductors) low current.
2) Series field winding :- (Thick conductors of strips heavy current)

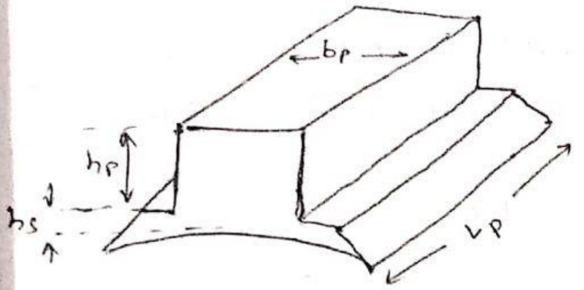
Factors to be considered for the design of field winding are

* mmf per pole and flux density
* loss dissipated from the surface of field coil
* Resistance of the field coil
* current density in the field ~~design~~ conductors.

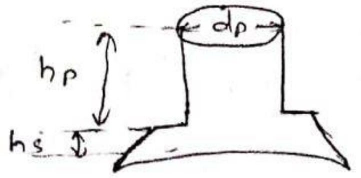
Design of Shunt field winding

* Dimensions of the main field pole
* Dimensions of field coil
* Dimension of the field conductor.
* current in shunt field winding
* Resistance of the field coil
* Number of turns in the field coil
* losses in the field coil.

Dimensions of Main Pole



(a) Rectangular pole



(b) Cylindrical pole

Fig: Dimensions of field pole.

Leakage co-efficient depend on the power output of dc m/c.

O/p in kW	Leakage co-efficient C_l
50	1.12 to 1.25
100	1.11 - 1.22
200	1.10 - 1.20
500	1.09 - 1.18
1000	1.08 - 1.16

Flux in the pole body $= \phi_p$

$$\phi_p = C_l \phi$$

Area of pole body $= A_p = \dfrac{\phi_p}{B_p}$

For circular poles

Area of pole body $A_p = \dfrac{\pi d_p^2}{4}$

Diameter of pole body $d_p = \sqrt{\dfrac{4A_p}{\pi}}$

Flux density range - 1.2 to 1.7 wb/m²

Rectangular poles are employed the length of the pole is choosen as 10 to 15 mm less than of armature to permit end play and to avoid magnetic centering.

Length of pole $L_p = L - (0.001 \text{ to } 0.015)$

Net iron length of pole $L_{pi} = 0.9 L_p$

width of the Pole $= b_p = \frac{A_p}{L_{pi}}$

The Height of the Pole body is given by the sum of height of field coil, thickness of insulation and clearance.

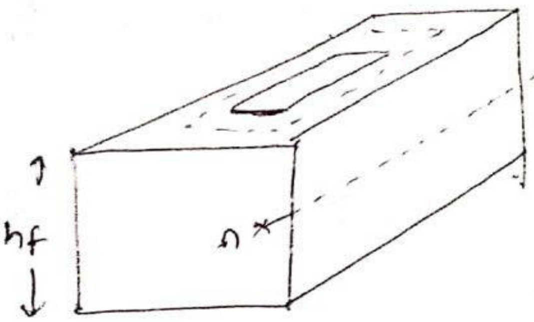
Height of pole body, $h_p = h_f +$ Thickness of insulation & clearance.

Total height of Pole, $h_{pl} = h_p + h_s$

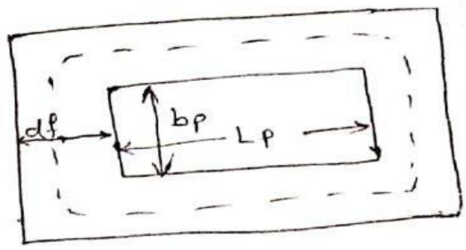
h_s – Height of Pole shoe at the centre of the Pole.

h_p – Height of the pole body.

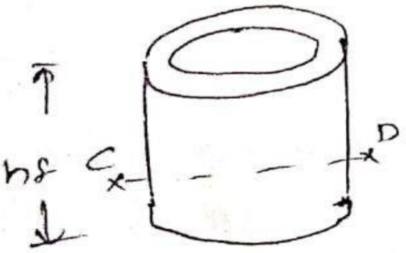
Dimensions of field coil



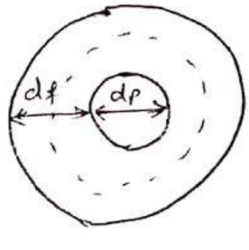
(a) Rectangular field coil



(b) cross section of rectangular field coil at AB



(c) Cylindrical field coil



(d) cross section of circular field coil at CD

Fig: Dimensions of field coil.

Depth of field winding

Armature diameter in m	Depth of field winding in mm
0.2	30
0.35	35
0.5	40
0.65	45
1.00	50
above 1 m	55

(Generally depth of field coil assumed and the value depends on the diameter).

Height depends on h_f - height of field coil and number of turns (T_f).

Length of mean turn (L_{mt}) of field coil can be calculated using dimensions of pole & depth of field coil. It is centre of field coil.

For rectangular field coil

$$L_{mt} = 2(L_p + b_p + 2d_f)$$

(or) $$L_{mt} = \frac{L_o + L_i}{2}$$

L_o - length of outermost turn

L_i - length of inner most turn

For cylindrical field coil

$$L_{mt} = \pi(d_p + d_f)$$

Current in shunt field winding

voltage across each shunt field coil $E_f = \dfrac{\text{Voltage across shunt field winding}}{\text{Number of poles}}$

Voltage a/c shunt field winding = (0.8 to 0.85) of rated voltage (V)

Voltage a/c each shunt field coil = $\dfrac{(0.8 \text{ to } 0.85) \times V}{P}$

The field current $I_f = \dfrac{E_f}{R_f}$

R_f - Resistance of each field coil.

Resistance of field coil

$$R_f = \rho \frac{\text{length of field coil}}{\text{area of c/s of field conductor}}$$

Length of field coil = $L_{mt} \times T_f$.

$$\therefore \quad R_f = \rho \frac{L_{mt} T_f}{a_f}$$

Dimensions of field conductor

Area of c/s of field conductor $a_f = \dfrac{I_f}{\delta_f}$.

(or)

$$R_f = \frac{\rho L_{mt} T_f}{a_f} \quad \text{and} \quad R_f = \frac{E_f}{I_f}.$$

$$\therefore \quad a_f = \frac{\rho L_{mt} T_f}{R_f}$$

$$\therefore \quad a_f = \frac{\rho L_{mt} T_f I_f}{E_f}.$$

we know that $AT_{fl} = T_f I_f$

$$\therefore \quad a_f = \frac{\rho L_{mt} AT_{fl}}{E_f}.$$

Conductors with circular cross section is used in field winding.

$$\therefore \quad a_f = \frac{\pi}{4} d_{fc}^2 \qquad \& \text{ diameter } d_{fc} = \sqrt{\frac{4 a_f}{\pi}}$$

Diameter of field conductor including insulation thickness $= d_{fci} = d_{fc} +$ thickness of insulation

Copper space factor $S_f = 0.75\left(\frac{d_{fc}}{d_{fci}}\right)^2$

Field amper turns on load $AT_{fl} = I_f T_f$.

Turns in field coil, $T_f = \frac{AT_{fl}}{I_f}$.

Power loss in the field coil

The heat can be dissipated from all the four sides of a coil ie, inner, top outer & bottom surface of the coil.

Inner surface area of the field coil $= L_{mt}(h_f - d_f)$

outer surface area of the field coil $= L_{mt}(h_f + d_f)$

Top surface area " $= L_{mt}\, d_f$

Bottom surface area " $= L_{mt}\, d_f$

Total surface area of field coil $= S$

$$S = L_{mt}(h_f - d_f) + L_{mt}(h_f + d_f) + L_{mt}\, d_f + L_{mt}\, d_f$$

$$S = 2L_{mt}(h_f + d_f)$$

Permissible copper loss $Q_f = S q_f$ where q_f is loss dissipated per unit area of field coil

$$Q_f = 2L_{mt}\, q_f (h_f + d_f)$$

actual copper loss in field coil $= I_f^2 R_f = \frac{E_f^2}{R_f}$

Actual Cu loss $= \dfrac{E_f^2}{\rho \, L_{mt} \, T_f / a_f} = \dfrac{E_f^2 a_f}{\rho \, L_{mt} \, T_f}$

Permissible copper loss = actual copper loss.

$$2 L_{mt} \, q_f \, (h_f + d_f) = \frac{E_f^2 \, a_f}{\rho \, L_{mt} \, T_f}$$

Conductor area in field coil = $T_f \times a_f$

or

Conductor area of field coil = Copper space factor × area of c/s of field coil

$= S_f \times h_f \, d_f$

$$T_f \, a_f = S_f \, h_f \, d_f$$

Check for temperature rise

cooling co-efficient $C = \dfrac{0.14 \text{ to } 0.16}{1 + 0.1 V_a}$

V_a = peripheral speed of armature

Temperature rise $\theta_m = \dfrac{\text{Actual copper loss} \times C}{S}$

$$\theta_m = \frac{q_f \, C}{S}.$$

Design of Series field winding:

The series field winding is wound with rectangular conductors. The conductors may be flat wound or wound on edge. In case of series machines each pole carries a series field coil and all the field coils are connected in series to form series field winding. The ampere turns to be developed by the series field coil in dc series machine is 1.15 to 1.25 times the full load armature current.

For compound machines ampere-turns to be developed by series field coil is 15 to 20% of full load armature ampere turns.

Design of Series field coil

Step-1. Estimate the ampere turns to be developed by series field coil.

$$\text{Armature amp turns at full load (per pole)} = \frac{\text{Current through a turn} \times \text{No. of armature turns}}{\text{No. of Poles}}$$

$$= \frac{I_z \times \frac{Z}{2}}{P} = \frac{I_z Z}{2P}$$

For Compound machies

Amp. turns developed by Series field coil

$$AT_{se} = 0.15 \text{ to } 0.25 \times \frac{I_z Z}{2P}$$

For Series machies

Amp turns developed by series field coil

$$AT_{se} = 1.15 \text{ to } 1.25 \times \frac{I_z Z}{2P}$$

Step - 2 Calculate the no. of turns in series field coil

$$T_{se} = \frac{AT_{se}}{I_{se}}$$

where

$I_{se} = I_a$ current through series field conductor.

step - 3.

Area of cross-section of series field conductor

$$a_{se} = \frac{I_{se}}{\delta_{se}}$$

where δ_{se} = current density in series field conductor.

δ_{se} = 2 to 2.3 A/mm²

low capacity → round
high capacity → rectangular
M/C. } Condu... are use...

Step - 4 Dimension of field coil

conductor area in field coil $= T_{se}\, a_{se}$

(or) = copper space factor × Height of coil × depth of ...

$= S_{fse} \times h_{se} \times d_{se}$.

S_{fse} = copper space factor for series field coil

S_{fse} for
Circular conductor → 0.6 to 0.7.
Rectangular Conductor → depends on thickness & type of insulation

$\therefore\; S_{fse}\, h_{se} \times d_{se} = T_{se}\, a_{se}$

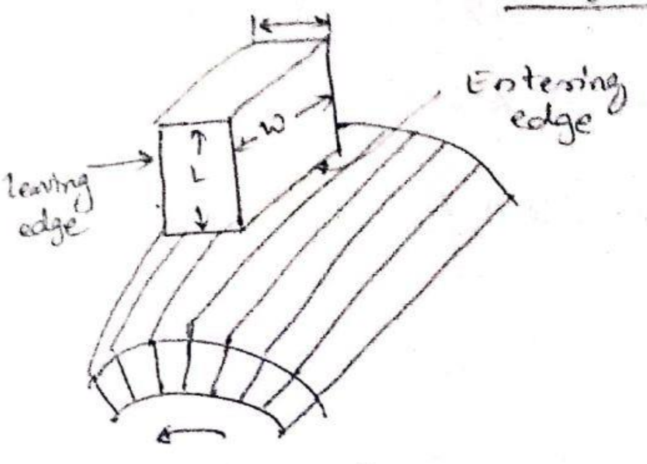
Height of field coil $h_{se} = \dfrac{T_{se}\, a_{se}}{S_{fse}\, d_{se}}$.

step - 5 Resistance of series field coil

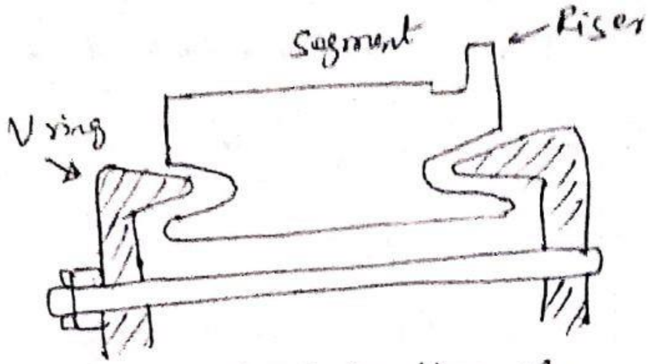
$$R_{se} = \frac{\rho\, L_{mtse}\, T_{se}}{a_{se}}$$

Length of mean turn of series coil $L_{mtse} = 2(L_p + b_p + 2d_{se})$

Design of Commutator & brushes



Carbon brush on commutator surface



Cross section of commutator.

The number of segments is equal to the number of coils or segments $C = \frac{1}{2} u S_a$.

$S_a \rightarrow$ no. of armature slot

$u \rightarrow$ no. of coil sides / slot

The minimum number of segments is that which gives a voltage of 15V between segments at no load.

$\therefore$ minimum number of segments $= E \times P/15 = \frac{EP}{15}$

Commutator segment pitch $\beta_c = \frac{\pi D_c}{C}$ should not less than 4 mm.

Thickness of brush is selected such that it covers 1 to 3 commutator segments.

Current carried by each brush $I_b = \frac{2 I_a}{P}$ for lap wdg

$I_b = I_a$ for wave wdg.

Total brush contact area per spindle, $A_b = I_b / \delta_b$

$A_b = \frac{2 I_a}{P \delta_b}$

Each brush does not carry more than 70A.

let a_b : Contact area of each brush

n_b - No. of brushes per spindle.

$\therefore$ Contact area of brush in a spindle $\cdot$ $A_b = n_b a_b$

Also $a_b = w_b t_b$

$\therefore A_b = n_b w_b t_b$

Thickness of brush t_b = 1 to 3 x β_c

Width of brush $w_b = \frac{A_b}{n_b t_b} = \frac{a_b}{t_b}$.

$$w_b = \frac{2 I_a}{P \delta_b n_b t_b}$$

Length of commutator

$$L_c = n_b (w_b + c_b) + c_1 + c_2$$

c_b - clearance b/w the brushes - 5mm

c_1 = clearance allowed for staggering the brushes - 10 mm - Small, 30 mm - large

c_2 = clearance for allowing end play - 10 to 25 mm.

Losses at Commutator Surface

Brush Contact losses + Brush friction losses.

The brush friction loss

$$P_{bf} = \mu P_b A_B V_c$$

$P_b \rightarrow$ brush contact pressure on commutator N/m2

A_B = Total contact area of all brushes m2

$A_B = P A_b$ for lap

$A_B = 2 A_b$ for wave

μ - Co-efficient of friction

V_c = Peripheral speed of commutator, m/sec

Solved Question paper problems

1) A 5 kW, 250V, 4 pole, 1500 rpm, shunt generator is designed to have a square pole face. The loadings are average flux density in the gap = 0.42 Wb/m² and ampere conductors per meter = 15,000. Find the main dimension of the machine. Assume full load efficiency = 0.87 and ratio of pole arc to pole pitch = 0.66.

Given:

$P = 5\,kW$, $V = 250\,V$, $P = 4$, $N = 1500\,rpm$

$B_{av} = 0.42\,Wb/m^2$, $ac = 15{,}000\,A\,cond/m$, $\eta = 0.87$

$\psi = 0.66$

Armature power $P_a = \frac{P}{\eta} = \frac{5}{0.87} = 5.75\,kW$

Speed $n_s = \frac{1500}{60} = 25\,rps$

$$C_0 = \pi^2 B_{av}\, ac \times 10^{-3}$$

$$= \pi^2 \times 0.42 \times 15{,}000 \times 10^{-3}$$

$$C_0 = \underline{\underline{62.1}}\ kW/m^3\text{-}rps$$

$$D^2L = \frac{P_a}{C_0 n_s} = \frac{5.75}{62.1 \times 25} = 3.69 \times 10^{-3}\,m^3$$

Square pole face $-$ $\frac{\text{Core length}}{\text{Pole arc}} = 1$ or $\frac{L}{\psi \tau} = 1$

$$L = \psi \frac{\pi D}{P} = 0.66 \frac{\pi \times D}{4} = 0.518\,D$$

$$0.518 D^3 = 3.69 \times 10^{-3}\,m^3$$

$$D = \underline{\underline{0.192\,m}}, \quad L = \underline{\underline{0.1\,m}}$$

(2) A design is required for a 50 KW, 4 Pole, 600 rpm, d.c. shunt generator. the full load terminal voltage being 220V. If the maximum gap density is 0.83 and the armature ampere conductor per meter are 30,000, Calculate suitable dimensions of armature core to give a square pole face.

Assume that the full load ampere voltage drop is 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.

$$C_0 = \pi^2 \psi B_g ac \times 10^{-3}$$

$$= \pi^2 \times 0.67 \times 0.83 \times 30{,}000 \times 10^{-3}$$

$$C_0 = 164.65 \text{ KW/m}^3\text{/rps}$$

$$n_s = \frac{N}{60} = \frac{600}{60} = 10 \text{ rps}$$

Back emf $E_b = 220 + 0.03 \times 220$ — 3% voltage drop.

$$= 226.6V$$

Full load current $= \frac{P}{V} = \frac{50 \times 1000}{220} = 227.27A$

Field current $= 0.01 \times 227$ — 1% of rated voltage

$$= 2.27A$$

Armature current

$$I_a = 227 + 2.27$$

$$I_a = 229.27A$$

Power developed by armature

$$P_a = E \cdot I_a \times 10^{-3}$$

$$= 226.6 \times 229.27 \times 10^{-3} = 51.9 \text{ KW}$$

$$D^2L = \frac{P_a}{C_0 n_s} = \frac{51.9}{164.65 \times 10} = 0.0311\,m^3$$

For a square pole face $\frac{L}{\psi\tau} = 1.$ or $\frac{L}{0.67 \times \frac{\pi D}{p}} = 1$

$$\frac{L}{0.67 \times \frac{\pi D}{4}} = 1 \qquad L = 0.526D.$$

Hence $D^3 = \frac{0.0311}{0.526} = 0.0591\,m^3.$

$D = 0.389\,m \qquad L = 0.20\,m$

3) A shunt field coil has to develop an mmf of 9000AT. The voltage drop in the coil is 40V. and the resistivity of round wire used is $0.021\Omega/m$ and mm^2 the depth of the winding is 35mm. approximately. and the length of mean turn is 1.4 m. Design a coil so that the power dissipated is 700W/m² of the total coil surface (ie outer, inner, top & bottom) Take the diameter of the insulated wire 0.2mm greater than that of bare wire.

Soln

Area of conductor $a_f = \frac{AT_f\,\rho L_{mt}}{E_f} = \frac{9000 \times 0.021 \times 1.4}{40}$

$a_f = 6.61\,mm^2 \qquad a_f = \frac{\pi d^2}{4}$

diameter of conductors $d = 2.9\,mm \qquad d = \sqrt{\frac{4a_f}{\pi}}$

diameter of insulated conductor $\qquad d = \sqrt{\frac{4 \times 6.61}{\pi}}$

$d_1 = 2.9 + 0.2 = 3.1\,mm.$

Space factor $S_f = 0.75\,(d/d_1)^2$

$$S_f = 0.75\left(\frac{2.9}{3.1}\right)^2 = 0.65$$

Total winding area $A_w = d_f \times h_f$

$d_f = 35\,mm = 0.035\,m$, $A_w = 0.035\,h_f$

~~∵ From ... d_f = 0.035 for 3.1 m² area~~

Total are of Conductor $A_{c} = S_f \times A_w$.

$= 0.66 \times 0.035\,h_f$.

$= 0.0231\,h_f$

winding area $= T_f\, a_f \times 10^{-6}$ (as a_f is expressed in mm²)

$T_f\, a_f \times 10^{-6} = S_f\, h_f\, d_f$

$= 0.0231\,h_f$

$$T_f = \frac{0.0231 \times 10^6}{6.6} \times h_f = 3.5 \times 10^3\,h_f \rightarrow ①$$

Total dissipating area of a coil considering all surfaces.

$S = 2 L_{mt}(h_f + d_f)$

$S = 2 \times 1.4(h_f + 0.035) = 2.8\,h_f + 0.098$

∴ Permissible loss $Q_f = S \cdot q_f$ $\qquad q_f = 700\,W/m^2$

$= 700\,(2.8\,h_f + 0.098)$

$Q_f = 1960\,h_f + 68.6 \longrightarrow ②$

$$Q_f = I_f^2 R_f = \frac{E_f^2}{R_f} = \frac{E_f^2 a_f}{\rho\, L_{mt}\, T_f}.$$

$$Q_f = \frac{40^2 \times 6.6}{T_f \times 0.021 \times 1.4} = \frac{0.36 \times 10^6}{T_f} \rightarrow ③$$

equating ② & ③ we have

$$1960\,h_f + 68.6 = \frac{0.36 \times 10^6}{T_f}$$

equating ① & ④ we ...

$$3.5\times10^{3} h_f = \frac{0.36\times10^6}{1960\, h_f + 68.6} \quad \text{or } h_f = 0.15\,m$$

No. of turns $T_f = \dfrac{0.36\times10^6}{1960\times0.15+68.6} = 992$

Permissible loss $Q_f = \dfrac{0.36\times10^6}{992} = 362\,\omega$

Field current $I_f = \dfrac{Q_f}{E_f} = \dfrac{362}{40} = 9.07\,A$

) Determine the total commutator losses for 800 kW, 400 V, 300 rpm, 10 pole generator having the following data. Commutator diameter - 100 cm. Current density in brushes = 0.075 A/mm². Brush pressure 14.7 KN/m²; co-efficient of friction: 0.23, total brush contact drop 2.2 V.

Sol:-

Armature current $I_a = \dfrac{P_a}{V} = \dfrac{800\times1000}{400} = 2000\,A.$

Current per brush arm $(I_b) = \dfrac{2 I_a}{P} = \dfrac{2\times2000}{10} = 400\,A.$

Brush area per brush arm $A_b = \dfrac{I_b}{\delta_b} = \dfrac{400}{0.075} = 5333\,mm^2$

Total brush area on the commutator $A_b = P.A_b$

$= 10\times5333$

$= 53.33\times10^3\,mm^2$

$= 53.33\times10^{-3}\,m^2$

Peripheral speed $V_c = \pi D_c n.$

$= \pi\times1\times\dfrac{300}{60}$

$D_c = 100\,cm$
$= 1\,m$

$V_c = 15.70\,m/s.$

Brush friction loss $W_{cf} = \mu P_b A_B V_c$

$= 0.23 \times 14.7 \times 10^3 \times 533 \times 10^{-3} \times$

$= 2829 W$

Brush contact loss $= I_b \times$ brush contact drop

$= 2000 \times 2.2$

$= 4400 W$

$\therefore$ Total commutator loss $= 2829 + 4400$

$= 7229 W.$

(5). An electromagnetic coil has an internal diameter of 0.8m and external diameter of 0.4 m. Its height is 0.2m. The outside cylindrical surface of the coil can dissipated 1000 W/m². Calculate the total mmf per coil if the voltage applied across the coil is 50 Volts. Assume the space factor to be 0.6 and the resistivity of the wire to be 0.02

Given: $E_f = 50V$; $d_p = 0.8m$; $d_f = 0.4m$; $h_f = 0.2m$

Length of mean turn of field coil

$L_{mt} = (d_p + d_f) = \pi (0.8 + 0.4)$

$= 3.77 m$

Resistance of each field coil. $R_f = \frac{\rho L_{mt} T_f}{a_f}$

Also $R_f = \frac{E_f}{I_f}$ and $I_f = \frac{q_f}{E_f}$

Given $q_f = 1000 W/m^2 = I_f = \frac{1000}{50} = 20A$

$R_f = \frac{50}{20} = 2.5 \Omega$

Current density in Shunt field winding lies b/w 1.2 to 2.5 A/mm² Assume $\delta = 2 A/mm^2$

Area of CS of field conductor $a_f = \frac{I_f}{\delta_f}$

$a_f = \frac{20}{2} = 10 mm^2$

$\therefore$ No. of turns $T_f = \frac{a_f R_f}{\rho L_{mt}}$

$= \frac{10 \times 2.5}{0.02 \times 3.77} = 332$ turns

$\therefore$ Total mmf per coil, $AT_f = I_f T_f$

$= 20 \times 332$

$AT_f = 6640$ Amp cond

UNIT 3
DESIGN OF TRANSFORMER

Design of Transformers

Transformers are classified as

1) Core type 2) Shell type

1) Step up 2) Step down

1) Distribution 2) Power

Comparison between Distribution & Power transformer

Sl.no.	Item of Comparison	Distribution Transformer	Power Transformer
1.	Capacity	up to 500 kVA	beyond 500 kVA up to 500 MVA or more.
2.	Voltage rating	11, 22 or 33 kV / 440V	400 kV / 33 kV;
3.	Connection	Delta / star 3ph, 4 wire.	Delta / Delta, Delta/star 3ph 3 wire
4.	Load	100% for few hrs, Part load for some time, no load for few hrs.	Nearly on full load
5.	Flux density	upto 1.5 Tesla with CRGOS	upto 1.7 tesla with CRGOS
6.	Current density	upto 2.6 A/mm²	upto 3.3 A/mm²
7.	Ratio of iron loss to copper loss	1:3 (approx)	1:1 (approx)
8	Regulation	4 to 9%.	6 to 10%
9	Cooling	Self oil cooled	Forced oil cooled
10	Type	Step down	Step up.
11.	Maximum efficiency	load much lesser than full load	at or near full load.
12	leakage reactance	Small	high

Core type	Shell type
1. Easy in design & construction	1. Comparatively complex
2. Has low mechanical strength due to non-bracing of windings	2. High mechanical strength
3. Reduction of leakage reactance is not easily possible	3. Reduction of leakage reactance is highly possible
4. The assembly can be easily dismantled for repair work	4. It cannot be easily dismantled for repair work.
5. Better heat dissipation from windings	5. Heat is not easily dissipated from windings since it is surrounded by core.
6. Long core length & short length of coil turn. Best suited for EHV requirements	6. It is not suitable for EHV requirements

IMP

* **Output Equation of Single phase Transformer.**

The equation which relates the rated KVA output of a Transformer to the area of core and window is called output equation. In Transformer the output KVA depends on flux density and ampere-turns.

Flux density $\longrightarrow$ core area

Ampere turns $\longrightarrow$ window area.

The induced emf in a transformer $E = 4.44 f \phi_m T$ Volts.

Emf per turn, $E_t = E/T = 4.44 f \phi_m$ Volts $\rightarrow$ ②

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

Window space factor, $K_w = \frac{\text{conductor area in window}}{\text{Total area of window}} = \frac{A_c}{A_w}$

$\therefore$ Conductor area in window, $A_c = K_w A_w \rightarrow (4)$.

The current density δ is same in both the windings.

$\therefore$ current density, $\delta = \frac{I_p}{a_p} = \frac{I_s}{a_s} \rightarrow (5)$

Area of cross - section of primary conductor, $a_p = \frac{I_p}{\delta} \rightarrow (6)$

Area of cross - section of secondary conductor $a_s = \frac{I_s}{\delta} \rightarrow (7)$

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

$\therefore$ Ampere turns $= AT = I_p T_p = I_s T_s \rightarrow (8)$

Total copper area in window. A_c = Copper area of primary winding + Copper area of secondary winding

= No. of primary turns x area of cross section of primary conductor + No. of sec turns x area of cross s. of sec conductor

$$A_c = T_p a_p + T_s a_s \qquad \left(\because a_p = \frac{I_p}{\delta} \; \& \; a_s = \frac{I_s}{\delta}\right)$$

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

$$= \frac{1}{\delta}(T_p I_p + T_s I_s) \qquad (\because AT = I_p T_p = I_s T_s$$

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

$$A_c = \frac{2AT}{\delta} \rightarrow (9)$$

On equating equation (4) and (9) we get.

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

$\therefore$ Ampere turns, $AT = \frac{K_w A_w \delta}{2} \rightarrow (10)$

The KVA rating of Single phase transformer is given by

KVA rating, $Q = V_p I_p \times 10^{-3} \approx E_p I_p \times 10^{-3}$ ($\because E_p$

$$= \frac{E_p}{T_p} \cdot T_p I_p \times 10^{-3} \quad \left(\because E_t = \frac{E_p}{T_p},\ AT = T_p I_p\right)$$

$$\therefore Q = E_T \cdot AT \times 10^{-3} \rightarrow (11)$$

On substituting for E_T and AT from equations (2) & (10) in equation (11) we get.

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

$$Q = 2.22 f \phi_m K_w A_w \delta \times 10^{-3} \quad \left(\because B_m = \frac{\phi_m}{A_i}\right)$$

$$\boxed{Q = 2.22 f B_m A_i K_w A_w \delta \times 10^{-3}}\ \text{KVA} \rightarrow (12)$$

The equation (12) is the output equation of Single phase Transformer (both core & shell type).

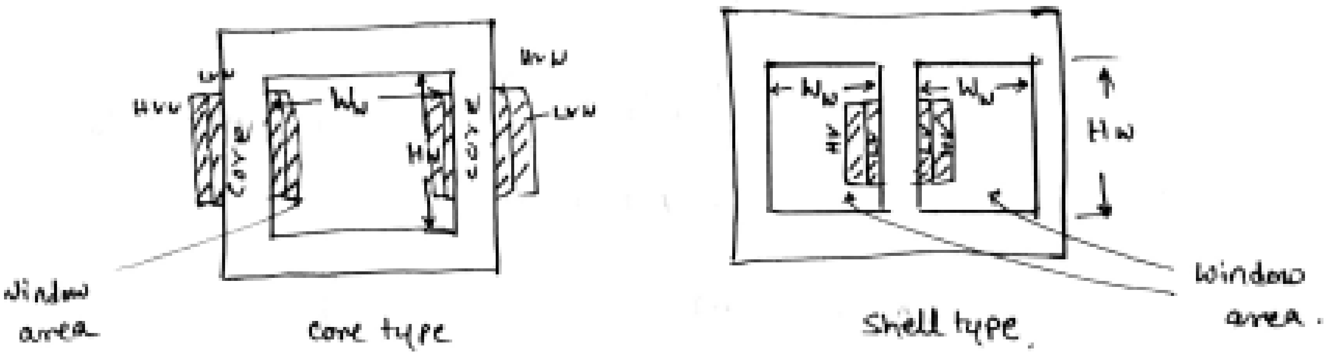


Fig. 1 Cross sectional area of core in Single phase Transformer.

* Output equation of Three phase Transformer

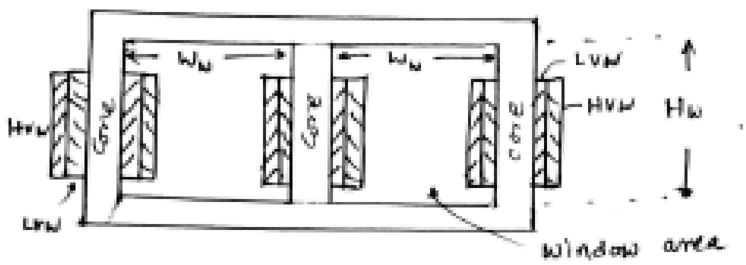


fig 2. Cross section of core type 3phase transformer.

The simplified cross-section of core type 3phase transformer is shown in fig.2. The cross-section has 3 limbs and 2 windows. Each limb carries the low voltage & High voltage winding of a phase.

The induced Emf per phase $E = 4.44 f \phi_m T$ volts $\rightarrow$ (1)

Emf per turn, $E_t = \frac{E}{T} = 4.44 f \phi_m$ volts $\rightarrow$ (2)

In case of Three phase transformer, each window has two primary and two secondary windings. The window space factor Kw,

$$K_w = \frac{\text{Conductor area in window}}{\text{Total area of window}} = \frac{A_c}{A_w} \rightarrow (3)$$

$\therefore$ Conductor area in window, $A_c = K_w A_w$ $\rightarrow$ (4)

Note: In three phase transformer, one window is considered

The current density δ is same in both the windings.

$$\therefore \text{ Current density}, \ \delta = \frac{I_p}{a_p} = \frac{I_s}{a_s} \rightarrow (5)$$

where I_p = Primary current per phase

I_s = Secondary current per phase.

Area of cross section of Primary conductor. $a_p = \frac{I_p}{\delta} \rightarrow (6)$

Area of cross-section of secondary conductor $a_s = \frac{I_s}{\delta} \rightarrow (7)$

If we neglect magnetizing mmf then primary ampere turns per phase is equal to Secondary ampere turns per phase

$\therefore$ Ampere turns $AT = I_p T_p = I_s T_s \rightarrow (8)$

Total copper area in window $A_c = \left\{ \begin{array}{l} 2 \times \text{No. of primary} \\ \text{turns} \times \text{area of} \\ \text{c/s of Pri. conductor} \end{array} \right\} + \left\{ \begin{array}{l} 2 \times \text{No of Sec. turns} \times \text{area} \\ \text{of c/s. of secondary} \\ \text{conductors} \end{array} \right\}$

$$A_c = 2 T_p a_p + 2 T_s a_s$$

$$= 2 T_p \frac{I_p}{\delta} + 2 T_s \frac{I_s}{\delta} \qquad \left(\because a_p = \frac{I_p}{\delta}, \; a_s = \frac{I_s}{\delta} \right)$$

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

$$= \frac{2}{\delta} (AT + AT) \qquad (\because AT = I_p T_p = I_s T_s)$$

$$A_c = \frac{4AT}{\delta} \longrightarrow (9)$$

On equating equation (4) and (9) we get

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

$$\therefore \text{Ampere turns } AT = \frac{K_w A_w \delta}{4} \longrightarrow (10)$$

The KVA rating of Three phase transformer is given by

$$\text{KVA rating } Q = 3 \times \text{Volt-ampere per phase} \times 10^{-3}$$

$$= 3\ V_p I_p \times 10^{-3} \qquad (\because E_p \simeq V_p)$$

$$= 3\ E_p I_p \times 10^{-3}$$

$$= 3\ \frac{E_p}{T_p} \times T_p I_p \times 10^{-3} \qquad \because E_t = \frac{E_p}{T_p}, \quad AT = T_p I_p$$

$$Q = 3\ E_t\ AT \times 10^{-3} \rightarrow (11)$$

On substituting for E_t and AT from equations (2) & (10) in equation (11) we get

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

$$= 3.33\, f\, \phi_m\, K_w\, A_w\, \delta \times 10^{-3} \qquad \left(\because B_m = \frac{\phi_m}{A_i}\right)$$

$$\boxed{\therefore Q = 3.33\, f B_m A_i\, K_w\, A_w\, \delta \times 10^{-3}}\ \text{KVA} \rightarrow (12).$$

The equation (12) is the output equation of three phase transformer. (both core & shell type).

Emf per turn: The transformer design starts with selection of an appropriate value for emf per turn. Hence an equation for emf per turn can be developed by relating output KVA, magnetic and electric loading.

In transformer the ratio of specific magnetic and electric loading is specified.

Let, ratio of specific magnetic & Electric loading $r = \frac{\phi_m}{AT} \rightarrow (1)$.

The volt-ampere per phase of a transformer is given by the product of voltage and current per phase.

Considering the primary voltage and current per phase we can write,

KVA per phase, $Q = V_p I_p \times 10^{-3}$ $\quad (\because V_p = E_p = 4.44 f \phi_m T_p)$

$$= 4.44 f \phi_m T_p I_p \times 10^{-3}$$

$$= 4.44 f \phi_m AT \times 10^{-3} \quad (\because T_p I_p = AT)$$

$$Q = 4.44 f \phi_m \frac{\phi_m}{r} \times 10^{-3} \quad \left(\because AT = \frac{\phi_m}{r}\right)$$

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

$$\phi_m = \sqrt{\frac{Q \cdot r \times 10^{+3}}{4.44 f}} \longrightarrow (2)$$

We know that,

emf per turn $E_t = 4.44 f \phi_m \longrightarrow (3)$

on substituting for ϕ_m from equation (2) in eqn (3) we get

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

$$= \sqrt{4.44 f r \times 10^3} \sqrt{Q}$$

$$\boxed{E_t = K \sqrt{Q}} \longrightarrow (4)$$

Where $K = \sqrt{4.44 f r \times 10^3} = \sqrt{4.44 f \frac{\phi_m}{AT} \times 10^3} \longrightarrow (5)$

From equation ④ we can say that the emf per turn is directly proportional to K. The value of K depends on the type, service condition and method of construction of transformer.

The value of K for different types of Transformer are listed in table.

Transformer Type	Value of K.
Single phase shell type	1.0 to 1.2
Single phase core type	0.75 to 0.85
Three phase shell type	1.3
Three phase core type (Distribution tran)	0.45
Three phase core type (Power transfor)	0.6 to 0.7

Note: in equation ④ the Q is KVA rating for single phase transformer and Q is KVA per phase for 3 phase transformer

Choice of Specific loading:-

a) Specific magnetic loading (B_m) (Flux density):-

The flux density decides the area of cross-section of core and core loss. Higher values of flux density results in smaller core area, lesser cost, reduction in length of mean turn of winding, higher iron losses & large magnetizing current.

The choice of flux density depends on service condition (distribution or transmission) and material used for lamination of the core.

The laminations made with CRGO silicon steel with higher flux densities than the hot rolled silicon steel.

usually the distribution transformer will have low flux density to achieve lesser iron loss.

When hot rolled silicon steel is used for lamination, The values can be used for max flux density (B_m) are

Power transformer - 1.2 to 1.5 Tesla

Distribution transformer - 1.1 to 1.4 Tesla.

Using cold rolled grain oriented silicon steel :

Power transformer - 1.5 to 1.7 Tesla

Distribution transformer - 1.4 to 1.5 Tesla

b) Specific Electric loading Current density

Sectional area of the conductor for the windings is reduced by choosing a higher current density, which results into saving of costly copper material, thus resulting into a cheaper design. Hence economics of the transformer suggests a higher current density for the winding.

However, with higher current density, the resistance of the windings will be comparatively higher, resulting into increased copper losses, thus reducing the efficiency and increasing the temperature rise of the transformer. this will results in deterioration of the insulation of the winding.

As such value of current density should be choosen, by making a proper compromise between the above conflicting factors.

Moreover, the current density for h.v. winding should be taken higher than the current density for L.V winding, because cooling conditions are better in the h.v. winding.

Values used for the average current density are

Distribution transformer - 2.0 to 2.5 A/mm^2

Power Transformer - 2.3 to 3.5 A/mm^2

Large transformers with forced circulation of oil - 3 to 4.5 A/mm^2.

Example: 1 Calculate the core and window areas required for a 1000 KVA, 6600/400 V, 50Hz, single phase core type transformer. Assume a maximum flux density of 1.25 wb/m^2 and a current density of 2.5 A/mm^2. Voltage per turn = 30V. Window space factor = 0.32

Given:

KVA = 1000, $f = 50Hz$, $B_m = 1.25\ wb/m^2$ $A_i = ?$

$A_w = ?$

$V_p = 6600V$, $V_s = 400V$, $\delta = 2.5\ A/mm^2$

$E_t = 30V$ $K_w = 0.32$ 1-ph core type.

Soln: Emf per turn, $E_t = 4.44 f \phi_m$

$$\phi_m = \frac{E_t}{4.44 f} = \frac{30}{4.44 \times 50} = 0.1351\ wb$$

Flux density, $B_m = \dfrac{\phi_m}{A_i}$

$\therefore$ net area of cross section of core $A_i = \dfrac{\phi_m}{B_m} = \dfrac{0.1351}{1.25} = 0.108\ m^2$

$A_i = 0.108 \times 10^6\ mm^2$

KVA rating of Transformer, $Q = 2.22 f B_m A_i K_w A_w \delta \times 10^{-3}$

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

$$= \frac{1000}{2.22 \times 50 \times 1.25 \times 0.108 \times 0.32 \times 2.5 \times 10^6 \times 10^{-3}}$$

$A_w = 0.0833\ m^2 = 0.0833 \times 10^6\ mm^2$

Design of core :

For core type transformer the cross-section may be rectangular, square or stepped.

Generally circular coils are used for LV & HV windings which
of the transformer because of better mechanical strength,
indicate theoretically that a circular core should be used.
It is very complicated to manufacture a circular core and
as a result the stepped core is generally used.

In case of small transformers, a square core can be used
but for large transformers stepped core is used in order to
to utilize fully the space available, which mean smaller diameter
of the circumscribing circle over the stepped core, Hence the
length of mean turn of the windings will be reduced which results
in saving of copper material for the windings.

However, with larger number of steps used for the core,
labour charges for shearing and assembling different laminations
will increase appreciably. Thus a compromise has to be made
between these factors to decide the number of steps.
The number of steps will depend upon the kVA rating of the
transformer

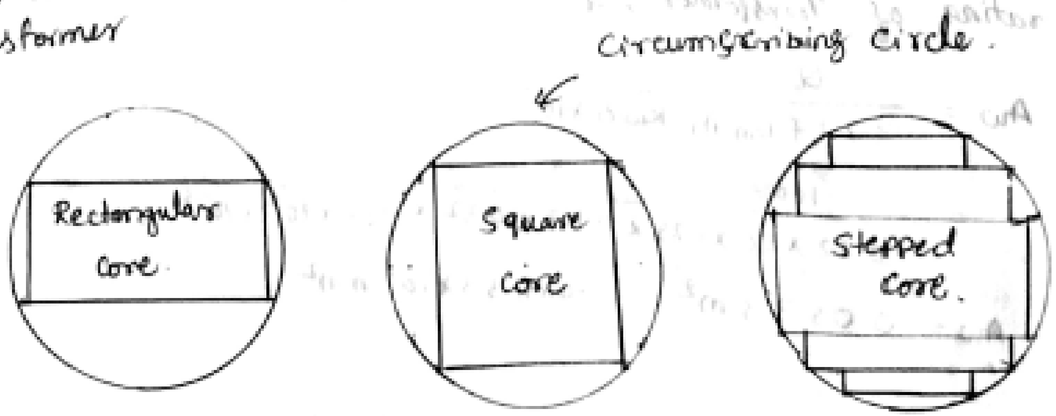


Fig.3 Cross Section of Transformer core.

Square core :-

Let d = diameter of circumscribing circle. Also d = diagonal of the square core.

a = side of core (width of the stamping (leg))

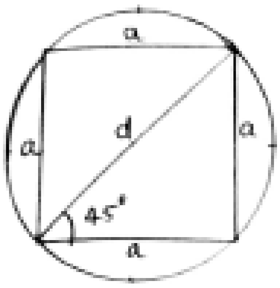


Fig: 4.

$a = d \sin 45°$

$a = 0.71 d$

A_{gi} = Gross core area $= a^2 = (0.71d)^2$

$\underline{\underline{A_{gi} = 0.5 d^2}}$

Let stacking factor, $S_f = 0.9$.

Net core area A_i = Stacking factor × gross core area

$A_i = 0.9 \times 0.5 d^2$

$\underline{\underline{A_i = 0.45 d^2}}$

Note: The gross core area is the area including insulation area and net core area is the area of iron alone excluding insulation area.

The ratio, $\dfrac{\text{Net Core area}}{\text{Area of circumscribing circle}} = \dfrac{0.45 d^2}{(\pi/4) d^2} = \underline{\underline{0.58}} \rightarrow (1)$

The ratio, $\dfrac{\text{Gross Core area}}{\text{Area of circumscribing circle}} = \dfrac{0.5 d^2}{(\pi/4) d^2} = \underline{\underline{0.64}} \rightarrow (2)$

Another useful ratio for the design of transformer core area factor, It is the ratio of net core area and square of the circumscribing circle

Core area factor, $K_c = \dfrac{\text{Net core area}}{\text{Square of circumscribing circle}} =$

$K_c = \dfrac{A_i}{d^2} = \dfrac{0.45 d^2}{d^2} = \underline{\underline{0.45}}$

Two stepped core or Cruciform core :

In stepped cores the dimensions of the steps should be choosen. Such as to occupy maximum area within a circle.

Let a = Length of the rectangle
(Width of the largest stamping)

b = breadth of the rectangle
(width of the smallest stamping)

d = Diameter of the circumscribing circle

Also d = diagonal of the rectangle

θ = Angle between the diagonal & length of the rectangle

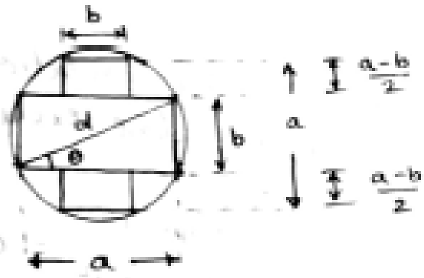


fig: 5 Cross section of two stepped core.

The Cross-section of two stepped core is shown in fig. The maximum core area for a given d is obtained when θ is maximum value. Hence differentiate A_{gi} with respect to θ and equate to zero to solve for maximum value of θ.

From fig 5. we get

$a = d\cos\theta$, $b = d\sin\theta$.

The two stepped core can be divided into three rectangles. The area of three rectangles gives the gross core area.

$$\text{Gross core area, } A_{gi} = ab + \left(\frac{a-b}{2}\right)b + \left(\frac{a-b}{2}\right)b$$

$$= ab + 2\frac{(a-b)}{2}b$$

$$= ab + ab - b^2$$

$$A_{gi} = 2ab - b^2$$

$$A_{gi} = 2(d\cos\theta)(d\sin\theta) - (d\sin\theta)^2$$
$$= 2d^2\cos\theta\sin\theta - d^2\sin^2\theta$$
$$= d^2(2\sin\theta\cos\theta - \sin^2\theta)$$
$$= d^2(\sin 2\theta - \sin^2\theta)$$
$$A_{gi} = d^2\sin 2\theta - d^2\sin^2\theta$$

To get maximum value of θ, differentiate A_{gi} w.r.t θ and equate to zero

ie. $\frac{d}{d\theta} A_{gi} = 0$

$$\frac{d}{d\theta} A_{gi} = d^2\cos 2\theta \times 2 - d^2\, 2\sin\theta\cos\theta$$
$$\therefore\ d^2\cos 2\theta \times 2 - d^2\, 2\sin\theta\cos\theta = 0$$
$$d^2\, 2\sin\theta\cos\theta = d^2\cos 2\theta \times 2$$
$$d^2\sin 2\theta = d^2\cos 2\theta \times 2$$
$$\frac{\sin 2\theta}{\cos 2\theta} = 2$$
$$\tan 2\theta = 2$$
$$2\theta = \tan^{-1} 2$$
$$\theta = \frac{\tan^{-1} 2}{2}$$
$$\theta = 31.72^\circ$$

when $\theta = 31.72^\circ$, the dimensions of the core (a & b) will give the maximum area for core for a specified d.

$$a = d\cos\theta \qquad b = d\sin\theta$$
$$= d\cos 31.72^\circ \qquad = d\sin 31.72^\circ$$
$$a = 0.85d \qquad b = 0.53d$$

$$\therefore\ A_{gi} = 2ab - b^2$$
$$= 2(0.85d)(0.53d) - (0.53d)^2$$
$$A_{gi} = 0.618d^2$$

Let stacking factor $S_f = 0.9$

Net core area, A_i = stacking factor × Gross core area
$$= 0.9 \times 0.618d^2$$
$$A_i = 0.56d^2$$

The ratio = $\dfrac{\text{Net core area}}{\text{Area of circumscribing circle}} = \dfrac{0.56d^2}{(\pi/4)d^2} = 0.71$

The ratio, $\dfrac{\text{Gross core area}}{\text{Area of circumscribing circle}} = \dfrac{0.618d^2}{(\pi/4)d^2} = 0.79$

Core area factor $K_c = \dfrac{\text{Net core area}}{\text{Square of circumscribing circle}}$

$$K_c = \frac{A_i}{d^2} = \frac{0.56\,d^2}{d^2} = \underline{\underline{0.56}}$$

By increasing the number of steps, the area of circumscribing circle is more effectively utilised. The most economical dimensions of various steps for a multistepped core can be calculated. The results are tabulated in the table.

Ratio	Square core	Cruciform core	3-Stepped core	4 Stepped core
$\dfrac{A_{gi}}{\text{Area of circumscribing circle}}$	0.64	0.79	0.84	0.87
$\dfrac{A_i}{\text{Area of circumscribing circle}}$	0.58	0.71	0.75	0.78
Core area factor $K_c = \dfrac{A_i}{d^2}$	0.45	0.56	0.6	0.62

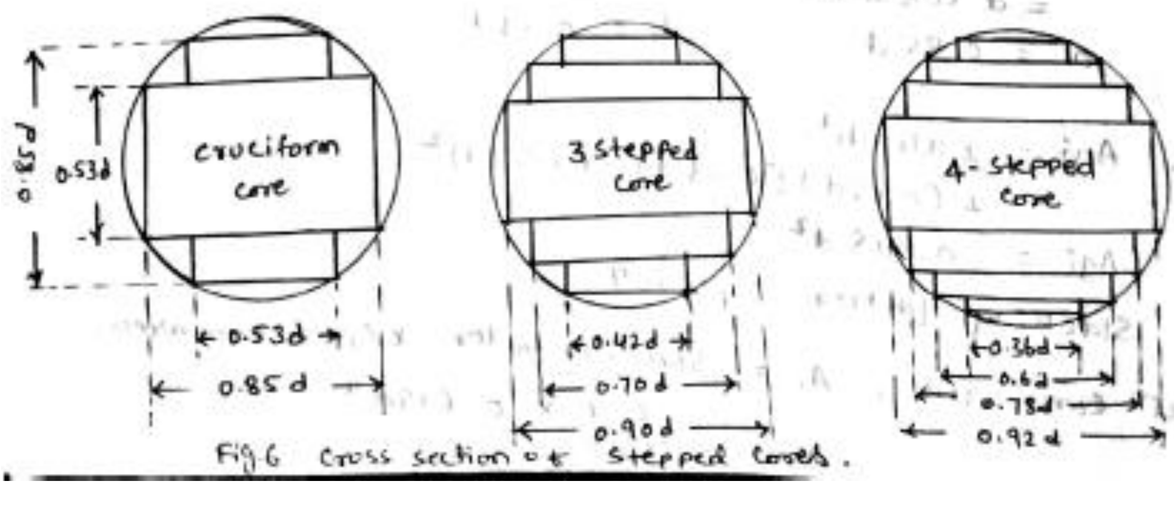
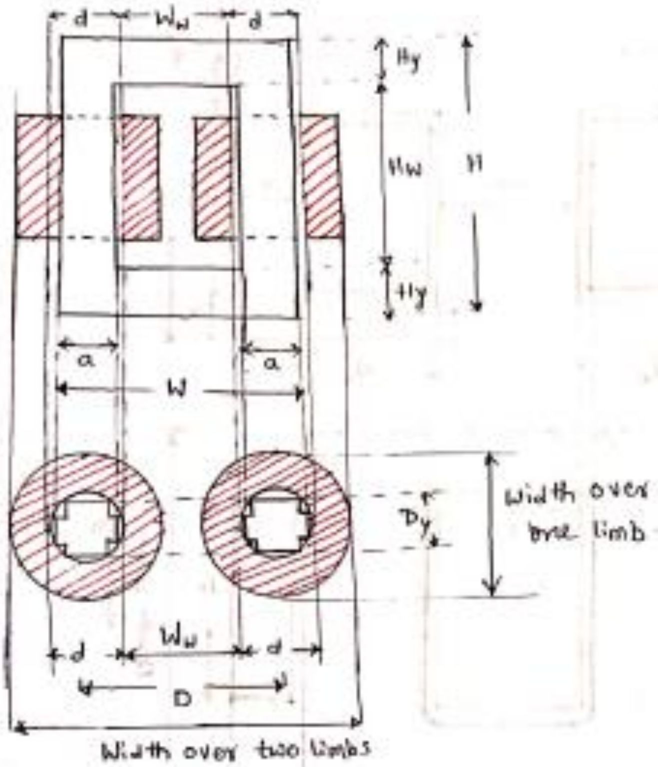


Fig.6 Cross section of stepped cores.

Overall Dimensions of the transformers:-

Vertical Cross Section



Horizontal Cross section

Fig:7 single phase core type transformer.

The main dimensions of the transformer are

H_w → Height of window

W_w → width of window

a → width of largest stamping

d → diameter of circumscribing circle.

D → distance between the core centres.

H_y → Height of yoke

D_y → Depth of yoke

H → overall Height of transformer frame.

W → overall width of transformer frame.

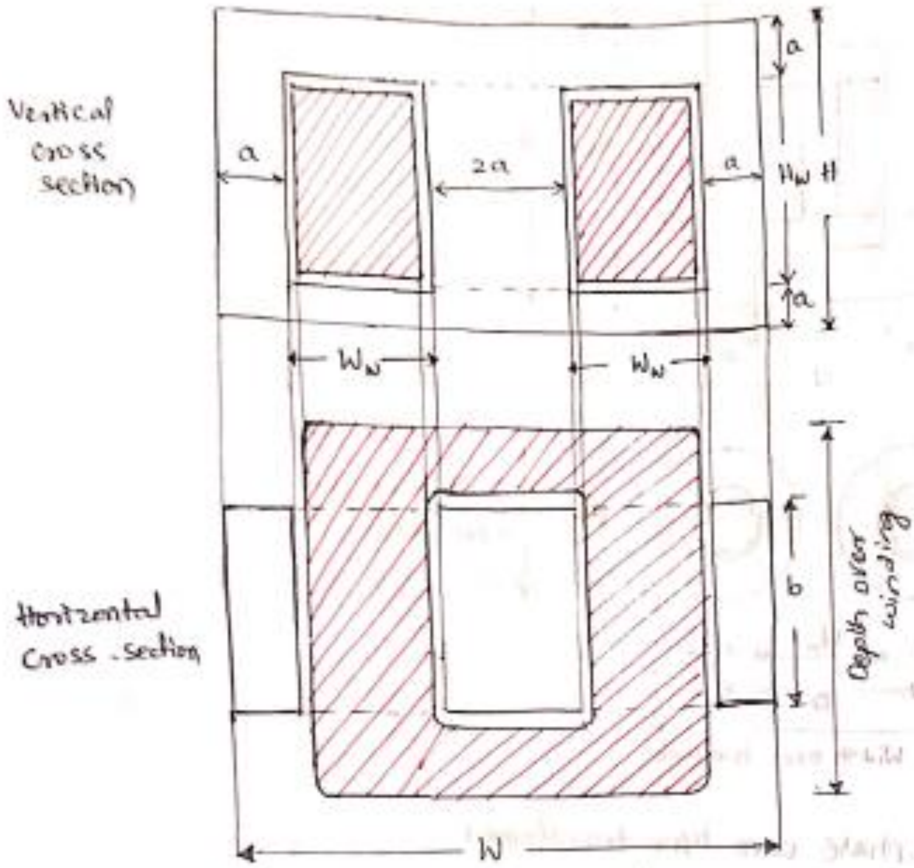


Fig:8 Single phase Shell type transformer

Area of Yoke A_y = depth of yoke x height of yoke.

$A_y = D_y \times H_y$, $D_y = a$,

$A_y = 1.1$ to $1.15 A_i$ (

$A_y = A_i$ (CRGO

Core type :-

W = overall length of the frame Single phase

$W = W_w + 2a$ (or) $D + a$ $\quad D = d + W_w$, $D_y = a$.

$W = (2W_w + 2d + a)$ (or) $2D + a$ → Three phase

H = overall Height $= H_w + 2H_y$ → both single & 3 ph.

For single phase Shell type

$D_y = b, \quad H_y = a.$

$W = 2W_w + 4a$

$H = H_w + 2a$ (or) $H_w + 2H_y$.

Design of winding:

The transformer has one high voltage winding & one one low voltage winding.

The design of winding involves the determination of number of turns and area of cross section of the conductor used for winding.

Number of turns → Voltage rating & Emf per turn

Area of cross section → rated current & current density.

$V_1 = E_1 = 4.44\,\phi_m f\,T_1 = E_t T_1$

∴ No. of Primary turns $T_1 = V_1 / E_t$ → single phase

$T_1 = V_{1ph} / E_t$ → 3 phase.

No. of Secondary turns $T_2 = V_2 / E_t$ → single phase

$T_2 = V_{2ph} / E_t$ → 3 phase.

Primary current $I_1 = \dfrac{KVA \times 10^3}{V_1}$ → 1 ph

$I_1 = \dfrac{KVA \times 10^3}{3V_{ph}}$ → 3 ph.

Secondary current $I_2 = \dfrac{KVA \times 10^3}{V_2}$ → 1 ph

$I_2 = \dfrac{KVA \times 10^3}{3V_{2ph}}$ → 3 ph

Cross sectional area of Primary winding $a_1 = \frac{I_1}{\delta}$ mm^2

Cross sectional area of secondary winding $a_2 = \frac{I_2}{\delta}$ mm^2.

Example: 2 Estimate the main dimensions including winding conductor area of 3-phase, Δ-Y core type transformer rated at 300KVA, 6600/440, 50Hz. A Suitable core with 3-steps having a circumscribing circle of 0.25m diameter and a leg spacing of 0.4m is available. Emf per turn = 8.5V, $\delta = 2.5A/mm^2$, $K_w = 0.28$ $S_f = 0.9$ (Stacking fa

Given data.

3ph Δ-Y. $f = 50Hz$ $E_t = 8.5V$, 6600/440V

3 Stepped core $\delta = 2.5A/mm^2$ $K_w = 0.28$ leg Spacing = 0.4m.

300KVA $d = 0.25m$ $S_f = 0.9$

∴ Secondary voltage per phase, $V_s = \frac{440}{\sqrt{3}} = 254V$

$E_s \approx V_s$

∴ Emf per turn $E_t = E_s / T_s$

∴ No. of secondary turns per phase, $T_s = \frac{E_s}{E_t} = \frac{254}{8.5} = 29.88 \simeq 30$

$$\therefore T_p = T_s \frac{V_p}{V_s} = 30 \times \frac{6600}{254}$$

$$T_p = 779.5 \simeq 780 \text{ turns}$$

The KVA rating of transformer $Q = \sqrt{3} V_{Lp} I_{Lp} \times 10^{-3} = \sqrt{3} V_{Ls} I_{Ls} \times 10^{-3}$

Line current on primary side $I_{Lp} = \frac{Q}{\sqrt{3} V_{Lp} \times 10^{-3}}$

$$= \frac{300}{\sqrt{3} \times 6600 \times 10^{-3}}$$

$$I_{Lp} = 26.24A$$

Since Primary is delta connected
The phase current on primary $I_p = \frac{I_{Lp}}{\sqrt{3}} = \frac{26.24}{\sqrt{3}} = 15.15A$

The area of cross section of primary conductor $a_p = \frac{I_p}{\delta}$

$$a_p = \frac{15.15}{2.5} = 6.06\ mm^2$$

The line current on secondary side

$$I_{Ls} = \frac{Q}{\sqrt{3} \times V_{Ls} \times 10^{-3}}$$

$$= \frac{300}{\sqrt{3} \times 440 \times 10^{-3}}$$

$$I_{Ls} = 393.65\ A$$

Since secondary is star connected.
The phase current on secondary $I_s = I_{Ls} = 393.65A$

The area of cross-section of secondary conductor $a_s = \frac{I_s}{\delta} = \frac{393.65}{2.5} = 157.7\ mm^2$

The copper area in window. $A_c = 2(a_p T_p + a_s T_s)$

$$= 2(6.06 \times 780 + 157.5 \times 30)$$

$$= 18903.6\ mm^2$$

Window Area = $A_w = \frac{A_c}{K_w} = \frac{18903.6}{0.28} = 67512.86\ mm^2$

$$= 67512.86 \times 10^{-6}\ m^2$$

$$= 0.0675 m^2$$

Area of circumscribing circle : $\frac{\pi d^2}{4} = \frac{\pi\ (0.25)^2}{4} = 0.049 m^2$

For 3 stepped core, the ratio : $\frac{\text{Gross core area}}{\text{Area of circum scribing circle}} = 0.84$

Gross core area A_{gi} = 0.84 x Area of circumscribing circle

$= 0.84 \times 0.049$

$A_{gi} = 0.041\, m^2$

Net core area $= A_i = S_f \times A_{gi}$

$= 0.9 \times 0.041$

$A_i = 0.0369\, m^2$

$= 0.037 \times 10^6\, mm^2$

Leg spacing = 0.45 m

width of window, W_w = Leg spacing = 0.45m

Height of window $H_w = \frac{A_w}{W_w} = \frac{0.0675}{0.45} = 0.15\, m$

Answers:

$T_p = 780$

$T_s = 30$

$a_p = 6.06\, mm^2$

$a_s = 157.5\, mm^2$

$A_i = 0.0369\, m^2$

$A_w = 0.0675\, m^2$

$H_w = 0.15\, m$

$W_w = 0.45\, m$

Example: 3 A 3phase, 50Hz. oil cooled core type transformer has the following dimensions:

Distance between core centres = 0.2m
Height of window = 0.24 m.
Diameter of circumscribing circle = 0.14m
The flux density in the core = 1.25 Wb/m^2
The current density in the conductor = 2.5 A/mm^2

Assume window space factor = 0.2 &
core area factor = 0.56.

The core is 2 stepped. Estimate KVA rating of the transformer

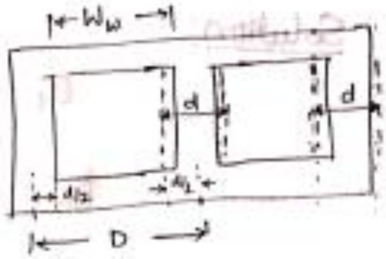
Given data:

3ph.
f = 50Hz
core type
2 stepped core

D = 0.2m
H_w = 0.24 m
d = 0.14 m
B_m = 1.25 Wb/m^2

δ = 2.5 A/mm^2
K_w = 0.2
K_c = 0.56.

KVA = ?
A_w = ?
A_i = ?



Soln:

The KVA rating of 3ph transformer $Q = 3.33 f B_m A_i K_w A_w \delta \times 10^{-3}$

Width of window = D − d
= 0.2 − 0.14 = 0.06m

Window area = $A_w = H_w \times W_w$
= 0.24 × 0.06
A_w = $0.0144 m^2$

For two stepped core K_c = 0.56. $K_c = \frac{A_i}{d^2}$

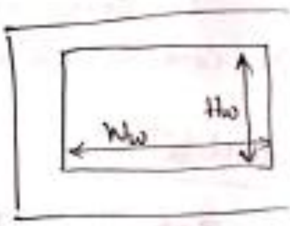
Hence net core area $A_i = K_c d^2 = 0.56 \times (0.14)^2 = 0.01098 m^2$
$= 0.011 m^2$

KVA rating, $Q = 3.33 f B_m A_i K_w A_w \delta \times 10^{-3}$
$= 3.33 \times 50 \times 1.25 \times 0.011 \times 0.2 \times 0.0144 \times 2.5 \times 10^6 \times 10^{-3}$

$\boxed{Q = 16.4835 \text{ KVA}}$

Example 4 Determine the dimensions of core and window for a 5KVA, 50Hz, Singlephase, core type transformer. A rectangular core is used with long side twice as long as short side. The window height is 3 times the width. Voltage per turn = 1.8V, space factor = 0.2. $\delta = 1.8\,A/mm^2$. $B_m = 1\,wb/m^2$

Given data



$Q = 5KVA$, coretype $\delta = 1.8\,A/mm^2$

$f = 50Hz$, rectangular core $B_m = 1\,wb/m^2$

1-ph $E_t = 1.8V$, long side = 2 x Short side

$H_w = 3W_w$ $k_w = 0.2$ $a = 2b$

Solution:

$$E_t = 4.44 f \phi_m$$

$$\phi_m = \frac{E_t}{4.44f} = \frac{1.8}{4.44 \times 50}$$

$$\phi_m = 0.0081\,wb$$

Net core area = $A_i = \frac{\phi_m}{B_m} = \frac{0.0081}{1} = 0.0081\,m^2$

Gross core area = $A_{gi} = \frac{A_i}{S_f} = \frac{0.0081}{0.9}$ let $S_f = 0.9$

$$A_{gi} = 0.009\,m^2$$

A_{gi} = length of the core x breadth of the core

$A_{gi} = a \times b$ $a = 2b$

$A_{gi} = 2b \times b$

$A_{gi} = 2b^2$

$$b = \sqrt{\frac{A_{gi}}{2}} = \sqrt{\frac{0.009}{2}} = 0.067\,m$$

$$a = 2b = 2 \times 0.067 = 0.134\,m$$

KVA rating of single phase transformer.

$$Q = 2.22\, f\, B_m\, A_i\, k_w\, A_w\, \delta \times 10^{-3}.$$

$$\text{Window area} = A_w = \frac{Q}{2.22\, f\, B_m\, A_i\, k_w\, \delta \times 10^{-3}}$$

$$A_w = \frac{5}{2.22 \times 50 \times 1 \times 0.0081 \times 0.2 \times 1.8 \times 10^{6} \times 10^{-3}}$$

$$A_w = 0.0154\,m^2$$

Also window area $A_w = H_w W_w$. $\left(\because H_w = 3W_w\right)$

$$A_w = 3W_w \times W_w = 3W_w^2$$

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

$$W_w = \sqrt{\frac{0.0154}{3}}$$

$$W_w = 0.0716\,m$$

$$H_w = 3W_w = 3 \times 0.0716 = 0.2148\,m$$

Answers.

The net core area $A_i = 0.0081\,m^2$

The dimensions of the core; $a \times b = 0.134 \times 0.067\,m$

The window area $A_w = 0.0154\,m^2$

The dimensions of window: $H_w \times W_w = 0.2148 \times 0.076\,m$.

Example: 5 Determine the dimensions of the core, the number of turns, the cross-sectional area of conductors in primary and secondary windings of a 100 KVA, 2200/480V, 1-ph, core type transformer, to operate at a frequency of 50Hz, by assuming the following data
Approx volt per turn = 7.5V
Max flux density = 1.2 wb/m^2.
Ratio of effective cross sectional area of core to square of diameter of circumscribing circle is 0.6.
Ratio of height to width of window is 2; window space factor:
current density = 2.5 A/mm^2

Given data:

100 KVA	$f = 50Hz$	$H_w/W_w = 2$	$\delta = 2.5\ A/mm^2$
2200/480V	$E_t = 7.5V$	1ph	
$K_w = 0.28$	$B_m = 1.2\ wb/m^2$	$A_i/d^2 = 0.6$	
Core type			

Solution:

$$E_t = 4.44 f \phi_m$$

$$\therefore \phi_m = \frac{E_t}{4.44\, \phi m} = \frac{7.5}{4.44 \times 50} = 0.03378\ wb$$

$$B_m = \frac{\phi_m}{A_i} \quad \therefore \text{Net core area } A_i = \frac{\phi_m}{B_m} = \frac{0.03378}{1.2} = 0.028$$

$\frac{A_i}{d^2} = 0.6$. Hence the core is 3-stepped core.

$$d = \sqrt{\frac{A_i}{0.6}} = \sqrt{\frac{0.0282}{0.6}} = 0.2168\ m$$

KVA rating of 1-Ph transformer $Q = 2.22 f B_m A_i K_w A_w \delta \times 10^{-3}$

Window area $A_w = \dfrac{Q}{2.22 f B_m A_i K_w \delta \times 10^{-3}}$

$= \dfrac{100}{2.22 \times 50 \times 1.2 \times 0.0282 \times 0.28 \times 2.5 \times 10^6 \times 10^{-3}}$

$A_w = 0.038\, m^2$

$\dfrac{H_w}{W_w} = 2$, $H_w = 2 W_w$

Window Area $A_w = H_w \times W_w$
$A_w = 2 W_w \times W_w = 2 W_w^2 = 0.038\, m^2$

$W_w = \sqrt{\dfrac{A_w}{2}} = \sqrt{\dfrac{0.038}{2}} = 0.1378\, m$

$H_w = 2 W_w = 2 \times 0.1378 = 0.2756\, m$

$V_s = 480\,V$ $\quad E_s \approx V_s \quad E_t = \dfrac{E_s}{T_s}$

$V_p = 2200\,V$.

$\therefore T_s = \dfrac{E_s}{E_t} = \dfrac{480}{7.5} = 64$ turns

$T_p = T_s \times \dfrac{V_p}{V_s} = 64 \times \dfrac{2200}{480}$

$T_p = 293$ turns

$Q = V_p I_p \times 10^{-3} = V_s I_s \times 10^{-3}$

$I_p = \dfrac{Q}{V_p \times 10^{-3}} = \dfrac{100}{2200 \times 10^{-3}} = 45.45\,A.$

$a_p = \dfrac{I_p}{\delta} = \dfrac{45.45}{2.5} = 18.1818\, mm^2$

$I_s = \dfrac{Q}{V_s \times 10^{-3}} = \dfrac{100}{480 \times 10^{-3}} = 208.33\,A$

$a_s = \dfrac{I_s}{\delta} = \dfrac{208.33}{2.5} = 83.33\, mm^2$

Answers

Net core area $A_i = 0.0282\ m^2$

Diameter of circumscribing circle $d = 0.2168\ m$

Window Area $A_w = 0.038\ m^2$

Window dimension $H_w \times W_w = 0.2756 \times 0.1378\ m$

No. Primary turns $= T_p = 293$

No. secondary turns $= T_s = 64$

Area of c/s of primary conductor $a_p = 18.18\ mm^2$

Area of c/s of secondary conductor $a_s = 83.33\ mm^2$.

Example: 6

Calculate the dimension of the core, the number of turns and Cross-sectional area of conductors in the primary and secondary windings of a 100KVA, 2300/400V, 50Hz, 1-phase, shell type transformer. Ratio of magnetic and electric loadings equal to 480×10^{-8} (ie flux to sec. mmf at full load). $B_m = 1.1\ wb/m^2$; $\delta = 2.2\ A/mm^2$. $K_w = 0.3$. Stacking factor $= 0.9$.

$$\frac{\text{Depth of stacked core}}{\text{width of central limb}} = 2.6 \qquad \frac{\text{Height of window}}{\text{width of window}} = 2.5$$

Given

100KVA.

2300/400 V.

1ph shell type

$$\frac{\phi_m}{AT} = 480 \times 10^{-8}$$

$B_m = 1.1\ wb/m^2$

$\delta = 2.2\ A/mm^2$

$K_w = 0.3$.

$$\frac{\text{Depth of the core}}{\text{Width of central limb}} = 2.6$$

$f = 50Hz$.

$H_w/W_w = 2.5$

$S_f = 0.9$.

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

$$\phi_m = B_m A_i \quad , \quad AT = \frac{K_w A_w \delta}{2}$$

$$\therefore Q = 2.22 f \phi_m 2AT \times 10^{-3}$$

$$\frac{\phi_m}{AT} = 480 \times 10^{-8} \qquad AT = \frac{\phi_m}{480 \times 10^{-8}}$$

Hence $Q = 2.22 f \phi_m \times 2 \dfrac{\phi_m}{480 \times 10^{-8}} \times 10^{-3}$

$$\phi_m^2 = \frac{Q \times 480 \times 10^{-8}}{4.44 \times 50 \times 10^{-3}} = \frac{100 \times 480 \times 10^{-8}}{4.44 \times 50 \times 10^{-3}}$$

$$\phi_m = \sqrt{\frac{100 \times 480 \times 10^{-8}}{4.44 \times 50 \times 10^{-3}}} = 0.0465 \text{ wb}$$

$$A_i = \frac{\phi_m}{B_m} = \frac{0.0465}{1.1} = 0.0423 \text{ m}^2$$

Gross core area, $A_{gi} = \dfrac{A_i}{S_f} = \dfrac{0.0423}{0.9} = 0.047 \text{ m}^2$

$$\frac{\text{depth of core}}{\text{width of core}} = 2.6 \qquad \therefore \text{depth} = 2.6 \times \text{width}$$

$A_{gi} = \text{depth} \times \text{width}$

$A_{gi} = 2.6 \times \text{width} \times \text{width}$

$\therefore$ width of core $= \sqrt{\dfrac{A_{gi}}{2.6}} = \sqrt{\dfrac{0.047}{2.6}} = 0.1345 \text{ m}$

Depth of core $= 2.6 \times \text{width} = 2.6 \times 0.1345 = 0.3497 \text{ m}$

$$\frac{\Phi_m}{AT} = 480 \times 10^{-8}$$

$$\therefore AT = \frac{\Phi m}{480 \times 10^{-8}} = \frac{0.0465}{480 \times 10^{-8}} = 9687.5\ AT$$

Also $AT = I_p T_p = I_s T_s$

$$Q = V_p I_p \times 10^{-3} = V_s I_s \times 10^{-3}$$

$$I_p = \frac{Q}{V_p \times 10^{-3}} = \frac{100}{2300 \times 10^{-3}} = 43.478\ A$$

$$I_s = \frac{Q}{V_s \times 10^{-3}} = \frac{100}{400 \times 10^{-3}} = 250\ A$$

$$T_s = \frac{AT}{I_s} \quad \frac{9687.5}{250} = 38.75 \approx 40 \text{ turns}$$

$$T_p = T_s \times \frac{V_p}{V_s} = 40 \times \frac{2300}{400} = 230 \text{ turns.}$$

Area of cross section

$$a_p = \frac{I_p}{\delta} = \frac{43.4782}{2.2} = 19.76\ mm^2$$

$$a_s = \frac{I_s}{\delta} = \frac{250}{2.2} = 113.636\ mm^2$$

Window dimensions:

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

$$\therefore \text{window Area } A_w = \frac{Q}{2.22 f\ B_m\ A_i\ k_w\ \delta \times 10^{-3}} = \frac{100}{2.22 \times 50 \times 1.1 \times 0.04 \times 0.3 \times 2.2 \times 10^{6} \times 10^{-3}}$$

$$A_w = 0.0293\ m^2$$

$\frac{H_w}{W_w} = 2.5 \quad \therefore H_w = 2.5\, W_w \qquad A_w = H_w W_w$

$A_w = 2.5\, W_w W_w$

$\therefore W_w = \sqrt{\frac{A_w}{2.5}}$

$W_w = 0.1083\, m$

$H_w = 2.5 \times W_w$

$= 2.5 \times 0.1083$

$H_w = 0.2708\, m$

Result:

Area of c/s of core $A_i = 0.0423\, m^2$

Core cross-section width x depth $= 0.1345 \times 0.3497\, m$

Area of window $A_w = 0.0293\, m^2$

Window dimensions $H_w \times A_w = 0.2708 \times 0.1083\, m$

No. of Primary turns $T_p = 230$ turns

No. of Secondary turns $T_s = 40$ turns

Area of c/s of Primary conductor $a_p = 19.76\, mm^2$

Area of c/s of Secondary conductor $a_s = 113.636\, mm^2$.

May 2013

Example : 7 Determine the dimensions of core and yoke for a 200 KVA, 50 Hz single phase core type transformer. A cruciform core is used with distance between adjacent limbs equal to 1.6 times the width of core laminations. Assume voltage/turn 14, maximum flux density 1.1 Wb/m², window space factor 0.32, current density 3 A/mm², and stacking factor = 0.9. The net iron area is 0.56d² in a cruciform core where d' is the diameter of circumscribing circle. Also the width of largest stamping is 0.85d.

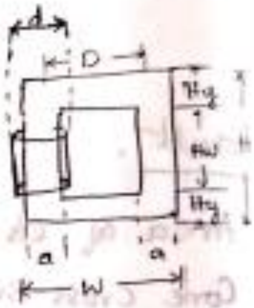
Given:

$Q = 200\,KVA$ $\quad D = 1.6\,a$ $\quad \delta = 3A/mm^2$

$f = 50Hz$ $\quad E_t = 14V$ $\quad S_f = 0.9$

1-ph $\quad B_m = 1.1\,Wb/m^2$ $\quad A_i = 0.56\,d^2$

2-stepped core $\quad K_w = 0.32$ $\quad a = 0.85\,d$



Solution:

$$E_t = 4.44\,\Phi_m f$$

$$E_t = 4.44\,B_m A_i f$$

$$A_i = \frac{E_t}{4.44\,B_m f} = \frac{14}{4.44 \times 1.1 \times 50}$$

$$A_i = \underline{0.0573\,m^2}$$

$$A_i = 0.56\,d^2$$

$$\therefore d = \sqrt{\frac{A_i}{0.56}} = \sqrt{\frac{0.0573}{0.56}} = 0.32\,m$$

width of largest stamping $\quad a = 0.85\,d$

$$= 0.85 \times 0.32$$

$$a = \underline{0.272\,m}$$

Distance between core centres $\quad D = 1.6\,a$

$$= 1.6 \times 0.272$$

$$D = \underline{\underline{0.435\,m}}$$

width of window $W_w = D - d$

$= 0.435 - 0.32$

$W_w = 0.115\,m$

$$Q = 2.22\, f\, B_m\, K_w\, \delta\, A_w\, A_i \times 10^{-3}$$

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

$$A_w = \frac{200}{2.22 \times 50 \times 1.1 \times 0.32 \times 3 \times 10^{6} \times 0.0573 \times 10^{-3}}$$

$A_w = 0.0298\, m^2$

$A_w = H_w \times W_w$

$H_w = \frac{A_w}{W_w} = \frac{0.0298}{0.115} = 0.26\,m$

$A_y = D_y \times H_y$

$A_y = 1.1\, A_i$

$= 1.1 \times 0.0573$

$A_y = 0.06303$

Depth of yoke $D_y = a = 0.272\,m$

Height of yoke $H_y = \frac{A_y}{D_y} = \frac{0.06303}{0.272} = $ $H_y = 0.231\,m$

Overall Height of frame $H = H_w + 2H_y$

$= 0.26 + (2 \times 0.231)$

$H = 0.723\,m$

Overall length of frame $W = D + a$

$= 0.435 + 0.272$

$W = 0.707\,m$

$\left.\begin{matrix} D_y = a \\ H_y = a \end{matrix}\right\} = 0.272\,m$

$\therefore H = H_w + 2H_y$

$0.26 + (2 \times 0.272)$

$H = 0.804\,m$ //

Example: 8

Calculate approximate overall dimensions for 200kVA, 6600/.. 50Hz, 3ph core type transformer. The following data may be assumed: emf per turn = 10V; maximum flux density = 1.3 Wb/m²; current density = 2.5A/mm²; window space factor = 0.3, overall height = overall width; stacking factor = 0.9. Use a 3 stepped core. Width of largest stamping = 0.9d & Net iron area = 0.6d².

Given:-

$Q = 200$ kVA $B_m = 1.3\ \text{Wb/m}^2$ $S_f = 0.9$ $E_t = 10V$

$f = 50Hz$. $\delta = 2.5\ \text{A/mm}^2$ $a = 0.9d$ $H = W$.

3-ph. $K_w = 0.3$ $A_i = 0.6d^2$

3-stepped

Soln:

$$A_i = \frac{E_t}{4.44 f B_m} \quad \frac{10}{4.44 \times 50 \times 1.3} = 0.0347\ m^2$$

$$d = \sqrt{\frac{A_i}{0.6}} = \sqrt{\frac{0.0347}{0.6}} = 0.24\ m.$$

$$a = 0.9d = 0.9 \times 0.24 = 0.216m$$

$$H_y = a = 0.216m$$

$$D_y = a = 0.216m$$

3ph. transformer

$$Q = 3.33 f B_m k_w A_w A_i \delta \times 10^{-3}$$

$$A_w = \frac{200}{3.33 \times 50 \times 1.3 \times 0.3 \times 2.5 \times 10^6 \times 0.0347 \times 10^{-3}}$$

$$A_w = 0.0355\ m^2$$

$$A_w = H_w \times W_w = 0.0355\ m^2 \qquad H = W.$$

$H = H_w + 2H_y$

$= H_w + 2 \times 0.216$

$H = H_w + 0.432$

$W = 2D + a$

$2(W_w + d) + a$

$= 2W_w + (2 \times 0.24) + 0.216$

$W = 2W_w + 0.696$

$H = W$

$H_w + 0.432 = 2W_w + 0.696$

$H_w = 2W_w + 0.264$

$A_w = H_w \times W_w$.

$0.0355 = (2W_w + 0.264) W_w$

$2W_w^2 + 0.264 W_w - 0.0355 = 0$.

$W_w = \underline{0.083 m}$ $\qquad H_w = \dfrac{0.0355}{0.083} = \underline{0.428 m}$

Thus dimensions of core are

$D = W_w + d$

$= 0.083 + 0.24$

$D = \underline{0.323 m}$

$H = H_w + 2H_y$

$= 0.428 + 2 \times (0.216)$

$H = \underline{0.86 m}$

$W = 2D + a$

$= (2 \times 0.323) + 0.216$

$W = \underline{0.862 m}$

Estimation of No load Current of Transformer

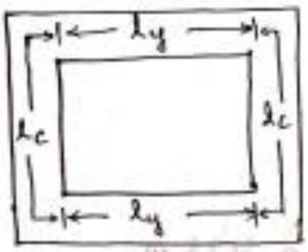
The no-load current of a Transformer has two Components. (i) magnetizing current (I_m) and
(ii) loss component (I_l)
or (Working component (I_w))

Thus the estimation of no load current I_o requires the calculation of its two components I_m & I_l.

I_m depends on the mmf required to establish the desired flux

I_l depends on the Iron losses.

No load Current of Single phase transformer:



Core type transformer.

Total length of core $= 2 l_c$

Total length of yoke $= 2 l_y$

Here $l_c = H_w$ = Height of Window.

and $l_y = W_w$ = Width of window.

mmf for core = mmf per meter for maximum flux density in core × Total length of core

$$= at_c \times 2 l_c$$

$$= 2\, at_c l_c$$

mmf for yoke = mmf per meter for maximum flux density in yoke × Total length of yoke

$$= at_y \times 2 l_y$$

$$= 2\, at_y l_y$$

Total magnetizing mmf

AT_0 = mmf for core + mmf for yoke + mmf for joints

$$AT_0 = 2 at_c l_c + 2 at_y l_y + \text{mmf for joints} \rightarrow (1)$$

Maximum value of magnetizing current $AT_0 / T_p \rightarrow (2)$

If the magnetizing current is sinusoidal then.

rms value of magnetizing current $I_m = \dfrac{AT_0}{\sqrt{2}\, T_p} \rightarrow (3)$.

When the magnetizing current is non sinusoidal, the peak factor K_{pk} should be used inplace of $\sqrt{2}$.

$$\therefore \; I_m = \frac{AT_0}{K_{pk} T_p} \rightarrow (4)$$

The values of at_c and at_y are taken from B-H curves for transformer steel. The joints in a magnetic circuit may be taken as short airgaps in parallel with iron paths

The loss component of no load current I_l

$$I_l = \frac{P_i}{V_p} \rightarrow (5)$$

where P_i = Iron loss in W

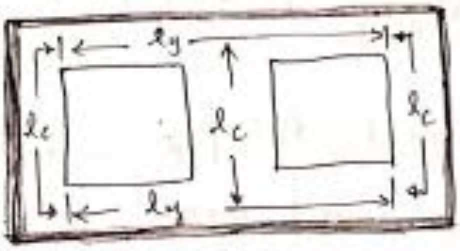
V_p = Terminal voltage of Primary winding.

The iron losses are calculated by finding the weight of cores and yokes.

The loss per kg of iron is taken from the loss curves given by the manufacturer of transformer laminations.

No load current $I_0 = \sqrt{I_m^2 + I_l^2} \rightarrow (6)$

No-load current of three-phase transformer



3ph core type transformer.

Total length of Core $= 3l_c$

Total length of yoke $= 2l_y$

Here $l_c = H_w$ = Height of window

$l_y = 2W_w + d$

where W_w = width of window

d = diameter of circumscribing circle.

mmf for core = mmf per meter for maximum flux density in core $\times$ Total length of core.

$= at_c \times 3l_c$

$= 3at_cl_c$.

mmf for yoke = mmf per meter for maximum flux density in yoke $\times$ Total length of yoke

$= at_y \times 2l_y$

$= 2at_yl_y$.

Total magnetizing mmf required for the transformer

= mmf for core + mmf for yoke + mmf for joints

$= 3at_cl_c + 2at_yl_y$ + mmf for joints

Total magnetizing mmf required per phase $AT_0 = \dfrac{3at_cl_c + 2at_yl_y + \text{mmf for joints}}{3}$

Maximum value of magnetizing current per phase $= \frac{AT_0}{T_p}$

If magnetizing current is sinusoidal then,

rms value of magnetizing current per phase $I_m = \frac{AT_0}{\sqrt{2}\,T_p}$

If the magnetizing current is non sinusoidal then K_{pk} should be used in the place of $\sqrt{2}$

$$\therefore I_m = \frac{AT_0}{\sqrt{2}\,T_p} \quad (\text{or}) \quad I_m = \frac{AT_0}{K_{pk}\,T_p} \rightarrow (2)$$

The values of at_c and at_y are taken from BH curves

Let P_i = Total iron loss for the three phases

$P_i = 3\, V_p I_l$

$\therefore$ loss component of no load current

$$I_l = \frac{P_i}{3 V_p}$$

Hence no load current per phase, $I_0 = \sqrt{I_m^2 + I_l^2} \rightarrow (3)$

Magnetizing Volt-ampere.

Induced Emf per phase in Primary. $E_p = 4.44\, f\, T_p B_m A_i \rightarrow (1)$

Magnetizing current $I_m = \frac{AT_0}{\sqrt{2}\,T_p} \rightarrow (2)$

AT_0 = Magnetizing mmf per meter $\times$ Length of flux path in iron

$AT_0 = at_m l_i$

Weight of iron $= A_i l_i \times 7.8 \times 10^3$

Where, density of iron $= 7.8 \times 10^3\ kg/m^3$

Magnetizing volt ampere, $VA_m = E_p I_m \rightarrow (3)$

on substituting for E_P & I_m from equation ① & ② in equation ③ we get

$$VA_m = E_P I_m$$

$$= 4.44 f T_P B_m A_i \times \frac{AT_0}{\sqrt{2} T_P}$$

$$VA_m = \frac{4.44 f B_m A_i AT_0}{\sqrt{2}} \qquad \because AT_0 = at_m l_i$$

$$VA_m = \frac{4.44 f B_m A_i at_m l_i}{\sqrt{2}}$$

$$VA_m = \frac{4.44 f B_m at_m A_i l_i}{\sqrt{2}} \rightarrow ④.$$

$$\text{Magnetizing Volt ampere per kg of iron} = \frac{VA_m}{\text{weight of iron}}$$

$$= \frac{4.44 f B_m at_m A_i l_i / \sqrt{2}}{A_i l_i \times 7.8 \times 10^3}$$

$$= \frac{4.44 f B_m at_m}{\sqrt{2} \times 7.8 \times 10^3}$$

$$= 0.4 f B_m at_m \times 10^{-3} \rightarrow ⑤$$

Now a curve can be plotted between B_m and magnetizing Volt amper per kg using the B-H curve of the material. Usually the manufacturers will supply the magnetizing VA/kg-B_m characteristics. From this characteristics the magnetizing current can be calculated.

$$\text{Magnetizing current } I_m = \frac{\text{Magnetizing VA per kg} \times \text{Weight of core}}{\text{Number of phases} \times \text{Voltage per phase}}$$

Example 4 A single phase 400V, 50Hz, transformer is built from stampings having a relative permeability of 1000. The length of the flux path is 2.5m, the area of cross section of the core is $2.5 \times 10^{-3}\ m^2$ and the primary winding has 800 turns. Estimate the maximum flux and no load current of the transformer. The iron loss at the working flux density is 2.6 W/kg. Iron weighs 7.8×10^3 Kg/m³. stacking factor is 0.9.

Solution

Given: $V = 400V$, $f = 50Hz$, $\mu_r = 1000$

$\mu_0 = 4\pi \times 10^{-7}$ H/m, $l_i = 2.5m$.

$A_{gi} = 2.5 \times 10^{-3}\ m^2$ $T_p = 800$ turns

$Sf = 0.9$. $P_i = 2.6$ W/kg.

Iron weight $= 7.8 \times 10^3$ Kg/m³

$I_0 = ?$ $B_m = ?$

Net iron Area $A_i = Sf \times A_{gi}$

$= 0.9 \times 2.5 \times 10^{-3}$

$A_i = 2.25 \times 10^{-3}\ m^2$

$$E_p = 4.44 f \phi_m T_p$$
$$= 4.44 f B_m A_i T_p$$

$$B_m = \frac{400}{4.44 \times 50 \times 2.25 \times 10^{-3} \times 800}$$

$B_m = 1.0$ Wb/m²

$\therefore$ Flux in the core $\phi_m = B_m \times A_i$

$= 1 \times 2.25 \times 10^{-3}$ Wb

$\phi_m = 2.25 \times 10^{-3}$ Wb

Magnetizing mmf AT_0 = Reluctance × flux

$$= \frac{l_i}{\mu_0 \mu_r A_i} \times \phi_m \qquad \phi_m = \frac{B_m}{A_i}$$

$$AT_0 = \frac{l_i B_m}{\mu_0 \mu_r} = \frac{2.5 \times 1}{1000 \times 4\pi \times 10^{-7}} = \underline{1989.43}$$

Magnetising Current $I_m = \frac{AT_0}{\sqrt{2}\, T_P}$

$$= \frac{1989.43}{\sqrt{2} \times 800}$$

$$I_m = \underline{1.75 A}$$

Volume of core $= A_i \times l_i$

$$= 2.25 \times 10^{-3} \times 2.5$$

$$= 5.625 \times 10^{-3}\ m^3$$

∴ Weight of core = Volume of core × 7.8×10^3

$A_i \times l_i \times 7.8 \times 10^3$

$$= 5.625 \times 10^{-3} \times 7.8 \times 10^3$$

weight of core = 43.8 Kg

Iron loss = Pi /kg × weight of core

$$= 2.6 \times 43.8$$

$$P_i = \underline{114\ W}$$

Loss component of no load current $I_l = \frac{P_i}{V_\phi} = \frac{114}{400}$

$$I_l = 0.285 A$$

∴ No load current $I_0 = \sqrt{I_m^2 + I_l^2} = \sqrt{1.75^2 + 0.285^2} = \underline{1.77 A}$

Example:10 Calculate the active and reactive components of no load current of a 400V, 50Hz, single phase transformer having the following particulars

core of transformer steel:

Stacking factor = 0.9, density = 7.8×10^3 kg/m³.

length of mean flux path = 2.2m ; gross iron section = 10×10^{-3} m²

Primary turns = 200 ; joints equivalent to 0.2mm airgap.

use the following data.

Bm Wb/m²	0.9	1.0	1.2	1.3	1.4
MMF AT/m	130	210	420	660	1300
Iron loss W/kg	0.8	1.3	1.9	2.4	2.9

Given: $Sf = 0.9$, $V = 400V$, $f = 50Hz$.

density = 7.8×10^3 kg/m³ $l_i = 2.2m$.

$A_{gi} = 10 \times 10^{-3}$ m². $T_p = 200$. $l_g = 0.2mm$
$= 0.2 \times 10^{-3} m$

Solution: $A_i = Sf \times A_{gi}$

$A_i = 0.9 \times A_{gi}$

$= 0.9 \times 10 \times 10^{-3}$

$A_i = 9 \times 10^{-3}$ m²

$$\phi_m = \frac{E}{4.44 f T_p}$$

$$\phi_m = \frac{400}{4.44 \times 50 \times 200} = 9.02 \times 10^{-3} \text{ Wb}$$

$$B_m = \frac{\phi_m}{A_i} = \frac{9.02 \times 10^{-3}}{9 \times 10^{-3}} = 1\ Wb/m^2$$

Corresponding to $B_m = 1.0\ Wb/m^2$ from the table

mmf /metre = 210 A

loss per kg = 1.3 W

$\therefore$ mmf for iron path $= l_i \times AT/m$.

$$2.2 \times 210$$

$$= \underline{462\ AT}$$

mmf for joints $= 0.8 \times 10^6\ B l_g$.

$$= 0.8 \times 10^6 \times 1 \times 0.2 \times 10^{-3}$$

$$= \underline{160\ AT}$$

Total magnetising mmf AT_0 = mmf for iron path + mmf for joints

$$= 462 + 160$$

$$AT_0 = \underline{622\ AT}$$

Reactive component of noload current

magnetising current $I_m = \dfrac{AT_0}{\sqrt{2} \times T_p}$

$$= \frac{622}{\sqrt{2} \times 200}$$

$$I_m = \underline{2.2\ A}$$

Volume of core $= A_i \times l_i$

$= 9 \times 10^{-3} \times 2.2$

$= 0.0198 \, m^3$

weight of core $=$ Volume of core $\times$ density of core

$0.0198 \times 7.8 \times 10^{3}$

$= 155 \, kg.$

Total iron loss $= 155 \times 1.3 \, W/kg$

$P_i = 201.5 \, W$

Loss component of no load current

active current. $I_l = \dfrac{P_i}{V}$

$= \dfrac{201.5}{400}$

$I_l = 0.5A$

No load current $I_o = \sqrt{I_m^2 + I_l^2}$

$= \sqrt{2.2^2 + 0.5^2}$

$I_o = 2.26A$

Cooling of Transformer

The losses developed in the transformer cores and windings are converted into thermal Energy and cause heating of corresponding transformer Parts.

The heat dissipation in transformer occurs by

Conduction
Convection &
Radiation.

1. Core or winding to their outer Surface in contact with oil → Conduction
2. From the outer surface of transformer Part to the oil that cools it → Convection
3. From the oil to the walls of cooler eg: wall of tank
4. From the walls of cooler to the cooling medium air or water → Convection & Radiation

The various methods of Cooling transformer are

1) Air natural - upto 1.5 MVA
2) Air blast
3) oil natural - upt 10 MVA
4) oil natural air forced
5) oil Natural Water forced
6) Forced circulation of oil
7) oil forced - air natural
8) oil forced - air forced
9) oil forced - water forced. → Power Plants

(items 4–8: upto 30 MVA.)

The choice of cooling method depends up on the size, type of application and type of conditions obtaining site where the transformers installed.

Transformer oil as a Cooling medium

For the transformer oil, the specific heat dissipation due to convection of oil is given by

$$\lambda_{conv} = 40.3 \left(\frac{\theta}{H}\right)^{1/4} \text{ W/m}^2\text{-}^\circ\text{C} \quad \rightarrow (1)$$

Where θ = Temperature difference of the surface relative to oil, °C

H = Height of dissipating surface, m.

The average working temperature of oil is 50°C to 60°C

For θ = 20°C and H = 0.5 to 1 m

The λ_{conv} = 80 to 100 W/m²-°C (oil)

λ_{conv} = 8 W/m²-°C (convection of air)

Thus convection due to oil is more than 10 times than that of air

Temperature rise in plain walled tanks:-

The transformer core and winding assembly is placed inside a container called tank. The walls of the tank dissipate heat by both radiation and convection.

For a temperature rise of 40°C above the ambient temperature of 20°C, the specific heat dissipation are as follows.

1. Specific heat dissipating due to radiation λ_{rad} = 6 W/m²-°C
2. Specific heat dissipation due to convection λ_{conv} = 6.5 W/m²-°C

∴ The total specific heat dissipation in plain walled tanks is $12.5\ W/m^2\text{-}^\circ C$

The temperature rise, $\theta = \dfrac{\text{Total loss}}{\text{Specific heat dissipation} \times \text{Heat dissipating surface of the tank}} = \dfrac{P_i + P_c}{12.5\ S_t}$ → (2)

where P_i - Iron loss

P_c - Copper loss

S_t - Heat dissipating surface of the tank

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. But the increase in dissipation of heat is not proportional to increase in area. because the tubes would screen some of the tank surface preventing radiation from the screened surface. On the other hand the tubes will improve the circulation of oil. This improves the dissipation of loss by convection. The circulation of oil is due to more effective pressure heads produced by columns of oil in tubes.

The improvement in loss dissipation by convection is equivalent to loss dissipated by 35% of tube surface area.

Hence to account for this improvement in dissipation of loss by convection an additional 35% tube area is added to actual tube surface area or the specific heat dissipation due to convection is taken as 35% more than that without tubes.

Let, The dissipating surface of the tank $= S_t$

The dissipating surface of the tubes $= x S_t$

Loss dissipated by surface of the tank by radiation and convection $\Big\} = (6 + 6.5) S_t$

$= 12.5\ S_t$

Loss dissipated by tubes by convection $= 6.5 \times \frac{135}{100} \times x S_t$

$= 8.8 x S_t$

Total loss dissipated by walls & tubes $= 12.5 S_t + 8.8\, x S_t$

$= (12.5 + 8.8x)\, S_t \rightarrow (1)$

Actual total area of tank walls and tubes $= S_t + x S_t$

$= S_t(1 + x)$

loss dissipated per m^2 of dissipating surface $= \frac{\text{Total loss dissipated}}{\text{Total area}} = \frac{S_t(12.5 + 8.8x)}{S_t(1 + x)}$

$= \frac{12.5 + 8.8x}{1 + x} \rightarrow (2)$

Temperature rise in transformer with cooling tubes $\Big\}\ \theta = \frac{\text{Total loss}}{\text{loss dissipated}}$

Total loss, $P_{loss} = P_i + P_c \rightarrow (3)$

P_i = iron loss

P_c = Cu loss

From eqn (1) and (3)

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

$$12.5 + 8.8x = \frac{P_i + P_c}{\theta S_t}$$

$$\therefore x = \left(\frac{P_i + P_c}{\theta S_t} - 12.5\right)\frac{1}{8.8} \rightarrow (4)$$

Total area of Cooling tubes = $x S_t$

On Substituting for x from eqn (4), we get

$$\text{Total area of cooling tubes} = \frac{1}{8.8}\left[\frac{P_i + P_c}{\theta S_t} - 12.5\right] S_t$$

$$= \frac{1}{8.8}\left[\frac{P_i + P_c}{\theta} - 12.5 S_t\right] \rightarrow (5)$$

Let l_t = length of the tube

d_t = Diameter of the tube.

$\therefore$ Surface area of each tube (cylinder) $= \pi d_t l_t$

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

$$\boxed{n_t = \frac{1}{8.8 \pi d_t l_t}\left[\frac{P_i + P_c}{\theta} - 12.5 S_t\right]} \rightarrow (6)$$

The Standard diameter of the Cooling tube is 50mm and the length of the tube depends on the height of the tank.

The tubes are arranged with a centre to centre spacing of 75MM

The dimensions of the tank are decided by the dimensions of the transformer frame and clearance required on all the sides. The dimensions of the tank are shown in fig:1

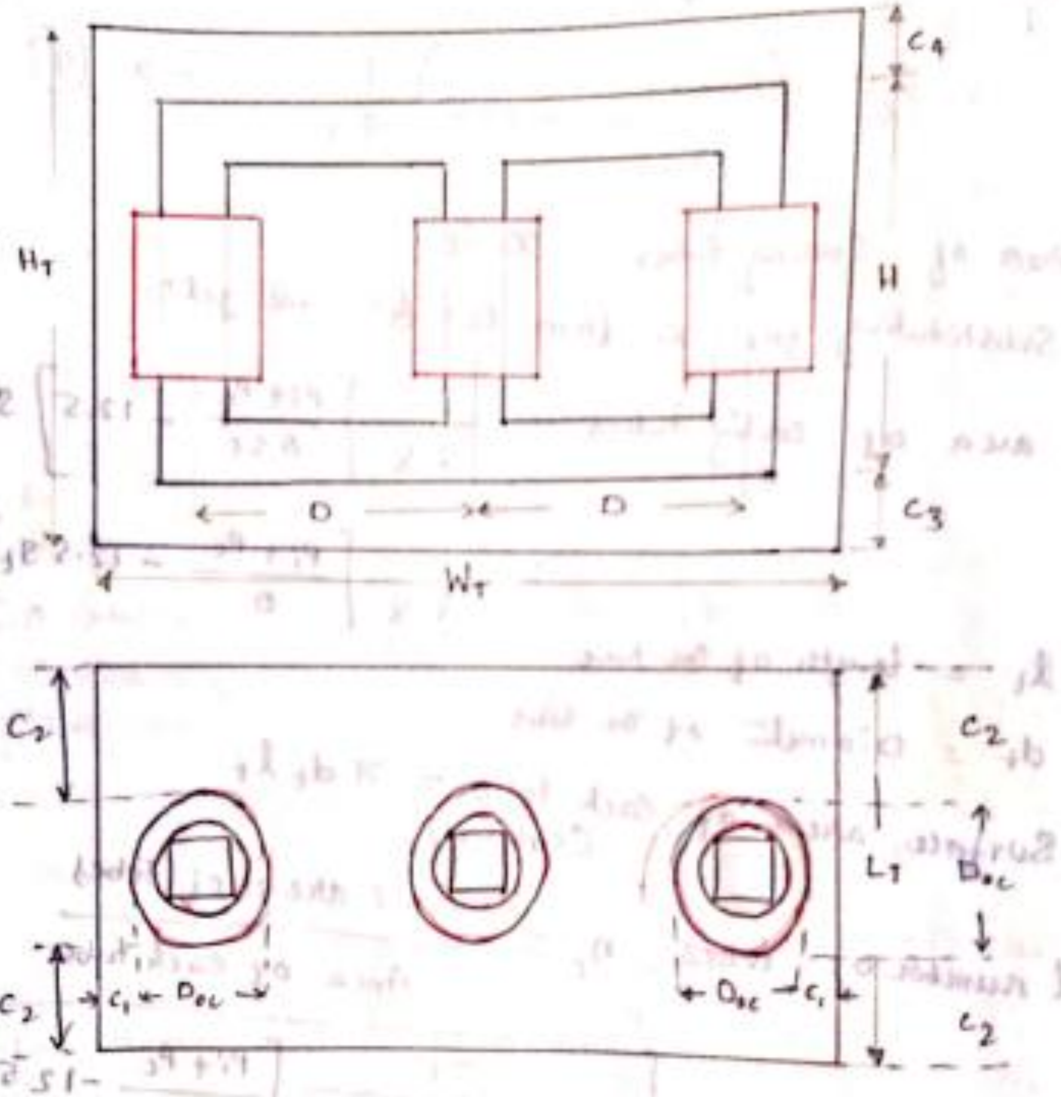


Fig:1 Dimensions of transformer tank

Let C_1 = Clearance between winding and tank along the width.
C_2 = Clearance between the winding and tank along the length.
C_3 = Clearance between the transformer frame and tank at the bottom.
C_4 = Clearance between the transformer frame and the tank at the top.
D_{oc} = outer diameter of coil.

With reference to the fig 1. we can write,

Width of the tank $W_T = 2D + D_{oc} + 2C_1$ (for 3ph)

$W_T = D + D_{oc} + 2C_1$ (for 1Ph)

Length of the tank $L_T = D_{oc} + 2C_2$

Height of the tank $H_T = H + C_3 + C_4$

Clearance on sides depends on voltage & power rating of winding.

Clearance at the TOP depends on the oil height above the assembled transformer and the space mounting the terminals and tap changing gear.

Clearance at the bottom depends on space required for mounting the transformer frame inside the tank.

Clearance between transformer frame & Tank

Voltage	KVA rating	Clearance in mm			
		C_1	C_2	C_3	C_4
Upto 11 KV	< 1000 KVA	40	50	75	375
Upto 11 KV	1000 to 5000 KVA	70	90	100	400
11 KV to 33 KV	< 1000 KVA	75	100	75	450
11 KV to 33 KV	1000 to 5000 KVA	85	125	100	475

The tank of 1250 kVA, natural oil cooled transformer has the dimension length width and height as 0.65 x 1.55 x 1.85 m respectively. The full load loss = 13.1 kW, loss dissipation due to radiations = 6 W/m²-°c, loss dissipation due to convection = 6.5 W/m²-°c, improvement in convection due to provision of tubes = 40%, temperature rise = 40°c. length of each tube = 1m. diameter of tube = 50 mm. Find the number of tubes for this transformer. Neglect the top and bottom surface of the tank as regard the cooling.

Given data

KVA = 1250

l_t = 1mt

d_t = 50mm

θ = 40°c

Tank dimension = 0.65 x 1.55 x 1.85 m

λ_{conv} = 6.5 W/m²-°c

λ_{rad} = 6 W/m²-°c

Improvement in Cooling = 40%

Full load loss = 13.1 kW

Solution:

L_T = length = 0.65m

W_T = Width = 1.55m

H_T = Height = 1.85m

Surface area of rectangle = 2ab + 2bc + 2ca

Heat dissipating surface of tank

S_t = Total area of Vertical sides (∵ neglecting top & bottom surface)

$= 2(L_T H_T + W_T H_T)$

$= 2H_T(L_T + W_T)$

$= 2 \times 1.85 \times (0.65 + 1.55)$

$S_t = 8.14\, m^2$

Loss dissipated by tank walls by radiation & convection $\Big\} = (6+6.5)S_t = 12.5\,S_t$

Let Heat dissipating area of tube $= x\,S_t$

Loss dissipated by cooling tubes due to convection $= 6.5 \times \frac{140}{100} \times x S_t$

$= 9.1\,x\,S_t$

Total loss dissipated by Tank & Tubes $= 12.5\,S_t + 9.1\,x\,S_t$

$= S_t(12.5 + 9.1x)$

Temperature rise in transformer with cooling tubes $\theta = \frac{\text{Total loss}}{\text{Total loss dissipated}}$

$P_{loss} = 13.1\,kW \qquad \therefore\ \theta = \frac{13.1\times10^3}{S_t(12.5+9.1x)}$

$12.5 + 9.1x = \frac{13.1\times10^3}{\theta S_t}$

$x = \frac{1}{9.1}\left(\frac{13.1\times10^3}{\theta S_t} - 12.5\right) = \frac{1}{9.1}\left(\frac{13.1\times10^3}{40\times8.14} - 12.5\right)$

$x = 3.0476$

Total area of Tubes $= x\,S_t = 3.0476 \times 8.14$

$x\,S_t = 24.8075\,m^2$

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

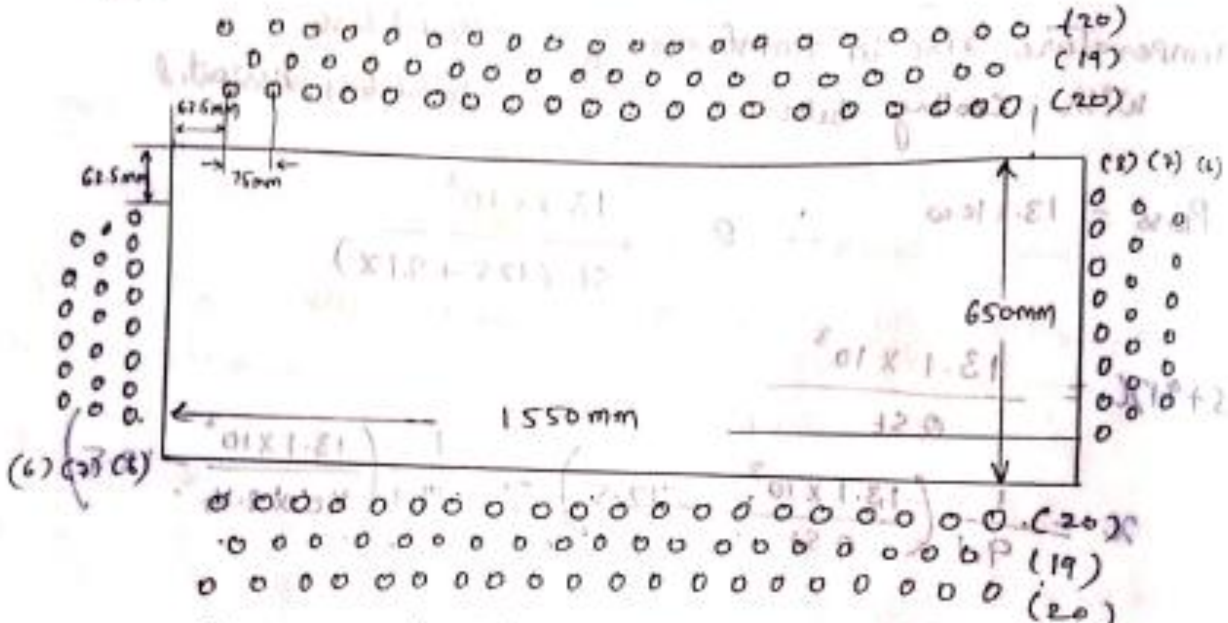
Area of each tube $= \pi d_t l_t$
$= \pi \times 50 \times 1$
$= 0.157\,m^2$ $\Big\} = \frac{24.8075}{0.157} = 158$ tubes

The diameter of the tube is 50mm and standard distance between the tubes is half of the diameter and so, let distance between tubes = 25mm.

The width of the tank is 1550mm. If we leave an edge spacing of 62.5mm on either sides. then we can arrange 20 tubes widthwise with a spacing of 75mm between centres of tubes.

On lengthwise we can arrange 8 tubes with three rows (i.e.) of 3 m

On widthwise we can arrange 20, 19, 20. tubes.



Total number of tubes provided = 160.

fig: 1. Plan showing the arrangement of cooling tubes.

Jan 2015

A 250 KVA, 6600/400V, 3 phase core type transformer has a total loss of 4800 W on full load. The transformer tank is 1.25 m in Height and 1m x 0.5 mt in plan. Design the suitable scheme for cooling tubes if the average temperature rise is to be limited to 35°C. The diameter of the tube is 50mm and are spaced 75mm from each other. The average height of the tube is 1.05 m.

Given data

KVA = 250. Tank dimension = 0.5 x 1 x 1.25 m , 6600/400V 3 ph. Core type.

$\theta = 35°C$ Total Power loss = 4800 W

$d_t = 50\,mm$ Distance between tube centres = 75 mm

$l_t = 1.05\,mt$.

Solution L_T = length = 0.5 m W_t = width = 1mt. H_T = Height = 1.25 mt.

Heat dissipating surface of tank S_t = Total area of vertical sides

$$= 2(L_T H_T + W_T H_T)$$
$$= 2H_T(L_T + W_T)$$
$$= 2 \times 1.25 \times (0.5 + 1)$$
$$S_t = 3.75\,m^2$$

Loss dissipated by tank walls by radiation & convection $= (6+6.5)\,S_t = 12.5\,S_t$.

Let heat dissipating area of tubes $= x\,S_t$.

Loss dissipated by cooling tubes due to convection $= 6.5 \times \frac{135}{100} \times x S_t$

$$= 8.8\,x\,S_t$$

Total loss dissipated by tank & tubes $= 12.5 S_t + 8.8\,x S_t$

$$= S_t(12.5 + 8.8\,x)$$

Temperature rise in transformer with cooling tubes $\theta = \frac{\text{Total loss}}{\text{Total loss dissipated}}$

Total loss $P_{loss} = 4800\,W$.

$$\theta = \frac{4800}{S_t\,(12.5 + 8.8x)}$$

$$x = \frac{1}{8.8}\left[\frac{4800}{\theta S_t} - 12.5\right]$$

$$= \frac{1}{8.8}\left[\frac{4800}{35 \times 3.75} - 12.5\right]$$

$$x = 2.7354$$

Total area of cooling tubes $= x\,S_t = 2.7354 \times 3.75$

$= 10.2578\,m^2$

Area of each cooling tube $= \pi d_t l_t$

$= \pi \times 50 \times 10^{-3} \times 1.05$

$= 0.1649\,m^2$

Number of cooling tubes $n_t = \dfrac{\text{Total area of tubes}}{\text{Area of each tube}}$

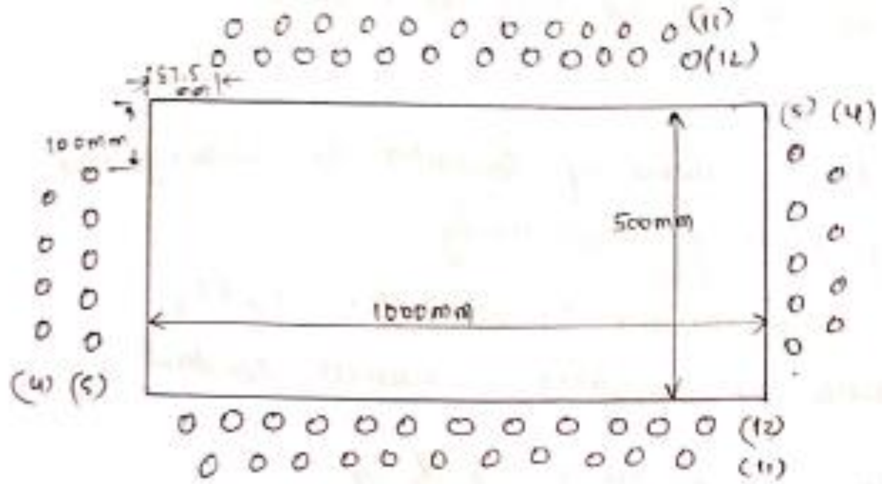
$$= \frac{10.2578}{0.1649}$$

$= 62.206$

$= 62$ tubes

width of the tank = 1000 mm. edge spacing = 87.5 mm.
arrange 12 tubes widthwise with a spacing of 75 mm.
between the centres of tubes.

length of tank = 500 mm. leave space 100 mm on either side, arrange 5 tubes.



Plan showing the arrangement of cooling tube.

Number of cooling tubes provided = 64.

3) The full load efficiency of a 200 kVA transformer is 98.2%. at upf. Design the number of cooling tubes necessary. If the temperature rise is 35°c the tank area may be assumed as $4.92 m^2$. Assume tube diameter as 5cm and average length as 105 cm. Heat dissipation may be assumed as $12.5 W/m^2/°c$

Given:
$d = 5cm = 0.05m$
$l = 105cm = 1.05m$
$S_t = 4.92 m^2$
$\theta = 35°c$

Soln: we have $kw = kVA \times \cos\phi$ $\cos\phi = 1$ (upf)
$kw = kVA = 200 = P_o$

Efficiency $\eta = \frac{o/p \text{ Power}}{i/p \text{ Power}} = \frac{P_o}{P_o + \text{losses}} = 0.982$

$= \frac{200}{200 + \text{losses}} = 0.982$

$(0.982 \times 200) + (0.982 \times \text{losses}) = 200$

losses = 3.66 kW. No. of cooling tubes required

$n_t = \frac{1}{8.8 \pi d_t l}\left[\frac{\text{losses}}{\theta} - 12.5 S_t\right]$

$= \frac{1}{8.8 \times \pi \times 0.05 \times 1.05}\left[\frac{3.66 \times 10^3}{35} - 12.5 \times 4.92\right]$

$\boxed{n_t = 30 \text{ tubes}}$

Jan 2016 For a constant total volume of conductors in a transformer. Show that for a minimum copper loss, current densities in the winding must be equal.

Soln:

Let U_p, U_s = Volume of conductors in primary and secondary winding respectively.

U_t = total volume of conductors = $U_p + U_s$.

Total volume of conductor is assumed constant.

I^2R loss in primary $= \rho \delta_p^2 U_p$.

I^2R loss in secondary $= \rho \delta_s^2 U_s$

$$= \rho \delta_s^2 (U_t - U_p).$$

Total I^2R loss $\quad P_c = \rho[\delta_p^2 U_p + \delta_s^2 (U_t - U_p)]$

Differentiate P_c w.r.t. U_p.

$$\frac{dP_c}{dU_p} = \rho[\delta_p^2 - \delta_s^2]$$

$$P_c = \rho[\delta_p^2(U_t - U_s) + \delta_s^2 U_s]$$

For minimum loss $\dfrac{dP_c}{dU_s} = \rho[\delta_p^2 - \delta_s^2] = 0$

$$\delta_p = \delta_s.$$

Therefore, for minimum copper loss, the value of current density in each of the two winding should be equal.

Expression for leakage reactance

Leakage reactance is mainly the estimation of the distribution of leakage flux and resulting line linkages with LV & HV winding (Primary & secondary).

However the expression for the leakage reactance will be developed based upon certain simplifying assumptions.

Generally concentric windings are used for core type transformers and sandwich winding for shell type transformer.

Fig 1 Concentric winding
Core type

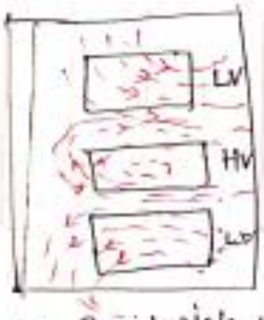


Fig 2 Sandwich winding
Shell type.

(a) Leakage reactance of core type transformer

The calculation of leakage reactance & leakage flux is greatly simplified by making the following assumptions:

1. The Primary & Secondary windings have equal axial length.
2. The flux paths are parallel to the windings along the axial Hight.
3. The permeance of leakage flux path (L_c) external to the winding is taken to be so large.
4. The Primary winding mmf is equal to the secondary winding mmf. Hence magnetizing current is Zero.

5. Half of the leakage flux in the duct links with each winding
6. The length of the mean turn of the windings are equal.
7. Reluctance of flux path through yoke is negligible, Hence reluctance doesnot affect flux distribution.
8. The windings are uniformly distributed and hence the winding mmf varies linearly from zero at one end to AT at the other end.

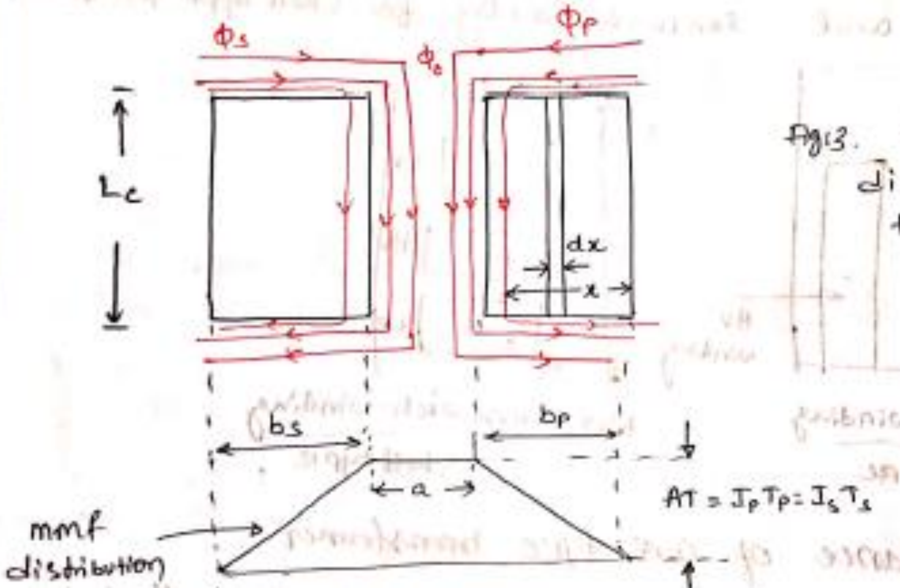


Fig.3. Leakage flux & mmf distribution in core type transformer

Here Φ_P, Φ_S are the leakage fluxes in the Primary & Secondary windings respectively. Φ_0 is the flux through the duct.

Let L_0 = mean circumference of the duct

L_c = axial height of the windings.

b_P, b_S = radial width of Primary & secondary windings

a = width of the radial duct.

The leakage flux of the windings is found as follows.

Conductor Portion: Consider an infinitesimal strip of width dx at a distance x from the edge of primary winding along its width.

MMF acting across the strip $= I_p T_p \frac{x}{b_p}$

Permeance of strip $= \mu_0 \frac{L_{mtp}\, dx}{L_c}$

L_{mtp} = length of mean turn of primary winding in mt.

Flux in the strip = MMF × Permeance.

$$= I_p T_p \frac{x}{b_p} \times \mu_0 \frac{L_{mtp}\, dx}{L_c}$$

This flux links with $\left(\frac{x}{b_p}\right) T_p$ turns.

Flux linkages of the strip = Flux links with $\left(\frac{x}{b_p}\right) T_p$ turns × Flux in strip.

$$d\psi_1 = \left(\frac{x}{b_p}\right) T_p \times I_p T_p \frac{x}{b_p} \cdot \mu_0 \frac{L_{mtp}\, dx}{L_c}$$

$$d\psi_1 = \frac{\mu_0 L_{mtp}}{L_c} I_p T_p^2 \left(\frac{x^2}{b_p^2}\right) dx.$$

Hence flux linkages of primary winding due to flux in the strip

$$\psi_1 = \int d\psi_1 = \mu_0 \frac{L_{mtp}}{L_c} I_p T_p^2 \int_0^{b_p} \left(\frac{x}{b_p}\right)^2 dx.$$

$$\psi_1 = \mu_0 \frac{L_{mtp}}{L_c} I_p T_p^2 \times \frac{1}{b_p^2} \left[\frac{x^3}{3}\right]_0^{b_p}$$

$$\psi_1 = \mu_0 \frac{L_{mtp}}{L_c} T_p^2 I_p \frac{b_p}{3}$$

Duct Portion :-

MMF acting across duct $= I_p T_p$

Permeance of duct $= \mu_0 \frac{L_0}{L_c} a$

Flux in duct $\phi_0 =$ MMF × Permeance.

$$\phi_0 = I_p T_p \times \mu_0 \frac{L_0}{L_c} a.$$

Half of the duct flux links with each of two windings or duct flux linking with primary winding.

$$= \frac{1}{2} \phi_0$$

$$= \frac{1}{2} I_p T_p \mu_0 \frac{L_0 a}{L_c}$$

This flux links with the entire primary winding

∴ Flux linkages of primary winding due to duct flux is

$$\psi_0 = \frac{1}{2} \mu_0 I_p T_p \frac{L_0 a}{L_c} \times T_p.$$

$$\psi_0 = \frac{1}{2} \mu_0 I_p T_p^2 \frac{L_0 a}{L_c}.$$

Hence, total flux linkages of primary winding is

$$\psi_p = \psi_1 + \psi_0$$

$$= \left[\mu_0 \frac{L_{mtp}}{L_c} I_p T_p^2 \frac{b_p}{3}\right] + \left[\frac{1}{2} \mu_0 I_p T_p^2 \frac{L_0 a}{L_c}\right]$$

$$\psi_p = \frac{\mu_0 I_p T_p^2}{L_c} \left[L_{mtp} \frac{b_p}{3} + \frac{L_0 a}{2}\right]$$

The above expression is simplified by assuming

$$L_{mt} = L_{mtp} = L_0$$

$$\therefore \quad \psi_p = \mu_0 \frac{I_p T_p^2}{L_c} L_{mt} \left[\frac{b_p}{3} + \frac{a}{2} \right]$$

Leakage Inductance of Primary winding $= \frac{\psi_p}{I_p}$

$$L_p = \mu_0 T_p^2 \frac{L_{mt}}{L_c} \left[\frac{b_p}{3} + \frac{a}{2} \right]$$

Leakage reactance of primary winding

$$X_p = 2\pi f L_p$$

$$X_p = 2\pi f \mu_0 T_p^2 \frac{L_{mt}}{L_c} \left[\frac{b_p}{3} + \frac{a}{2} \right] \rightarrow (1)$$

Similarly leakage reactance of secondary winding is

$$X_s = 2\pi f \mu_0 T_s^2 \frac{L_{mt}}{L_c} \left[\frac{b_s}{3} + \frac{a}{2} \right] \rightarrow (2)$$

Leakage reactance of secondary winding referred to Primary side.

$$X_s' = X_s \left(\frac{T_p}{T_s} \right)^2$$

$$X_s' = 2\pi f \mu_0 T_p^2 \frac{L_{mt}}{L_c} \left[\frac{b_s}{3} + \frac{a}{2} \right]$$

Total reactance of Transformer Per Phase referred to primary side,

$$X_p = X_p + X_s'$$

$$\boxed{X_p = 2\pi f \mu_0 T_p^2 \frac{L_{mt}}{L_c} \left[\frac{b_p + b_s}{3} + a \right]} \rightarrow (3)$$

Per unit reactance $\quad \varepsilon_x = \dfrac{I_p X_p}{V_p}$

$I_p T_p = AT$

$$\varepsilon_x = 2\pi f \mu_0 \frac{I_p T_p^2}{V_p} \frac{L_{mt}}{L_c} \left(a + \frac{b_p + b_s}{3} \right)$$

$\dfrac{1}{E_t} = \dfrac{T_p}{V_p}$

$$\varepsilon_x = 2\pi f \mu_0 \frac{AT}{E_t} \frac{L_{mt}}{L_c} \left(a + \frac{b_p + b_s}{3} \right) \rightarrow (4)$$

In order to reduce the leakage reactance, the actual arrangement of the windings on each leg consists of two groups of coils connected in series with each group consisting of half the number of turns per phase for each winding. with this modified arrangement the eqn (3) becomes

$$\boxed{X_p = \pi f \mu_0 T_p^2 \frac{L_{mt}}{L_c} \left[\frac{b_p + b_s}{6} + a \right]} \longrightarrow (5)$$

(b) Leakage reactance of sandwich coils.

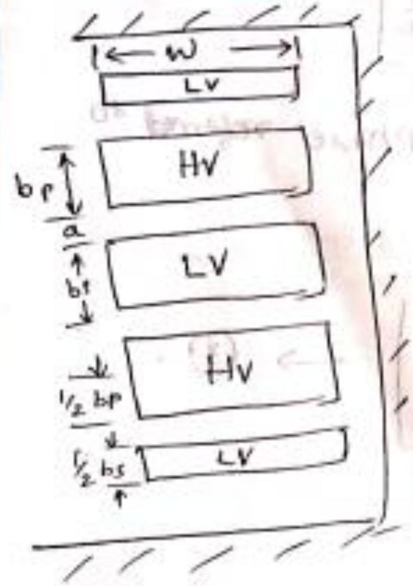


fig: Sandwich winding.

The distribution in shell type transformer using sandwich coils is shown in fig.

Let HV winding have n coils.

Each of n coils is sandwiched between two coils of LV. winding.

This requires the LV winding to have two half coils.

Each half coil of LV winding contains half the number of turns of a full LV coil.

The winding can be considered as consisting of 2n units connected in series with each unit consisting of a half l.v. coil and a half h.v. coil.

Each of these units can be treated on the same basis as that of cylindrical concentric winding.

W → width of the coil. analogous to axial length L_c. of the cylindrical windings.

Leakage reactance of each unit (per phase) referred to primary side with analogy to eqn (3).

$$X_u = 2\pi f \mu_0 \left(\frac{T_p}{2n}\right)^2 \frac{L_{mt}}{W}\left(a + \frac{b_p + b_s}{6}\right)$$

$T_p/2n$ = number of turns in each half coil of primary winding.

∴ Total reactance of transformer (per phase) referred on the primary side.

$$X_p = 2n \times 2\pi f \mu_0 \left(\frac{T_p}{2n}\right)^2 \frac{L_{mt}}{W}\left(a + \frac{b_p + b_s}{6}\right)$$

$$X_p = \pi f \mu_0 \frac{L_{mt}}{W} \frac{T_p^2}{n}\left(a + \frac{b_p + b_s}{6}\right) \rightarrow (6).$$

Per unit reactance

$$\boxed{\varepsilon_x = \frac{\pi f \mu_0}{n} \cdot \frac{AT}{E_t} \frac{L_{mt}}{W}\left(a + \frac{b_p + b_s}{6}\right)} \rightarrow (7)$$

$\varepsilon_x = \dfrac{I_p X_p}{V_p}$, $I_p T_p = AT$. $E_t = \dfrac{V_p}{T_p}$.

① A 300 KVA, 6600/400 V, 50 Hz., delta/star 3-phase core type transformer has the following data

width of hv winding = 25 mm; width of lv winding = 16 mm
height of coils = 0.5 m. length of mean turn = 0.9 m.
hv winding turns = 830.
width of duct between hv & LV winding = 15 mm.

ⓐ. Calculate the leakage reactance of the transformer referred to the hv side.

ⓑ. If the lv core is split into two parts with one part on each side of the hv coil, calculate the leakage reac referred to the hv side. Assume that there is a duct 15 mm wide between hv winding and each part of lv winding.

Sdu: ⓐ Leakage reactance referred to the Primary side

$$X_p = 2\pi f \mu_0 T_p^2 \frac{L_{mt}}{L_c}\left(a + \frac{b_p + b_s}{3}\right)$$

$$= 2\pi \times 50 \times 4\pi \times 10^{-7} \times (830)^2 \times \frac{0.9}{0.5}\left(0.015 + \frac{0.025+0.016}{3}\right)$$

$$X_p = \underline{14\,\Omega}$$

ⓑ The l.v. winding divided into two parts, one each side of h.v. winding & therefore

$$X_p = \pi f \mu_0 T_p^2 \frac{L_{mt}}{L_c}\left(a + \frac{b_p + b_s}{6}\right)$$

$$= \pi \times 50 \times 4\pi \times 10^{-7} \times (830)^2 \times \frac{0.9}{0.5} \times \left(0.015 + \frac{0.025 + 0.016}{6}\right)$$

$$X_p = \underline{5.36\,\Omega}$$

6. A 100 kVA, 2000/400V, 50Hz, Single phase Shell type transformer has sandwich coils. There are two full hv coils, one full lv coil and two half l.v. coils. Calculate the value of leakage reactance referred to h.v. side. Also calculate p.u. leakage reactance. The data given is

depth of hv coil = 40 mm

depth of lv coil = 36 mm

depth of duct between hv & lv = 16 mm.

width of winding = 0.12 m, length of mean turn = 1.5 m

The number of turns in hv winding are 200.

Soln: leakage reactance referred to hv side

$$X_P = \pi f \mu_0 \frac{L_{mt}}{w} \frac{T_P^2}{n}\left(a + \frac{b_P + b_S}{6}\right)$$

$$= \pi \times 50 \times 4\pi \times 10^{-7} \times \frac{1.5}{0.12} \times \frac{(200)^2}{2}\left(0.016 + \frac{0.04 + 0.036}{6}\right)$$

$$X_P = 1.41\,\Omega$$

H.V. winding current at full load = $I_P = \frac{KVA}{V_P}$

$$= \frac{100 \times 1000}{2000}$$

$$I_P = 50\,A$$

∴ Per unit leakage reactance

$$\varepsilon_x = \frac{I_P X_P}{V_P}$$

$$= \frac{50 \times 1.41}{2000}$$

$$\varepsilon_x = 0.0353\,\Omega$$

Regulation

The regulation of a Transformer is defined as the change Secondary terminal voltage between no load and full load Conditions expressed as a percentage of the secondary no load voltage. the Primary voltage assumed as a constant.
ie.

$$\text{Regulation} = \frac{E_s - V_s}{E_s} \times 100.$$

The approximate value of % regulation of transformer expressed in terms of equivalent resistance & reactance referred to h.v. (Primary side) load current & its power factor is given by

$$\%\ \text{Regulation} = \frac{I_P(R_P \cos\phi \pm X_P \sin\phi)}{V_P} \times 100.$$

$+ \rightarrow$ lagging p.f.
$- \rightarrow$ leading p.f.

$$\%\ \text{Regulation} = \varepsilon_r \cos\phi + \varepsilon_p \sin\phi.$$

$$\varepsilon_r = \frac{I_P R_P}{V_P} \qquad \varepsilon_p = \frac{I_P X_P}{V_P}.$$

1) Estimate the per unit regulation, at full load and 0.8 P.f lagging, for a 300 kVA, 50Hz, 6600/400V, 3ph, delta-star Core type transformer. The data given is

HV winding

outside diameter = 0.36m, inside diameter = 0.29m.
area of conductor = 5.4 mm².

LV winding.

Outside dia = 0.26m. inside dia = 0.22m, area of cond = 170mm²
Length of coils = 0.5m, Voltage per turn = 8V resistivity = 0.021Ω!

Soln: $V_s = \frac{400}{\sqrt{3}} = 231V$ (per phase. star).

$T_s = \frac{V_s}{E_t} = \frac{231}{8} = 29$.

$V_p = 6600V$. (delta. $V_L = V_{ph}$).

$T_p = \frac{6600}{8} = 825$

Mean diameter of LV winding $= \frac{0.26+0.22}{2} = 0.24\,m$

length of mean turn of LV winding $= \pi d = \pi \times 0.24$
$= 0.753\,m$

Resistance of LV winding: $r_s = \rho \frac{T_s L_{mts}}{a_s}$

$r_s = \rho \frac{T_s L_{mts}}{a_s}$ $= \frac{0.021 \times (29 \times 0.753)}{170}$

$r_s = 0.00269\,\Omega$

Mean diameter of h.v. winding $= \frac{0.36+0.29}{2} = 0.325\,m$

length of mean turn of h.v winding $= \pi \times d$
$= \pi \times 0.325 = 1.02\,mt$

Resistance of h.v. winding $r_p = \rho \frac{T_p L_{mtp}}{a_p}$

$r_p = \rho \frac{T_p L_{mtp}}{a_p}$ $= \frac{0.021 \times (825 \times 1.02)}{5.4}$

$r_p = 3.275\,\Omega$

Resistance of Transformer referred to primary.

$R_p = r_p + r_s \left(\frac{T_p}{T_s}\right)^2$

$= 3.28 + 0.00269 \left(\frac{825}{29}\right)^2$

$R_p = 5.47\,\Omega$

H.V. winding current per phase

$$I_p = \frac{P}{3V} = \frac{300 \times 1000}{3 \times 6600} = 15.1\,A$$

$\therefore$ PU resistance $\qquad \varepsilon_r = \frac{I_p R_p}{V_p}$

$$= \frac{15.1 \times 5.47}{6600}$$

$$\varepsilon_r = 0.0126.$$

Mean diameter of winding $= \frac{0.36 + 0.22}{2}$

$$= 0.29\,m$$

length of mean turn $\quad L_{mt} = \pi \times d$

$$= \pi \times 0.29 = 0.91\,m$$

width of LV winding $\quad b_s = \frac{(0.26 - 0.22)}{2} = 0.02\,m$

width of h.v. winding $\quad b_p = \frac{(0.36 - 0.29)}{2} = 0.035\,m$

width of duct $\quad a = \frac{(0.29 - 0.26)}{2}$

$$a = 0.015\,m$$

Leakage reactance of transformer referred to Primary Side.

$$X_p = 2\pi f \mu_0 T_p^2 \frac{L_{mt}}{L_c}\left(a + \frac{b_p + b_s}{3}\right).$$

$$= 2\pi \times 50 \times 4\pi \times 10^{-7} \times \frac{826^2 \times 0.91}{0.5}\left(0.015 + \frac{0.035 + 0.02}{3}\right)$$

$$X_p = 16.34\,\Omega.$$

P.U. leakage reactance :

$$\varepsilon_x = \frac{I_p X_p}{V_p}$$

$$= \frac{15.1 \times 16.34}{6600}$$

$$\varepsilon_x = \underline{\underline{0.0373}}$$

Per unit regulation.

$$\varepsilon = \varepsilon_r \cos\phi + \varepsilon_x \sin\phi$$

$$= 0.0126 \times 0.8 + 0.0373 \times 0.6$$

$$\varepsilon = \underline{\underline{0.0325}}$$

UNIT 4
DESIGN OF INDUCTION MOTOR

UNIT: V

Design of Induction Motor

Introduction:

Induction motors are the ac motors which are employed as the primemovers in most of the industries. Such motors are widely used in industrial applications from small workshops to large industries.

These motors are employed in applications such as centrifugal pumps, conveyers, compressors, crushers & drilling machines.

The two major parts of 3phase induction motor are

1. Stator &
2. Rotor

Stator

a) Stator core → laminated sheet steel of 0.5mm thickness. (internal diameter & length) → main dimensions

b) windings.

Rotor:

a) squirrel cage → core, bars & endrings

b) slipring (wound rotor) → core, winding, sliprings & brushes.

Specific magnetic loading (B_{av})

The average flux density B_{av} is ratio of flux per pole & area under a pole

$$B_{av} = \frac{\text{Flux Per Pole}}{\text{Area under a pole}} = \frac{\text{Flux Per Pole}}{\text{Pole pitch} \times \text{length of armature}}$$

$$B_{av} = \frac{\phi P}{\frac{\pi D}{P} \times L} \qquad \because \text{Pole pitch} = \tau = \frac{\pi D}{P}$$

Specific Electric loading (ac)

It is the ratio of total armature ampere Conductors and armature periphery (circumference) at air gap

$$\therefore ac = \frac{\text{Total armature amp conductors}}{\text{Armature Periphery at airgap}} = \frac{I_z Z}{\pi D}$$

Output Equation for 3ph Induction motor:

The equations of induced Emf, frequency, Total number of armature conductors of an ac machine are given below.

Induced Emf per phase = $E_{ph} = 4.44\, K_d\, K_p\, \phi\, f\, T_{ph}$ volts. → (1)

($K_w = K_d . K_p$ → winding factor) $E_{ph} = 2.22\, K_d\, K_p\, \phi\, f\, Z$ volts.

frequency = $f = \frac{PN_s}{120} = \frac{P n_s}{2}$ in H_z ($\because n_s = \frac{N_s}{60}$) r.p.s → (2)

Total no. of armature conductors Z = No. of phases × $2 T_{ph}$

$3 \times 2\, T_{ph}$

$Z = 6\, T_{ph}$. → (3)

Specific magnetic loading: $B_{av} = \frac{P\phi}{\pi D L}$

$P\phi = \pi D L B_{av}$ → (4)

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

$I_z Z = \pi D\, ac$. → (5)

KVA rating of 3-phase machine

$Q = 3\, E_{ph}\, I_{ph} \times 10^{-3}$ → (6)

$I_z = I_{ph}$

$$Q = 3 \times 4.44 f\phi T_{ph} K_w I_2 \times 10^{-3}$$

$$= 3 \times 4.44 \frac{P n_s}{2} \times \phi T_{ph} K_w I_2 \times 10^{-3}$$

$$= 6.66 P n_s \phi T_{ph} K_w I_2 \times 10^{-3}$$

$$Q = 1.11 P\phi I_2 6T_{ph} n_s K_w \times 10^{-3} \rightarrow (7)$$

On substituting eqn (3) in eqn (7) we get

$$Q = 1.11 P\phi I_2 Z n_s \times K_w \times 10^{-3}$$

$$= 1.11 \pi D L B_{av} \pi D ac \times n_s K_w \times 10^{-3}$$

$$Q = 1.11 \pi^2 B_{av} ac K_w \times 10^{-3} D^2 L n_s$$

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

$$\boxed{Q = C_o D^2 L n_s} \rightarrow (8)$$

where $C_o = 11 B_{av} ac K_w \times 10^{-3} \rightarrow (9)$.

The equation $Q = C_o D^2 L n_s$ is called output equation. &

C_o = output coefficient.

In case of induction motor the equation for input KVA is considered as output equation.

The input KVA = $Q = C_o D^2 L n_s$, $\left\{ \text{KVA input} = \frac{KW}{\eta \cos\phi} \right.$

The rating of an induction motor is expressed in horse power.

The KVA input for the motor can be calculated as

$$\text{KVA input} = Q = \frac{HP \times 0.746}{\eta \times \cos\phi} \rightarrow (10).$$

Example: 1

Calculate the specific electric & magnetic loading of 100 HP, 300V, 3-phase, 50 Hz, 8 pole, star connected, induction motor having stator core length = 0.5 m and stator bore = 0.66 Turns/phase = 286. Assume full load efficiency as 0.938 and P.f. as 0.86

bore (diameter)

Given data.

100 HP.	$\eta = 0.938$	star connected
V = 3000V	L = 0.5 m	P.f = 0.86.
3 ph	D = 0.66 m	$T_{ph} = 286$
f = 50 Hz		

Soln:-

$$\text{Input KVA},\quad Q = \frac{HP \times 0.746}{\eta \times Pf}$$

$$= \frac{100 \times 0.746}{0.938 \times 0.86} = \underline{\underline{92.48 \text{ KVA}}}$$

$$\text{KVA in 3ph circuit} = \sqrt{3}\, V_L I_L \times 10^{-3}$$

$$I_L = \frac{KVA}{\sqrt{3}\, V_L \times 10^{3}} = \frac{92.48}{\sqrt{3} \times 3000 \times 10^{3}}$$

$$I_L = \underline{\underline{17.8 \text{ A}}}$$

Since motor is star connected $I_L = I_{ph} = I_Z = 17.8$ A.

Total number of armature conductors $Z = \text{no of phase} \times 2 \times T_{ph}$

$$= 3 \times 2 \times 286$$

$$Z = \underline{1716}$$

Specific electric loading, $ac = \frac{I_z Z}{\pi D} = \frac{17.8 \times 1716}{\pi \times 0.66}$

$ac = \underline{14731.38}$ Ampere conductors/m

Synch. Speed $n_s = \frac{2f}{P} = \frac{2 \times 50}{8} = 12.5$ rps

Input KVA $= Q = C_0 D^2 L n_s$ & $C_0 = 11 B_{av}\, ac\, K_w \times 10^{-3}$

let $K_w = 0.955$

Specific magnetic loading $B_{av} = \frac{Q}{11\, ac\, K_w \times 10^{-3} D^2 L n_s}$

$= \frac{92.48}{11 \times 14731.38 \times 0.955 \times 10^{-3} \times 0.66^2 \times 0.5 \times 12.5}$

$B_{av} = \underline{0.22 \text{ wb/m}^2}$

Specific magnetic loading $= B_{av} = \underline{0.22 \text{ wb/m}^2}$

Specific Electric loading $ac = \underline{14731.38 \text{ A cond./m}}$

Choice of Specific loadings:

i) Specific magnetic loading (B_{av}): (Air gap flux density):

(a) Power factor: The value of flux density in airgap should be small as otherwise the machine will draw a large magnetising current giving a poor power factor. However in induction motors the flux density in the airgap, should be such that there is no saturation in any part of the magnetic circuit.

(b) Iron loss: An increased value of gap density results in increased iron loss and decreased efficiency.

(c) overload capacity: A high value of B_{av} means the flux per pole is large. Thus for the same voltage, the winding requires less turns per phase. If the number of turns is less, leakage reactance becomes small. Hence the maximum output which the machine is capable of giving is large. ie. the machine has large overload capacity.

For 50Hz induction motors $B_{av} = (0.3 \text{ to } 0.6)\ wb/m^2$.

(2) Choice of Specific electric loading (ac). (Ampere cond/mt).

(a) Copper loss and temperature rise:- A large value of "ac" means that a greater amount of copper is employed in the machine. This results in higher copper losses and large temperature rise of embedded conductors.

(b) Voltage: A small value of 'ac' should be taken for high voltage machines as in their case the space required for insulation is large.

(c) overload capacity:- If 'ac' is high number of turns becomes more and increases the inductive reactance. High X_L reduces the overload capacity of the machine.

Hence the value of ac depends upon size of the motor.

It varies 5000 to 45000 amp cond/mt.

Main Dimensions:-

The main dimensions of induction motor are the diameter of Stator bore, D and the length of Stator core L. The Product of D^2L is determined from input KVA, specific electric & magnetic loadings. The seperation of D & L from the Product D^2L depends on the ratio L/τ.

Where $\tau = \frac{\pi D}{P}$ → Polepitch

In induction motors most of the operating characteristics are decided by L/τ ratio of the motor.

The ratio of core length to Polepitch (L/τ) for various design features are listed below.

For minimum cost, $L/\tau = 1.5$ to 2.

For good P.f - $L/\tau = 1.0$ to 1.25

For good efficiency, - $L/\tau = 1.5$

For good overall design - $L/\tau = 1$.

Generally L/τ lies between 0.6 to 2. It can be shown that, for best power factor the pole pitch τ is given by the equation.

$$\tau = \sqrt{0.18L}$$

The diameter of the stator bore & hence the diameter of rotor is also limited by peripheral speed. Standard constructions are employed for peripheral speeds upto 60 m/s. For higher peripheral speeds upto 75 m/s, special construction methods should be employed for rotor which results in higher cost.

For normal design, the diameter should be so choosen that the peripheral speed does not exceed about 30 m/sec.

The stator is provided with radial ventilating ducts if the core length exceeds 125 mm. The width of each duct is about 8 to 10 mm.

Stator winding:

For small motors upto 5 Hp, single layer windings like mush winding, whole coil concentric winding & bifurcated concentric winding are employed.

For large capacity machines, double layer windings (either lap or wave winding) are employed with dimond shaped coils.

The stator winding can be designed for either star or delta depending on the running condition.

Turns per phase:

The turns per phase T_s can be estimated from stator phase voltage and maximum flux in the core.

Specific magnetic loading $B_{av} = \frac{P\phi}{\pi D L}$

Pole pitch $= \tau = \frac{\pi D}{P}$

Flux per pole $\phi_m = B_{av} \, \tau \, L$

$$\phi_m = B_{av} \cdot \frac{\pi D}{P} \cdot L$$

Stator voltage per phase $E_s = 4.44 f \Phi_m K_w T_s$

where T_s = number turns per phase in stator.

$$\boxed{T_s = \frac{E_s}{4.44 f \Phi_m K_w}}$$

Stator conductors :

The area of cross section of stator conductors can be estimated by current density, KVA rating of machine & stator phase voltage.

The current density in stator winding is usually 3 to 5 A/mm².

KVA rating of 3ph IM = $Q = 3 E_s I_s \times 10^{-3}$

$$I_s = \frac{Q}{3 E_s \times 10^{-3}}$$

area of each stator conductors $a_s = \frac{I_s}{\delta_s}$

where δ_s = current density of stator conductors.

$$a_s = \frac{\pi d_s^2}{4}$$

$$d_s = \sqrt{\frac{4 a_s}{\pi}}$$

a_s = area of c/s of stator conductor

d_s = diameter of stator conductor.

Round conductors are used for small diameters. If the diameter is more than 2 or 3 mm then bar or strip conductors are used.

Stator core.

The stator core is made of laminations of thickness 0.5 mm. The design of stator core involves selection of number of slots, estimation of dimension of teeth & depth of stator core.

Stator slots:

fig 1. Semi enclosed slots with tapered slot & Parallel sided teeth.

fig 2. open slot with Parallel sided slots & tapered teeth.

The different types of slots used in induction motor are open slots and semienclosed slots. The shape of the slots have an important effect upon the operating performance of the motor as well as the problem of installing the winding.

When open slots are used the winding coils can be formed and fully insulated before installing and also it is easier to replace the individual coils. Another advantage of open slots is that their use avoids excessive slot leakage thereby reducing the leakage reactance.

Tapered → narrow.

When semienclosed slots are used, the coils must be taped & insulated after they are placed in the slots. The advantages of semienclosed slot are less air gap contraction factor giving a small value of magnetizing current, low tooth pulsation loss and much quieter operation (less noise). Semi enclosed slots are mostly preferred for induction motors.

In small motors where round conductors are used, the tapered slot with parallel sided tooth arrangement is useful as it gives the maximum slot area for a particular tooth density.

In large & medium size machines where strip conductors are preferred, parallel sided slots with tapered teeth are used.

Choice of Stator Slots:

The number of stator slots depends on tooth pulsation loss, leakage reactance, ventilation, magnetizing current, iron loss and cost.

In general the number of slots should be selected to give an integral number of slot per pole per phase.

The slot pitch at the air gap for open type slots should be between 15 to 25mm.

For semienclosed slots the slot pitch may be less than 15mm.

The stator slot pitch

$$Y_{ss} = \frac{\text{Gap Surface}}{\text{Total number of stator slots}} = \frac{\pi D}{S_s}$$

Where $S_s \rightarrow$ no. of stator slots $\quad S_s = \frac{\pi D}{Y_{ss}}$

$\pi D \rightarrow$ Gap surface.

Total number of stator conductors = No. of phases X Conductor per phase

$= 3 \times 2T_s = 6T_s$.

T_s = Turns per phase.

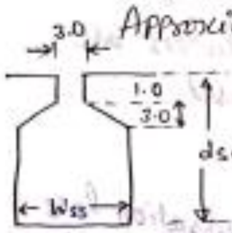
Conductors per stator slot

$$Z_{ss} = \frac{\text{Total stator conductors}}{\text{Number of stator slots}} = \frac{6T_s}{S_{ss}}$$

Z_{ss} must be even for double layer winding.

Area of stator slot:

Approximate area of each slot $= \dfrac{\text{Copper area per slot}}{\text{Space factor}}$



$$= \frac{Z_{sgs} \times a_s}{\text{Space factor}}$$

The space factor vary from 0.25 to 0.4. High voltage machines have lower space factors due to large thickness of insulation. After obtaining the area of the slot, the dimensions of the slot should be adjusted. The slot should not be too wide to give a thin tooth. The width of the slot should be so adjusted such that the mean flux density in the tooth lies between 1.3 to 1.7 wb/m^2

The width of tooth should not be too large as it results in narrow and deep slots.

The deeper slot give a large value of leakage reactance. In general the ratio of slot depth to slot width should be between 3 and 6

Length of mean turn:

The approximate length of mean turn of the winding on induction motor stators, for use on voltage upto 650 V may be calculated from the following empirical relationship

Length of mean turn of stator $L_{mts} = 2L + 2.3\tau + 0.24$

L & τ are expressed in mt.

Stator teeth: The dimensions of the slot determine the value of flux density in the teeth. A high value of flux density in the teeth is not desirable, as it leads to a higher iron loss and a greater magnetizing mmf. The max. value of B_{ts} (mean flux density in stator tooth) should not exceed $1.7\ \text{wb/m}^2$.

$\therefore$ minimum teeth area per pole $= \dfrac{\Phi_m}{1.7}$

$$\boxed{\text{Tooth area per pole} = \text{No. of slots per pole} \times \text{Net iron length} \times \text{width of tooth}}$$

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

When teeth area per pole is minimum, the width of tooth will be minimum

$$\therefore \frac{\Phi_m}{1.7} = (S_s/p) \times L_i \times W_{ts\,min}$$

The minimum width of stator tooth $\boxed{W_{ts(min)} = \dfrac{\Phi_m}{1.7(S_s/p)L_i}}$

The minimum width of stator tooth is either near the gap surface or at one third height of tooth from slot opening. A check for minimum tooth width using the above equation should be applied before finally deciding the dimensions of stator slot.

Depth of stator core:

The cross-section of stator core is shown in fig. The depth of stator core depends on the flux density in the core. The flux density in the stator core lies between 1.2 to $1.5\ \text{wb/m}^2$.

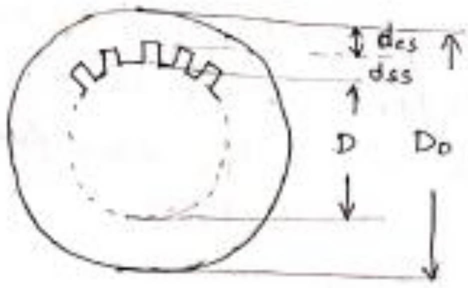


fig. Cross section of Stator core.

The flux passing through the stator core is half of the flux per pole.

$\therefore$ Flux in the Stator core $= \frac{\phi_m}{2}$

let B_{cs} = Flux density in Stator Core

$\therefore$ Area of Stator core $= \frac{\text{Flux through Core}}{\text{Flux density in stator core}}$

$= \frac{\phi_m}{2 B_{cs}}$

Also, Area of Stator Core = Length x depth

$= L_i \times d_{cs}$

Thus $\boxed{L_i d_{cs} = \frac{\phi_m}{2 B_{cs}}}$

$\therefore$ $\boxed{\text{Depth of core} \quad d_{cs} = \frac{\phi_m}{2 B_{cs} L_i}}$

outer diameter of Stator core $D_o = D + 2$ (Depth of stator slot + Depth of core)

$$\boxed{D_o = D + 2(d_{ss} + d_{cs})}$$

Example:2 Determine the approximate diameter and length of Stator core, the number of Stator slots and the number of Stator conductors for a 11 KW, 400V, 3ph, 4-Pole, 1425 rpm, delta connected induction motor. $B_{av} = 0.45\ wb/m^2$, $ac = 23000$ amp cond/m, fullload efficiency $= 0.85$, $pf = 0.88$, $L/\tau = 1$. The stator employs a double layer winding.

Given Data:

11 KW, 3ph, $P = 4$, $V = 400V$

Delta connected, Double layer, $ac = 23000$ amp cond/m, $\eta = 0.85$.

$N = 1425$ rpm, $B_{av} = 0.45\ wb/m^2$, $p.f = 0.88$, $L/\tau = 1$

Soln:

$$\text{KVA input} = \frac{O/P}{\eta \times p.f} = \frac{11}{0.85 \times 0.88} = 14.7\ \text{KVA}$$

$$n_s = \frac{2f}{P} = \frac{2 \times 50}{4} = 25\ \text{rps.}$$

let $K_w = 0.955$

$$C_0 = 11\, K_w\, B_{av}\, ac \times 10^{-3}$$

$$= 11 \times 0.955 \times 0.45 \times 23000 \times 10^{-3}$$

$$C_0 = 108.7268\ \text{KVA}/m^3\text{-rps.}$$

$$\text{KVA input} = Q = C_0 D^2 L n_s$$

$$D^2L = \frac{Q}{C_0 n_s} = \frac{14.7}{108.7268 \times 25} = 0.0054\ m^3.$$

$$L/\tau = 1 \quad \therefore L = \tau = \frac{\pi D}{P}$$

$$D^2 L = D^2 . \frac{\pi D}{P} = 0.0054$$

$$= D^3 \frac{\pi}{P} = 0.0054$$

$$\therefore D = \left(\frac{0.0054 \times P}{\pi}\right)^{1/3} = \underline{0.1902\,m}$$

$$L = \frac{\pi D}{P} = \frac{\pi \times 0.1902}{4} = \underline{0.1494\,m}$$

$D = 0.19\,m \qquad L = 0.15\,m$

$$\phi_m = \frac{B_{av}\,\pi D L}{P} = \frac{0.45 \times \pi \times 0.19 \times 0.15}{4}$$

$$\phi_m = \underline{0.01\,wb}$$

Stator is Delta Connected line vtg = Ph. Voltage.

$$\text{Stator turns/ph} = T_s = \frac{E_s}{4.44\, f\, \phi_m\, k_w}$$

$$= \frac{400}{4.44 \times 50 \times 0.01 \times 0.955}$$

$$T_s = \underline{188}$$

The Stator slots should be multiple of q.
where q is slots per pole per phase.

Stator Slots, S_s = No. of Phases × Poles × q

For $q = 2$, $S_s = 3 \times 4 \times 2 = 24$

$q = 3$, $S_s = 3 \times 4 \times 3 = 36$

$q = 4$, $S_s = 3 \times 4 \times 4 = 48$

The stator slot pitch should lie between 15mm to 25mm.

When $S_s = 36$.

$$Y_{ss} = \frac{\pi D}{S_s} = \frac{\pi \times 0.19 \times 10^3}{36} = 16.58\ mm$$

When $S_s = 36$, the Slot Pitch (Y_{ss}) lies between 15 to 25mm.

Hence the Stator slots can be 36.

Conductor per Slot $\quad Z_{ss} = \frac{6 T_s}{S_s} = \frac{6 \times 188}{36} = 31.33$

Z_{ss} should be even integer for double layer winding and so it is 30 or 32.

let $Z_{ss} = 32$. Total Stator conductors $= S_s \times Z_{ss}$

$$= 36 \times 32$$

$$Z_s = 1152$$

New value of turns per phase $T_s = \frac{Z_{ss} S_s}{6} = \frac{32 \times 36}{6} = 192$

Results:

$D = 0.19m$
$L = 0.15m$
$S_s = 36$.
$Z_s = 1152$
$T_s = 192$

3) Estimate the stator core dimensions, number of stator slots and number of stator conductors per slot for a 100kW, 3300V, 50Hz, 12 Pole, star connected slipring induction motor. ac = 25000 amp cond/m. $\eta = 0.9$. p.f = 0.9. $B_{av} = 0.4\ Wb/m^2$. choose main dimensions to give best powerfactor. The slot loading should not exceed 500 amp. conductors.

Given Data.

100kW. $V = 3300V$ $\quad B_{av} = 0.4\ Wb/m^2$
$f = 50Hz$, $P = 12$ $\quad ac = 25000$ amp.cond/m.
$\eta = 0.9$ $\quad$ P.f = 0.9 $\quad$ Slot loading $\leq$ 500 amp. cond.
Star $\quad$ 3ph

KVA input $Q = \frac{\text{output}}{\eta \times p.f} = \frac{100}{0.9 \times 0.9} = 123.457$ KVA.

let $k_w = 0.96$.

Output Co-efficient $C_0 = 11\, B_{av}\, ac\, k_w \times 10^{-3}$

$= 11 \times 0.4 \times 25000 \times 0.96 \times 10^{-3}$

$= 105.6$ kVA/m³-rps.

$n_s = \frac{2f}{P} = \frac{2 \times 50}{12} = 8.33$ rps.

KVA input $= Q = C_0 D^2 L n_s$

$D^2 L = \frac{Q}{C_0 n_s} = \frac{123.457}{105.6 \times 8.33} = 0.1403\, m^3$.

For best Power factor $\tau = \sqrt{0.18L}$ $\tau = \frac{\pi D}{P}$

on squaring we get $\frac{\pi^2 D^2}{P^2} = 0.18L$

$D^2 = \frac{0.18\, L\, P^2}{\pi^2} = \frac{0.18 \times 12^2}{\pi^2} L = 2.6262\, L$

$\therefore D^2 L = 2.6262 L \times L = 0.1403$

$L = \sqrt{\frac{0.1403}{2.6262}} = 0.2311\, m$

$D^2 = 2.6262 L$

$D = \sqrt{2.6262 \times 0.23}$

$D = 0.772\, m \simeq 0.78\, m$

$L = 0.23\, m$. & $D = 0.78\, m$

Star Connected

$$E_s = \frac{3300}{\sqrt{3}} = 1905.25\ V$$

$$\phi_m = \frac{B_{av}\,\pi D L}{P} = \frac{0.4 \times \pi \times 0.78 \times 0.23}{12} = 0.0188\ wb$$

$$T_s = \frac{E_s}{4.44 f \phi_m k_w} = \frac{1905.256}{4.44 \times 50 \times 0.0188 \times 0.96} = \underline{\underline{478}}$$

The Stator slot pitch should lie between 15 to 25 mm.

Stator Slots, $S_s = \frac{\pi D}{Y_{ss}}$

When $Y_{ss} = 15mm$, $S_s = \frac{\pi \times 0.78}{15 \times 10^{-3}} = 163.$

When $Y_{ss} = 25mm$ $S_s = \frac{\pi \times 0.78}{25 \times 10^{-3}} = 98$

- The Stator Slots S_s should lie between 98 to 163.

The Stator slots be multiple of q, where q is slot per pole per phase

S_s = No. of phases × Poles × q

$q = 2$ $S_s = 3 \times 12 \times 2 = 72$

$q = 3$ $S_s = 3 \times 12 \times 2 = 108$

$q = 4$ $S_s = 3 \times 12 \times 4 = 144$

Check for Slot loading

$$\text{Stator current per phase} = \frac{KVA \times 10^3}{\sqrt{3} \times V_L} = \frac{123.457 \times 10^3}{\sqrt{3} \times 3300}$$

Star - $I_L = I_{ph} = 21.6A.$

When $S_s = 108.$

$$Z_{ss} = \frac{6T_s}{S_s} = \frac{6 \times 478}{108} = 26.55 = 26$$

Slot loading $Z_{ss} I_s = 26 \times 21.6 = 561.6$ amp cond

When $S_s = 144$.

$$Z_{ss} = \frac{6T_s}{S_s} = \frac{6 \times 478}{144} = 19.91 \approx 20.$$

Slot loading $Z_{ss} I_s = 20 \times 21.6 = 432$ amp.cond.

When $S_s = 144$ the slot loading does not exceed 500 amp.cond. Hence 144 slots is suitable for the machine.

Total stator conductors $= S_s \times Z_s = 144 \times 20$
$= 2880$

New value of turns per phase

$$T_s = \frac{Z_{ss} S_s}{6} = \frac{20 \times 144}{6}$$

$$T_s = 480.$$

Results:

$D = 0.78 m$
$L = 0.23 m$
$S_s = 144.$
$Z_1 = 2880$
$T_s = 480$

Example: 4 Determine the D and L of a 70 HP, 415V, 3-phase 50Hz star connected, 6 pole induction motor for which ac = 30,000 amp.cond/m and $B_{av} = 0.51$ Wb/m². Take $\eta = 90\%$ and p.f. $= 0.91$. Assume $\tau = L$. Estimate the number of stator conductors required for a winding in which the conductors are connected in 2-parallel paths. Choose a suitable number of conductors per slot, so that the slot loading doesnot exceed 750 amp conductors.

Given Data:-

70 HP $\quad V = 415V \quad B_{av} = 0.51 wb/m^2$

3-phase $\quad f = 50Hz \quad ac = 30,000$ amp cond/m

$\eta = 0.9 \quad p.f = 0.91 \quad$ star

$P = 6 \quad \tau = L \quad$ slot loading ≤ 750 amp cond.

Soln:

KVA input, $Q = \frac{HP \times 0.746}{\eta \times p.f}$

$$Q = \frac{70 \times 0.746}{0.9 \times 0.91} = 63.76 \text{ KVA}$$

output co-efficient $C_o = 11 B_{av}\, ac\, K_w \times 10^{-3}$

$= 11 \times 0.51 \times 30,000 \times 0.955 \times 10^{-3}$

$= 160.7265$ KVA/m³ · rps.

Synchronous speed $n_s = \frac{2f}{P} = \frac{2 \times 50}{6} = 16.66$ rps

$Q = C_o D^2 L n_s$

$\therefore D^2 L = \frac{Q}{C_o n_s} = \frac{63.76}{160.7265 \times 16.66}$

$D^2 L = \underline{\underline{0.0238 m^3}}$

$\tau = L$.

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

$L = \frac{\pi D}{6} = 0.5236 D$

$D^2 L = 0.0238$

$D^2 (0.5236 D) = 0.0238$

$D = \left(\frac{0.0238}{0.5236}\right)^{1/3}$

$D = 0.35688 m$

$D = 0.36 m$.

$L = 0.5236 D$

$L = 0.5236 \times 0.36 = L = \underline{\underline{0.19 m}}$

Flux per pole $\phi_m = \dfrac{B_{av}\pi DL}{P}$

$$\phi_m = \frac{0.51 \times \pi \times 0.36 \times 0.19}{6}$$

$$\phi_m = 0.0183\,Wb$$

let $K_w = 0.955$

Turns per phase $T_s = \dfrac{E_s}{4.44 f \phi_m K_w}$

$$= \frac{415/\sqrt{3}}{4.44 \times 50 \times 0.0183 \times 0.955}$$

(Star Connection) $V_{ph} = \dfrac{V_L}{\sqrt{3}}$

$$T_s = 61.756 \approx 62$$

Since the conductors are placed in two parallel paths,

Total stator conductors $= 6T_s \times 2$

$12T_s = 12 \times 62$

$= 744$ conductors

The slot pitch y_{ss} should lie between 15 to 25 mm.

when $y_{ss} = 15\,mm$

$$S_s = \frac{\pi D}{y_{ss}} = \frac{\pi \times 0.36}{15 \times 10^{-3}}$$

$$S_s = 75$$

when $y_{ss} = 25\,mm$

$$S_s = \frac{\pi D}{y_{ss}} = \frac{\pi \times 0.36}{25 \times 10^{-3}}$$

$$S_s = 45$$

The number of slots lies in the range of 45 to 75.

The stator slots should be multiple of q where q is Slots per pole per phase.

Stator slots S_s = No. of phases × Poles × q

when $q = 2$ $\quad S_s = 3 \times 6 \times 2 = 36$

$q = 3 \quad S_s = 3 \times 6 \times 3 = 54$

$q = 4 \quad S_s = 3 \times 6 \times 4 = 72$

The values of S_s which lies between 45 to 75 are

$S_s = 54$ and $S_s = 72$.

Stator current per phase $I_s = \dfrac{KVA \times 10^3}{\sqrt{3}\, V_2} = \dfrac{63.76 \times 10^3}{\sqrt{3} \times 415}$

$I_s = 88.7A$ $\quad (I_L = I_{ph}$ star$)$.

$I_z = \dfrac{I_s}{a} = \dfrac{88.7}{2} = 44.35A$. (two parallel paths).

Check for slot loading

When $S_s = 54$

Conductors per slot $Z_{ss} = \dfrac{744}{54} = 13.77 \approx 14$

Slot loading $= Z_{ss} I_s$
$= 14 \times 44.35$
$= 620.9$ Amp cond

When $S_s = 72$

Conductor per slot $Z_{ss} = \dfrac{744}{72} = 10.33 \approx 11$.

Slot loading $= Z_{ss} \times I_s$
$= 11 \times 44.35$
$= 487.85$ amp cond.

In both cases slot loading is not exceeded.

For lower fabrication costs $S_s = 54$

For lower temperature rise $S_s = 72$.

let $S_s = 54$. $\quad Z_{ss} = 14$

Total stator conductors $Z_{ss} \times S_s = 14 \times 54 = 756$ conductors

New value of turns per phase $T_s = \dfrac{Z_{ss} \times S_s}{6 \times 2} = \dfrac{756}{6 \times 2} = 63$

$Z_{ss} = \dfrac{6 T_s}{S_s}$

Result: $D = 0.36\,m$ $T_s = 63$ $Z_{ss} = 14$
$L = 0.19\,m$ $S_s = 54$

July 2015

Example 15. Determine the main Dimensions, turns per phase, number of slots, conductors cross section & slot area of 250HP 3 phase 50Hz, 400V, 1500 rpm, slipring induction motor.

Assume. $B_{av} = 0.5\ wb/m^2$. $ac = 30{,}000\ A\,cond/m$.
$\eta = 0.9$. $P.f = 0.9$. $K_w = 0.955$.
$\delta = 3.5\,A/mm^2$ Slot space factor $= 0.4$
$L/\tau = 1.2$. Delta connected.

Soln:

$N_s = 1500\ rpm$

$n_s = \frac{1500}{60} = 25\ rps$

$P = \frac{2f}{n_s} = \frac{2\times 50}{25} = 4$ Pole.

$$Q = \frac{\text{output}}{\eta \times Pf} = \frac{250\times 0.746}{0.9\times 0.9}$$

input $Q = 230.246$ KVA

$Q = C_o D^2 L n_s$

$C_o = 11\, B_{av}\, ac\, K_w \times 10^{-3}$

$= 11 \times 0.5 \times 30{,}000 \times 0.955 \times 10^{-3}$

$C_o = 157.575\ \text{KVA}/m^3\text{-rps}$

$$D^2L = \frac{Q}{C_o\, n_s} = \frac{230.246}{157.575\times 25} = 0.0595\ m^3.$$

$\frac{L}{\tau} = 1.2$ $\tau = \frac{\pi D}{P}$

$L = 1.2\,\frac{\pi D}{P} = 0.942D.$

$D^2L = 0.0595$

$D^2 \times 0.942D = 0.0595$

$$0.942 D^3 = 0.0595$$

$$D = \left(\frac{0.0595}{0.942}\right)^{1/3}$$

$$D = 0.398\ m \simeq \underline{0.4 m}$$

$$L = 1.2 \frac{\pi D}{P} = \frac{\pi \times 0.4}{4} \times 1.2 = 0.376 \simeq \underline{0.38 m}$$

$$\phi_m = B_{av} \frac{\pi D L}{P} = \frac{0.5 \times \pi \times 0.4 \times 0.38}{4} = \underline{0.0596\ wb}$$

Delta connected

$$E_s = 4.44 f \phi K_w T_s$$

$$T_s = \frac{400}{4.44 \times 50 \times 0.0596 \times 0.955} = 31.60 \simeq \underline{32 \text{ turns}}$$

Stator conductors

$$Z_s = 6 T_s = 6 \times 32 = 192 \text{ conductors}.$$

No. stator slots, Pitch lie between (y_{ss}) = 15mm to 25 mm.

$$S_s = \frac{\pi D}{y_{ss}} = \frac{\pi \times 0.4}{15 \times 10^{-3}} = 83.77 \simeq 84$$

$$S_s = \frac{\pi D}{y_{ss}} = \frac{\pi \times 0.4}{25 \times 10^{-3}} = 50.26 \simeq 50.$$

no. of slots lies between 50 to 84.

S_s = no. of phase × pole × q

$S_s = 3 \times 4 \times 2 = 24$

$S_s = 3 \times 4 \times 3 = 36$

$S_s = 3 \times 4 \times 4 = 48$

$S_s = 3 \times 4 \times 5 = 60$

$S_s = 3 \times 4 \times 6 = 72$

$S_s = 60$. or $S_s = 72$

Area of cross section of conductors

$$I_s = \frac{KVA}{\sqrt{3}\, V_L} \quad \cancel{I_s = \frac{KW\,(max)}{\sqrt{3}\, E_s \cos\phi}} = \frac{230.246 \times 1000}{\sqrt{3} \times 400 \times 0.9}$$

$\cancel{I_s = 213.18A}$ $\quad I_L = 332.33A \quad I_{ph} = \frac{I_L}{\sqrt{3}}$

$I_{ph} = I_s = 191.87A$

$$a_s = \frac{I_s}{\delta} = \frac{\cancel{213.18}\ 191.87}{3.5} = \cancel{60.9}\ 54.82 = \cancel{61\,mm^2}\ 55\,mm^2$$

Copper area in each slot $= a_s \times Z_{ss}$

$= 55 \times 3$

$= \cancel{183\,mm^2}\ 165\,mm^2$

Considering $S_s = 60$.

$$Z_{ss} = \frac{6T_s}{S_s} = \frac{6 \times 32}{60} = 3.2 \approx 3$$

$$\therefore \text{Area of slot} = \frac{a_s Z_{ss}}{\text{Slot space factor}} = \cancel{\frac{183}{0.4} = 457.5\,mm^2}$$

$$= \frac{165}{0.4} = 412.5\,m$$

Slot loading $= I_s Z_{ss}$

$= \cancel{213.18 \times 3}$

$= \cancel{639.54}$ Amp cond.

191.87×3

Slot loading $= 575.61$ Amp cond.

Choice of length of airgap:

The following factors should be considered when choosing the length of airgap

i) Power factor ii) overload capacity (iii) Tooth pulsation loss

iv) unbalanced magnetic pull v) cooling & vi) Noise

(i) Powerfactor: The mmf required to send the flux through airgap is directly proportional to the product of flux density and airgap length.

ie $AT_g = 800000 B_g l_g$

Therefore length of airgap primarily determines the magnetising current drawn by the machine

ie. If $l_g \rightarrow$ High, AT_g - High & I_m = High.

The following fig shown the phasor diagram of Induction motor with two different airgap length.

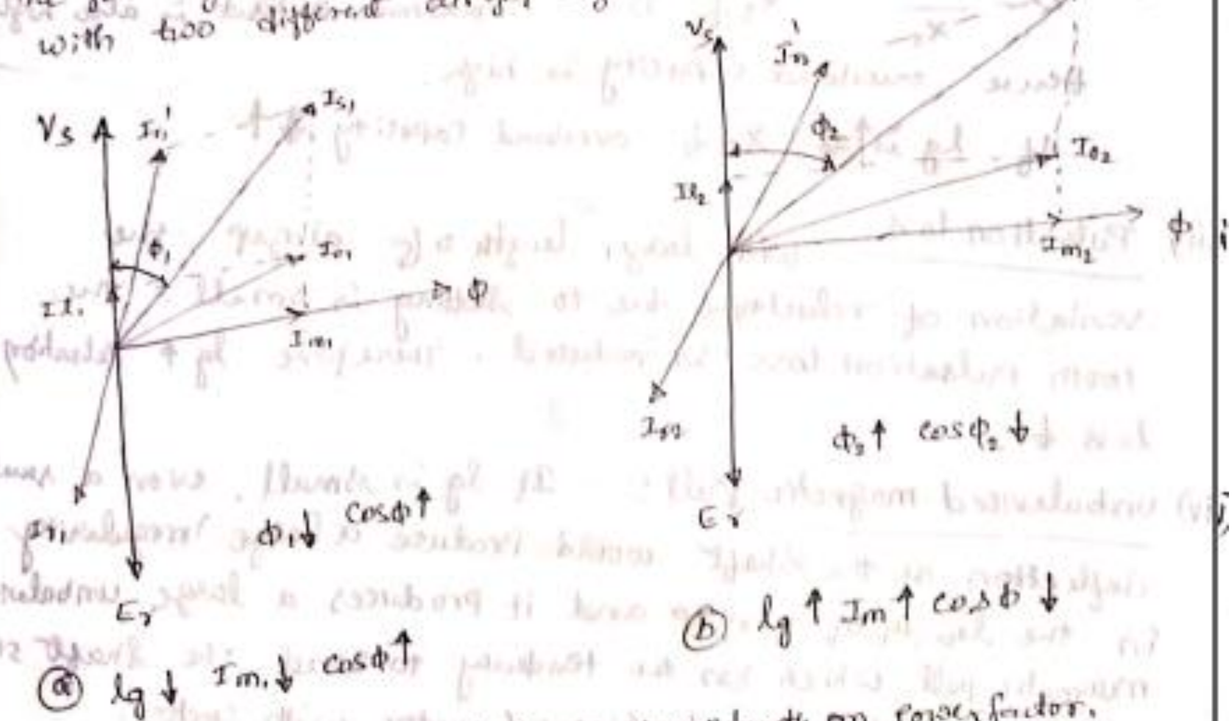


Fig:- Effect on airgap length on Powerfactor.

$V_s \rightarrow$ Stator applied voltage $\phi \rightarrow$ airgap flux

E_r = rotor induced emf (back emf) $I_r \rightarrow$ rotor current

I_r' = rotor current referred to stator.

I_m = Magnetizing current. I_l = loss component of no load current.

I_0 = no load current ; I_s = stator current

ϕ_1 & ϕ_2 = Phase angle between stator voltage & stator current.

Subscripts 1 & 2 refer to two different cases of Induction motor with different airgap lengths. If $l_g \uparrow$ $\cos\phi \downarrow$.

ii) **Overload capacity:** It is defined as the ratio of the maximum output to the rated output.

The maximum output to the Induction motor is obtained from its circle diagram. The diameter of circle diagram is V_s / X_s;

$X_s \rightarrow$ leakage reactance referred to the stator. If X_s is low Diameter is large. and

$$D = \frac{V_s}{X_s}$$

$X_s \downarrow$ $D \uparrow$. maximum output is also high.

Hence overload capacity is high.

overload capacity $\uparrow$

If l_g is $\uparrow$ $X_s \downarrow$ overload capacity $\uparrow$

i) **Pulsation loss:** With larger length of airgap, the variation of reluctance due to slotting is small. The tooth pulsation loss is reduced. Therefore $l_g \uparrow$ Pulsation loss $\downarrow$.

) **Unbalanced magnetic Pull:-** If l_g is small, even a small deflection of the shaft would produce a large irregularity in the length of airgap and it produces a large unbalanced magnetic pull which has the tendency to bend the shaft still more resulting in fouling of rotor with stator.

v) **Cooling**: If l_g is ↑ the distance between stator & rotor is ↑. This would afford better facilities for cooling at the gap surface.

vi) **Noise**: If l_g ↑ the zig zag leakage flux ↓. This reduces the noise in the induction motor.

From the above, we conclude that the length of airgap in induction machine should be as small as mechanically possible in order to keep down the magnetizing current and to improve the power factor. This is a major consideration. But if a higher overload capacity, better cooling, reduction in noise or reduction in unbalanced magnetic pull is ~~approve~~ important, then larger airgap lengths should be used.

Relations for Calculation of Length of Airgap

The following empirical formulae can be used to calculate the length of airgap (l_g).

1. For Small Induction motor

$$l_g = 0.2 + 2\sqrt{DL} \text{ in mm} \rightarrow (1)$$

2. Alternate formula for Small IM

$$l_g = 0.125 + 0.35D + L + 0.015\,V_a \text{ in mm} \rightarrow (2)$$

3. Another formula for general ~~side~~ use

$$l_g = 0.2 + D \text{ in mm} \rightarrow (3)$$

4. For machines with journal bearings

$$l_g = 1.6\sqrt{D} - 0.25 \text{ in mm} \rightarrow (4).$$

D & L are in mt. & V_a in m/sec.

Table

D in mm	l_g in mm
0.15	0.35
0.20	0.50
0.25	0.60
0.30	0.70
0.45	1.3
0.55	1.8
0.65	2.5
0.80	4.0

Typical values of length of airgap for 4 pole machines in relation to the main dimension D are listed in table.

Crawling & Cogging

With certain combinations of Stator & rotor slots the machine may refuse to start or may crawl at some sub synchronous speed and severe vibrations are developed and so the noise will be excessive.

These effects are produced by harmonic fields.

The effects of harmonics are

1) Harmonic induction torque (crawling)
2) Harmonic synchronous torque (Cogging)

Crawling: A 3phase winding carrying sinusoidal currents produces harmonics of the order

$n = 6N \pm 1$, where N is an integer.

The movement of the harmonics is with or against the direction of rotation depending up on the sign. (+ means with the rotation & − means against the rotation).

A 3phase winding will produces a forward rotating 7th harmonic and backward rotating 5th harmonics for N=1.

For N=2, forward rotating 13th harmonics, backward rotating 11th harmonic.

In induction motors only 5th & 7th harmonics are more pronounced & produces dips in the torque-speed characteristics.

The 7th harmonic produces dip at 1/7th synchronous speed. The 5th harmonic produces dip at −1/5th synchronous speed.

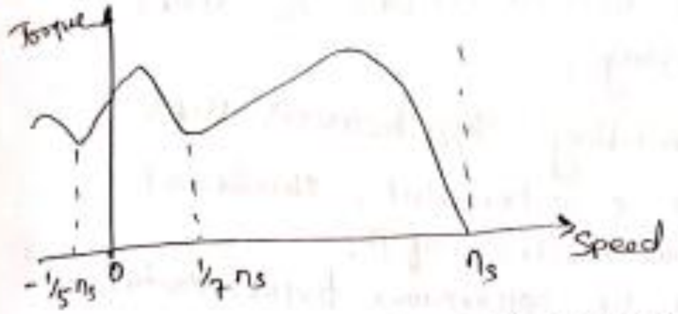


Fig: Dips caused by 5th & 7th harmonics in the torque speed characteristics

The torque developed may fall below the load torque and when this occurs the motor cannot accelerate upon its full speed but continues to run at a speed little lower than the 1/7th synchronous speed. This is called Crawling.

Cogging: — If the stator and rotor harmonics are of the same order then the torque will be alternately in opposite directions. But if their speeds happen to coincide they will lock together and if sufficiently powerful giving rise to a synchronous torque. In such case the motor would crawl at constant subsynchronous speed.

The stator produces harmonics of the order $n = 6A \pm 1$ $= 2(S_s/P) \pm 1$ for $(A = 1)$.

These harmonics resolve at a speed $1/n$ of synchronous speed w.r.t. stator.

The speed would be equal if $2(S_s/P) \pm 1 = 2(S_r/P) \pm 1$

One of the possibilities for this to happen is when $S_s = S_r$.

When the number of rotor slots is equal to the number of stator slots, the speed of all the harmonics produced by stator slotting coincide with the speed of corresponding rotor harmonics. Thus harmonics of every order would try to exert synchronous torque at their corresponding synchronous

Speeds and the machine would refuse to start. This is known as cogging.

Thus order of avoiding Synchronous Cups the difference of Stator & rotor slots should not be equal to $\pm P$ or a multiple of P.

Synchronous cups are the Synchronous torques producing due to harmonic Synchronous Speeds. Due to Synchronous cups the machine well crawl.

Reduction of Harmonic torques:

The methods used for reduction or elimination of harmonic torques are

i) Chording: The chorded winding with integral number of slots per pole per phase weakens the stator winding mmf harmonics. Hence Harmonic Induction torques can be eliminated.

ii) Integral slot winding: Fractional number of slots per pole per phase create asymmetrical mmf distribution around the airgap and creates noise in the motor. Hence integral slot windings are used.

iii) Skewing: The motor noise, vibrations, cogging & Synchronous cups can be reduced or eliminated by skewing either the stator or the rotor.

in order to eliminate the effect of any harmonic, the rotor bars should be skewed through an angle so that the bars lie under alternate harmonic poles of the same polarity or the bars must be skewed through two pitches.

∴ Angle between two adjacent harmonic poles = $\frac{360}{np}$

For elimination of n^{th} harmonic by skewing.

Angle of skew, $\theta_s = \frac{720}{np}$ deg mech.

The electrical angle of skew $\theta_{sk} = \frac{720}{np} \times \frac{P}{2}$

$= \frac{360}{n}$ deg elect $= \frac{2\pi}{n}$ rad.elec

iv) Increasing airgaplength. It reduces the harmonic torques but increase the noload current & results in poor power factor.

Example :- 6. A 3phase, 4 pole induction motor has 24 slots. Calculate the order of slot harmonics produced. It is desired to completely eliminate the higher order slot harmonic, find the angle through which the bars must be skewed. Find the effect of skewing on the lower order harmonic.

Soln: order of slot harmonic: $n = 2(S_s/P) \pm 1$

$= 2(24/4) \pm 1$

$n = 13, 11.$

It is desired to completely eliminate the 13^{th} harmonic

∴ Angle of skew $\theta_s = \frac{720}{nP} = \frac{720}{13 \times 4} = 13.85^\circ$ mech.

Electrical angle of skew $\theta_{sk} = \frac{720}{nP} \times \frac{P}{2} = \frac{720}{13 \times 4} \times \frac{4}{2}$

$\theta_{sk} = 0.483$ rad.

Distribution factor for 11^{th} harmonic

$$K_{d11} = \frac{\sin n\,\theta_{sk}/2}{n\,\theta_{sk}/2} = \frac{\sin 11 \times 0.483/2}{11 \times 0.483/2} = 0.176$$

Therefore the 11^{th} harmonic emf with skewing is reduced to 17.6% of value obtained without skewing.

Design of Rotor bars and slots : (Squirrel cage rotor)

For 3 ph machine, the rotor bar current is given by the equation

$$\text{Rotor bar current } I_b = \frac{2 m_s K_w T_s I_s \cos\phi}{S_r}$$

where $m_s \rightarrow$ no. of phases in stator winding = 3

$K_w \rightarrow$ Stator winding factor

$T_s \rightarrow$ no. of stator turns / phase

$I_s \rightarrow$ Stator current / phase.

$S_r \rightarrow$ No. of rotor slots.

$$\therefore I_b = \frac{6 K_w T_s I_s \cos\phi}{S_r}$$

$$I_b \simeq 0.85 \frac{6 I_s T_s}{S_r}$$

Let $\cos\phi = 0.9$, $K_w = 0.955$, $0.9 \times 0.955 = 0.85$

The above relation is interpreted as that the rotor mmf is about 85 percent of stator mmf.

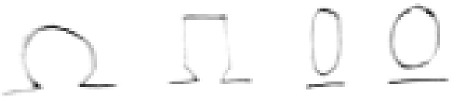
Area of rotor slots :-

The performance of an induction motor is greatly influenced by the resistance of rotor. Higher rotor resistance has higher starting torque but lesser efficiency. The rotor resistance is the sum of the resistance of the bars and the end rings. The cross section of the bars & end rings are selected to meet both the requirements of starting torque as well as efficiency.

The current density in the rotor bar δ_b may be taken between 4 to 7 A/mm²

$\therefore$ Area of each rotor bar $a_b = \dfrac{I_b}{\delta_b}$ in mm²

Shape & size of rotor ~~bars~~ slots



Types of rotor slots.

In case of squirrel cage motor the cross section of bars will take the shape of the slot & insulation is not b/w bars & rotor core.

The rotor slots ~~provide~~ of squirrel cage rotor may be either closed or semienclosed types. The semienclosed slots provides better overload capacity.

Advantages of closed slots

* Low reluctance
* Less magnetising current
* Quieter operation
* Large leakage reactance & so starting current is limited

Disadvantage of closed slots

* Reduced overload capacity.

Generally, the rotor slots and so the rotor bars are rectangular in shape. In rectangular bars, during starting most of current flows through top portion of the bar and so the effective rotor resistance is increased. This improves the starting torque.

Rules for selecting rotor slots

1. No of stator slots should never be equal to rotor slots. Satisfactory results are obtained when S_r is 15 to 30 percent larger or smaller than the S_s.
2. The difference $(S_s - S_r)$ should not be equal to $\pm P$, $\pm 2P$ or $\pm 5P$ to avoid synchronous cusps.
3. The difference $(S_s - S_r)$ should not be equal to $\pm 3P$ for 3-ph machine to avoid magnetic locking.
4. The difference $(S_s - S_r)$ should not be equal to ± 1, ± 2 $\pm(P\pm 1)$ or $\pm(P\pm 2)$ to avoid noise & vibrations.

Summarising $(S_s - S_r)$ should not be equal to

$$0, \pm P, \pm 2P \pm 3P, \pm 5P \pm 1, \pm 2, \pm(P\pm 1) \pm (P\pm 2)$$

Design of End rings

The stator winding is a 3ph distributed winding and thus produces a rotating magnetic field. & this induces emf's in the rotor bars. These emf in the rotor bars will circulate currents.

Fig (a) shows a developed cage winding under pole pitches

Fig (b) shows sinusoidal distributed emfs in the bars over two pole pitches.

Fig (c) shows the distribution of currents in the rotor bars and end rings

Fig (d) shows the sinusoidal waveforms of rotor bar currents and the end ring current.

Fig (a)

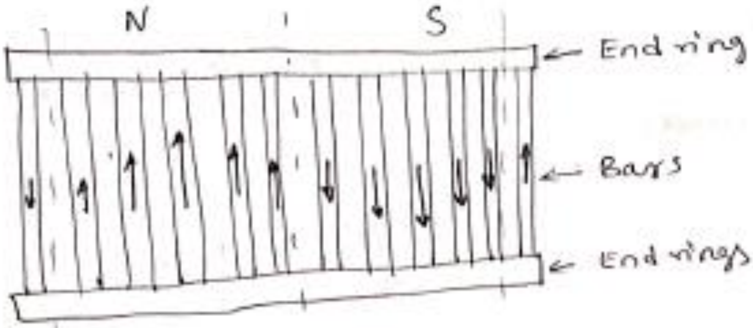


Fig (b)

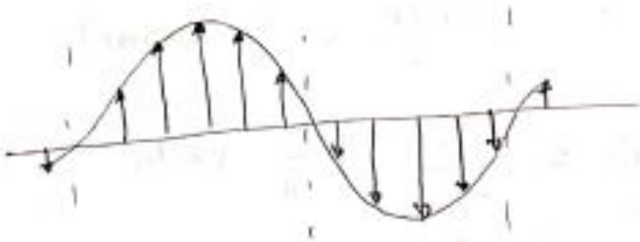


Fig (c)

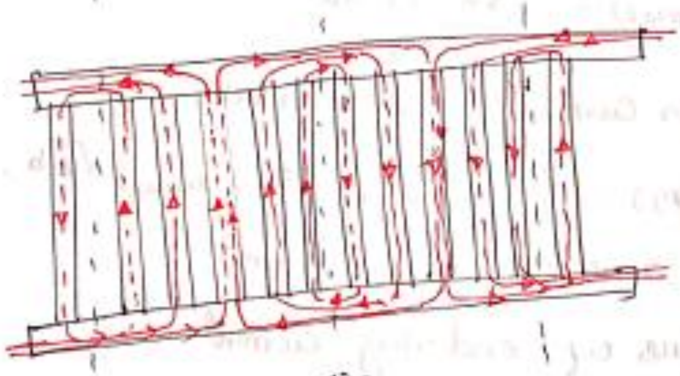
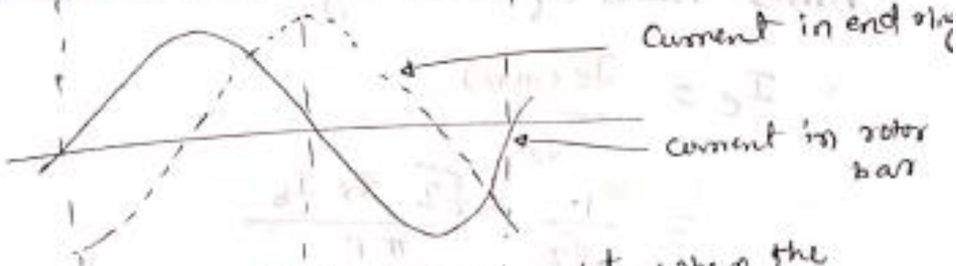


Fig (d).



It is observed from fig (c) & (d) that at points where the currents is maximum when the current in the bar is zero. Consider a group of bars under one pole pitch. Let one half send current to an end ring in one direction and the other half in the other direction. If the maximum value of the current in each bar is $I_b\,max$.

The maximum value of the current in the end ring is given by,

$$I_{e(max)} = \frac{\text{No. of bars per pole}}{2} \times \text{current per bar}$$

$$= \frac{S_r/P}{2} \times I_b(ave)$$

$$= \frac{S_r/P}{2} \times \frac{2}{\pi} I_b(max)$$

$$I_{e(max)} = \frac{S_r/P}{2} \times \frac{2}{\pi} \sqrt{2} I_b$$

$$I_{e(max)} = \frac{\sqrt{2}\, S_r I_b}{\pi P}$$

Here the bar current is sinusoidal.

$I_b(avg) = \frac{2}{\pi} I_b(max)$ & $I_{b(max)} = \sqrt{2} I_b$.

I_b = rms value of bar current.

r.m.s. value of end ring current

$$I_e = \frac{I_{e(max)}}{\sqrt{2}}$$

$$= \frac{1}{\sqrt{2}} \times \frac{\sqrt{2}\, S_r I_b}{\pi P}$$

$$\boxed{I_e = \frac{S_r I_b}{\pi P}}$$

Area of End rings.

Area of cross section of each end rings.

$$a_e = \frac{I_e}{\delta_e} \text{ in } mm^2$$

Also Area of end ring

a_e = Depth of end ring x Thickness of end ring

$$a_e = d_e \times t_e.$$

Full load Slip:

It is given by $\frac{\text{rotor copper loss}}{\text{rotor output}} = \frac{s}{1-s}$

$s \Rightarrow$ per unit slip.

Example: 7 A 11kW, 3ph, 6pole, 50Hz, 220V, star connected induction motor has 54 slots, each containing 9 conductors. Calculate the values of bar and end ring currents. The number of rotor bars is 64. The machine has an efficiency of 0.86 and a p.f. of 0.85. The rotor mmf may be assumed as 85 percent of stator mmf. Also find the bar and the end ring sections if the current density is 5A/mm².

Given

11kW, 3ph, $P = 6$, $f = 50Hz$

$V = 220V$, $S_s = 54$, $Z_{ss} = 9$

$S_r = 64$, $\eta = 0.86$, $pf = 0.85$

$AT_r = 0.85\, AT_s$, $\delta = 5A/mm^2$

$I_b = ?$ $I_e = ?$ a_b, $a_e = ?$

$$I_s = \frac{kW \times 10^3}{\sqrt{3}\, V_L\, \eta \times pf} = \frac{11 \times 1000}{\sqrt{3} \times 220 \times 0.86 \times 0.85}$$

$$= 39.49A.$$

$$I_s \simeq 40A$$

$$Z_s = S_s \times Z_{ss}$$
$$= 54 \times 9 = \underline{486}$$

$$T_s = \frac{Z_s}{6} = \frac{486}{6} = 81.$$

AT_s : Stator mmf $= 3 I_s T_s = 3 \times 40 \times 81 = 9720\ AT.$

AT_r : Rotor mmf $= 0.85 \times AT_s = 0.85 \times 9720 = 8262\ AT$

But rotor mmf $= \frac{S_r I_b}{2}$

$$AT_r = \frac{64}{2} I_b = 32 I_b$$

$$32 I_b = 8262.$$

$$I_b = \frac{8262}{32} = 258.18 \approx \underline{\underline{258\ A}}$$

End ring current $I_e = \frac{S_r I_b}{\pi P} = \frac{64 \times 258}{\pi \times 6} = 875.98\ A$

Area of each bar $= a_b = \frac{I_b}{\delta} = \frac{258}{5} = \underline{\underline{51.6\ mm^2}}$

Area of each end ring $a_e = \frac{I_e}{\delta} = \frac{876}{5} = \underline{\underline{175.2\ mm^2}}$

Example 18: Estimate the main Dimensions, airgap length, stator slots, stator turns per phase and cross sectional area of stator and rotor conductors for a 3ph, 15 HP, 400V, 6 Pole 50 Hz 975 rpm Induction motor. The motor is suitable for Star delta starting. $B_{av} = 0.45\ Wb/m^2$, $ac = 20{,}000$ Amp cond/mt. $L/\tau = 0.85$, $\eta = 0.9$, P.f $= 0.85$.

Given data

3-ph, 400V, $B_{av} = 0.45\ wb/m^2$

15HP, $L/\tau = 0.85$, $ac = 20{,}000$ amp cond/m.

$\eta = 0.9$, $P = 6$, $f = 50Hz$, $p.f = 0.85$,

$N = 975$ rpm, Star-Delta starting.

Solution:

kVA input $Q = \dfrac{HP \times 0.746}{\eta \times p.f} = \dfrac{15 \times 0.746}{0.9 \times 0.85}$

$= 14.63$ kVA

$C_0 = 11\ B_{av}\ ac\ k_{ws} \times 10^{-3}$

$= 11 \times 0.45 \times 20{,}000 \times 0.955 \times 10^{-3}$

$= 94.545$ kVA/m³-rps.

$n_s = \dfrac{2f}{P} = \dfrac{2 \times 50}{6} = 16.667$ rps.

$D^2L = \dfrac{Q}{C_0 n_s} = \dfrac{14.63}{94.545 \times 16.667} = 9.284 \times 10^{-3}$

$L/\tau = 0.85$. $\quad L = 0.85\ \dfrac{\pi D}{P}$

$L = \dfrac{0.85 \times \pi}{6} D = 0.445D$.

$D^2L = 9.284 \times 10^{-3}$

$D^2(0.445D) = 9.284 \times 10^{-3}$

$D = \left(\dfrac{9.284 \times 10^{-3}}{0.445}\right)^{1/3} = 0.2753\,m$

$L = 0.445D = 0.445 \times 0.275 = 0.1224\,m$

$\boxed{D = 0.27\,m}$ $\qquad$ $\boxed{L = 0.12\,m}$

$$\phi_m = \frac{B_{av}\,\pi D L}{P} = \frac{0.45 \times \pi \times 0.275 \times 0.12}{6}$$

$$\phi_m = 7.775 \times 10^{-3}\ \text{wb}$$

Star delta starting winding is delta connected at running,

$$T_s = \frac{E_s}{4.44 f \phi_m k_{ws}} = \frac{400}{4.44 \times 50 \times 7.775 \times 10^{-3} \times 0.955}$$

$$= 242.66 \approx \underline{242}$$

$$Z_s = 6T_s = 6 \times 242 = \underline{1452} \text{ conductors}$$

Slot pitch lie b/w 15mm to 25 mm.

$y_{ss} = 15\text{mm}$

$$S_s = \frac{\pi D}{y_{ss}} = \frac{\pi \times 0.275}{15 \times 10^{-3}}$$

$$S_s = \underline{58}$$

$y_{ss} = 25\text{mm}$

$$S_s = \frac{\pi \times 0.275}{25 \times 10^{-3}} = 34.55$$

$$S_s = \underline{34}$$

S_s lie b/w 34 to 58.

$q = 2 \qquad S_s = 3 \times 6 \times 2 = 36$

$q = 3 \qquad S_s = 3 \times 6 \times 3 = 54$

$q = 4 \qquad S_s = 3 \times 6 \times 4 = 72$

let $S_s = 36$

$$Z_{ss} = \frac{6T_s}{S_s} = \frac{1452}{36} = 40.33 \approx \underline{40}$$

$$Z_s = Z_{ss} \times S_s = 36 \times 40 = \underline{1440} \text{ Conductors.}$$

New value of turns/ph $\quad T_s = \dfrac{Z_{ss} \times S_s}{6} = \dfrac{40 \times 36}{6} = \underline{240}$

KVA input $= Q = \sqrt{3}\, V_L I_L \times 10^{-3} = 3 E_{ph} I_{ph} \times 10^{-3}$

$$I_{ph} = \frac{Q \times 10^3}{3 E_{ph}} = \frac{14.62 \times 10^3}{3 \times 400}$$

$I_{ph} = 12.183\,A$

let $\delta = 3\,A/mm^2$

$$\therefore a_s = \frac{I_{ph}}{\delta} = \frac{12.183}{3} = 4.061\,mm^2$$

$a_s = 4.061\,mm^2$

$$l_g = 0.2 + 2\sqrt{DL} = 0.2 + 2\sqrt{0.275 \times 0.12}$$

$l_g = 0.5633\,mm$

let $l_g = 0.6\,mm$

Rotor slots

let S_r – rotor slots $\quad S_s$ – stator slots

$(S_s - S_r) \neq 0, \pm P, \pm 2P, \pm 3P \pm 5P, \pm 1, \pm 2, \pm (P \pm 1),$
$\pm (P \pm 2)$

$P = 6$

$\therefore (S_s - S_r) \neq 0, \pm 6, \pm 12 \pm 18 \pm 30 \pm 1, \pm 2, \pm 5, \pm 7,$
$\pm 8 \;\pm 4$

$\therefore$ let $(S_s - S_r) = \pm 3, \pm 9, \pm 10, \pm 11$ etc.

let $(S_s - S_r) = \pm 3$

$\therefore S_r = S_s + 3$ or $S_r = S_s - 3$
$36 + 3 = 39$ or $36 - 3 = 33$.

let $S_r = 33$

$$I_b = 0.85 \frac{6T_s I_s}{S_r} = 0.85 \frac{6 \times 240 \times 12.18}{33}$$

$$I_b = 451.88\ A$$

let $\delta_b = 4A/mm^2$

$$a_b = \frac{I_b}{\delta_b} = \frac{451.88}{4} = 112.96 = 113\ mm^2$$

$$I_e = \frac{S_r I_b}{\pi P} = \frac{33 \times 451.88}{\pi \times 6} = 791.1A$$

let $\delta_e = 4A/mm^2$

$$a_e = \frac{I_e}{\delta_e} = \frac{791.1}{4} = 197.775\ mm^2 \approx 200mm^2$$

Result:

$D = 0.27\ m$
$L = 0.12\ m$
$T_s = 240$ turns
$S_s = 36$
$S_r = 33$
$a_s = 4.061\ mm^2$
$a_b = 113\ mm^2$
$a_e = 200\ mm^2$

Example - 9

Design a cage rotor for a 40HP, 3ph, 400V, 50Hz 6pole, delta connected IM having a full load $\eta = 0.87$ and full load pf = 0.85. Take D = 33cm, L = 17cm. $S_s = 54$, $Z_{ss} = 14$. Assume the missing data if any.

Given:

3ph	P = 6	$S_s = 54$
40HP	Delta	$Z_{ss} = 14$
V = 400V	$\eta = 0.87$	D = 33 cm $\approx$ 0.33 m
f = 50 Hz	pf = 0.85	L = 17 cm $\approx$ 0.17 m

Soln:

$$(S_s - S_r) \neq 0, \pm P, \pm 2P, \pm 3P \pm 5P, \pm 1, \pm 2, \pm (P+1), \pm (P \pm 2)$$

P = 6.
$$(S_s - S_r) \neq 0, \pm 6, \pm 12, \pm 18, \pm 30, \pm 1, \pm 2, \pm 7, \pm 5, \pm 8 \pm 4$$

$$(S_s - S_r) = \pm 3 \text{ or } \pm 9$$

Let $S_r = S_s - 3 = 54 - 3 = 51$

$Z_s = 6 T_s$.

$$T_s = \frac{Z_s}{6} = \frac{54 \times 14}{6} = 126$$

$$Q = \frac{Hp \times 0.746}{\eta \times pf} = \frac{40 \times 0.746}{0.87 \times 0.85} = 40.351 \text{ kVA}$$

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

$$I_{ph} = I_s = \frac{Q}{3 E_{ph} 10^{-3}} = 33.62 A.$$

delta connected. ($E_{ph} = V_L = 400V$)

$$I_b = \frac{6 T_s I_s}{S_r} \times 0.85 = \frac{6 \times 126 \times 33.62}{51} \times 0.85$$

$$I_b = 423.6\ A$$

let $\delta_b = 4A/mm^2$ $\quad a_b = \frac{I_b}{\delta_b} = \frac{423.6}{4} = 105.9 = 106 mm^2$

$$I_e = \frac{S_r I_b}{\pi P} = \frac{51 \times 423.6}{\pi \times 6} = 1146.139\ A$$

let $\delta_e = 4A/mm^2$

$$a_e = \frac{I_e}{\delta_e} = \frac{1146.139}{4} = 286.53\ mm^2$$

In induction motors the length of rotor core is same as that of stator core.

$\therefore$ Length of rotor core $L_r = 17cm = 0.17m$

Length of air gap, $l_g = 0.2 + 2\sqrt{DL}$

$$= 0.2 + 2\sqrt{0.33 \times 0.17}$$

$$l_g = 0.67 mm$$

$$l_g \approx 0.7 mm$$

Diameter of rotor. $D_r = D - 2 l_g$

$$= 0.33 - 2 \times 0.7 \times 10^{-3}$$

$$D_r = 0.3286\ m$$

Results:

$L_r = 0.17m$

$D_r = 0.3286m$

$l_g = 0.7mm$

Example-10

A 3ph IM. has 54 stator slots with 8 conductors per slot and 72 rotor slots with 4 conductors per slot. Find the no. of stator & rotor turns per slot. Find the voltage across the rotor sliprings. when the rotor is open circuited & at rest. Both stator & rotor are star connected & voltage of 400V is applied across the stator terminals.

Given:

3ph

$S_s = 54$

$S_r = 72$

Stator conductors/slot = 8

rotor cond/slot = 4

$V = 400V$

Soln

Stator cond / slot $Z_{ss} = \frac{6T_s}{S_s}$

$\therefore$ Stator turns/ph = $T_s = \frac{Z_{ss} \times S_s}{6} = \frac{8 \times 54}{6} = 72$.

Rotor turns per ph = $T_r = \frac{Z_{rs} \times S_r}{6} = \frac{4 \times 72}{6} = 48$.

Let us $K_{ws} = K_{wr}$

$$\frac{E_r}{E_s} = \frac{K_{wr} T_r}{K_{ws} T_s} = \frac{T_r}{T_s}$$

Rotor emf at stand still, $E_r = E_s \frac{T_r}{T_s} = \frac{400}{\sqrt{3}} \times \frac{48}{72}$

$E_r = 153.96\ V \approx 154V$

Rotor emf b/w sliprings (line value) $= \sqrt{3} \times E_r$

$= \sqrt{3} \times 154$

$= 266.7V$

Results:

$T_s = 72$, $T_r = 48$. $E_{r\,line} = 266.7V$

Design of wound rotor (slip ring rotor)

The wound rotor has the facility of adding external resistance to rotor circuit in order to improve the torque developed by the motor. The rotor consists of laminated core with semi-enclosed slots and carries a threephase winding.

Rotor windings:

For small motors → Mush windings are Employed for the rotor

For large motors → Double layer bar type wave winding

In motor of o/p more than 750 kW → More no. of bars per slot to reduce the current handled by slip ring

Barrel winding & is usually wave winding

Number of rotor turns:

For IM. the turns ratio is given by $\frac{E_r}{E_s} = \frac{k_{wr}\, T_r}{k_{ws}\, T_s}$

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

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

$\therefore$ Rotor ampere turn = 0.85 × stator amp turn.

$$I_r T_r = 0.85\, I_s T_s$$

Hence rotor current $I_r = \frac{0.85\, I_s T_s}{T_r}$.

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

The range of current density in rotor is 3 to 5 A/mm²

let δ_r = Current density in rotor

$\therefore$ Area of rotor conductor, $a_r = \frac{I_r}{\delta_r}$

No. of rotor slots:

The winding are 3phase windings, the number of slots should be such that a balanced winding is obtained. Generally windings with an integral number of slots per pole per phase are used for the rotor. The fractional slot windings are used. it is preferable to have the number of slots are multiples of phases & pair of poles.

Rotor teeth: The width of rotor slot should be such that the flux density in the rotor teeth does not exceed about 1.7 Wb/m². The maximum flux density for rotor teeth occurs at its root since its section is minimum there.

let W_{tr} = width of rotor tooth

& W_{sr} = Rotor slot width or pitch.

$$\text{Min. teeth area per pole} = \frac{\text{Flux per pole}}{\text{Max. flux density}} = \frac{\Phi_m}{1.7}$$

Total teeth area per pole = No. of rotor slots/pole × Net iron length × width of tooth

$$= \frac{S_r}{P} \times L_i \times W_{tr}$$

Minimum width of rotor tooth can be obtained by

$$\frac{S_r}{P} L_i W_{tr(min)} = \frac{\phi_m}{1.7}$$

$$W_{tr(min)} = \frac{\phi_m / 1.7}{\frac{S_r}{P} \times L_i}$$

$$\boxed{W_{tr_{min}} = \frac{\phi_m}{1.7 \; S_r/_P \; L_i}}$$

A check has to made so that the actual minimum width of tooth is not more than $W_{t\,min}$.

Actual min. width of rotor tooth = Rotor slot pitch at the root − Rotor slot width

$$= \frac{\pi (D_r - 2 D_{sr})}{S_r} W_{sr}.$$

Where d_{sr} = depth of rotor slot

W_{sr} = width of rotor slot

Rotor core :

The flux density in the rotor core is generally equal to stator core density.

Depth of rotor core $d_{cr} = \dfrac{\phi_m}{2 \times B_{cr} \times L_i}$

Where B_{cr} = Flux density in the rotor core

Inner diameter of rotor lamination $D_i = D_r - 2(d_{sr} + d_{cr})$

Where d_{cr} = Depth of rotor core.

Slip rings & Brushes :

Slip rings → Brass or phosphor bronze, 4 to 7 A/mm^2 (δ)

Brushes → metal graphite → alloy of copper & carbon with low resistance → 0.1 to 0.2 A/mm^2 (δ).

No load current

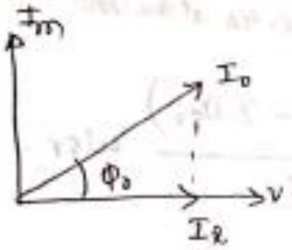
No load current drawn by an induction motor consists of two components

i) Magnetizing component (I_m) of current

ii) Loss component of current (I_l)

I_m is lagging the applied voltage by 90°. and I_l is inphase with voltage.

Thus No load current per phase $I_0 = \sqrt{I_m^2 + I_l^2}$



No load power factor

$$\cos\phi_0 = \frac{I_l}{I_0}$$

$$\& \quad \phi_0 = \cos^{-1}\left(\frac{I_l}{I_0}\right)$$

Magnetizing current (I_m)

Magnetizing component of no load current can be calculated from the magnetic circuit of induction motor. The magnetic circuit of an induction motor consists of the following five parts.

1) Airgap
2) Stator teeth
3) Rotor teeth
4) Stator core
5) Rotor core.

MMF at 60° from interpolar axis (or 30° from pole axis)

$$AT_{60} = AT_{ml} \sin 60°$$

$$AT_{60} = AT_{ml} \cdot \sqrt{3}/2$$

$$AT_{60} = \frac{\sqrt{3}}{2} \times \frac{2.7\, I_{ph}\, T_{ph}\, k_{ws}}{P}$$

$$\therefore \quad I_{ph} = \frac{AT_{60} \times 2\, P}{2.7\, \sqrt{3}\, T_{ph}\, k_{ws}}$$

ie $$\boxed{I_m = \frac{0.427\, P\, AT_{60}}{k_{ws}\, T_s}}$$

Total magnetising mmf per pole for B_{60}.

$$AT_{60} = AT_g + AT_{ts} + AT_{tr} + AT_{cs} + AT_{cr}$$

$AT_g \rightarrow$ MMf for Air gap

$AT_g = 800{,}000\, B_{g60}\, l_g\, k_g$, $B_{g60} = 1.36\, B_{av}$.

AT_{ts} = MMF required for stator teeth

$AT_{ts} = at_{ts} \times d_{ss}$

$at_{ts} \rightarrow$ mmf/mt length of stator teeth.

d_{ss} = depth (length) of stator teeth.

AT_{tr} = MMf for rotor teeth.

$AT_{tr} = at_{tr} \times d_{sr}$

d_{sr} = depth of rotor slot = depth of rotor teeth.

at_{tr} = mmf/m. length of rotor teeth.

AT_{cs} = MMF for stator core

$AT_{cs} = at_{cs}\, l_{cs}$

l_{cs} → length of flux path in stator core

at_{cs} → mmf / m length of stator core.

l_{cs} = $\frac{1}{3}$ Pole pitch at mean diameter

$$l_{cs} = \frac{1}{3} \frac{\pi (D + 2d_{ss} + \frac{1}{2} d_{cs} + \frac{1}{2} d_{cs})}{P}$$

$$l_{cs} = \frac{\pi}{3P} (D + 2d_{ss} + d_{cs})$$

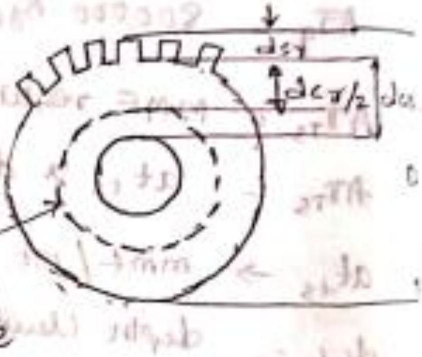
d_{cs} → depth of stator core.

AT_{cr} = MMF for rotor core

$AT_{cr} = at_{cr}\, l_{cr}$.

l_{cr} = length of flux path through rotor core

$$l_{cr} = \frac{\pi (D_r - 2d_{sr} - d_{cr})}{3P}$$



loss component of no load current.

The calculation of loss component involves the determination of no load losses

loss component of no load current per phase.

$$I_l = \frac{\text{Total no load losses}}{3 \times \text{voltage per phase}}$$

∴ No load current I_0 (per phase) $= \sqrt{I_m^2 + I_l^2}$

1) A 15 KW, 400V, 3ph. 50Hz, 6pole induction motor has diameter of 0.3m and the length of the core is 0.12m. The no.of stator slot is 72 with 20 cond/slot. the stator is delta connected. Calculate the value of magnetizing current/ph, if the length of airgap is 0.55m. The gap contraction factor is 1.2 Assume the mmf required for iron parts to be 35 percent of the airgap mmf. coil span is = 11 slot.

Given:

15 KW, $P = 6$. $S_s = 72$. $I_m = ?$

$V = 400V$. $D = 0.3\,m$ $Z_{ss} = 20$. coil span = 11 slots

3ph, $f = 50Hz$ $L = 0.12\,m$ $l_g = 0.55m$ (short pitched by 1 slot).

$K_g = 1.2$.

Soln:

m = no. of slots / pole / phase $= \frac{72}{3 \times 6} = 4$ $n = \frac{72}{6} = 12$

Distribution factor $k_d = \frac{\sin m\beta/2}{m \sin \beta/2}$ $\beta = \frac{180}{n} = \frac{180}{12} = 15^\circ$

$\therefore k_{ds} = \frac{\sin\left(\frac{4 \times 15}{2}\right)}{4 \sin\left(\frac{15}{2}\right)} = 0.958$

Angle of chording $\alpha = \frac{180^\circ}{12} = 15^\circ$.

pitch factor $k_{ps} = \cos \alpha/2 = \cos \frac{15}{2} = 0.9914$

$\therefore$ Stator winding factor $k_{ws} = k_{ds} \times k_{ps}$

$= 0.958 \times 0.9914$

$k_{ws} = 0.95$.

Total stator conductors $= Z_s = Z_{ss} \times S_s$

$Z_s = 20 \times 72 = 1440$

$$T_S = \frac{Z_s}{6} = \frac{1440}{6} = 240$$

$V = 400\,V = E_s$ Delta

$$\phi = \frac{E_s}{4.44\, T_s\, k_{ws} \cdot f}$$

$$\phi = \frac{400}{4.44 \times 50 \times 240 \times 0.95}$$

$$\phi = 7.9 \times 10^{-3}\ wb.$$

$$B_{av} = \frac{P\phi}{\pi D L} = \frac{6 \times 7.9 \times 10^{-3}}{\pi \times 0.3 \times 0.12}$$

$$B_{av} = \cancel{18.85 \times 10^{-3}\ m^2}\ 0.418\ wb/m^2$$

Air gap flux density at 60° from interpolar axis.

$$B_{g60} = 1.36\, B_{av}$$

$$= 1.36 \times 0.418$$

$$B_{g60} = 0.57\ wb/m^2$$

$$AT_{g60} = 800000\, B_{g60}\, l_g\, k_g$$

$$= 800000 \times 0.57 \times 0.55 \times 10^{-3} \times 1.2$$

$$AT_{g60} = 301\, AT$$

Given that MMF for ironparts = 35% of air gap MMF

ie. $(AT_{ts} + AT_{tr} + AT_{cs} + AT_{cr}) = 0.35\, AT_{g60}$

$$= 0.35 \times 301 = 105.5\, AT$$

$\therefore AT_{60} = AT_{g60} + AT\ (\text{iron Parts})$

$= [301 + 105.5]$

$AT_{60} = 406.5\ AT$

Magnetizing current /ph.

$$I_m = \frac{0.427\, P\, AT_{60}}{K_{ws} T_s} = \frac{0.427 \times 6 \times 406.5}{0.95 \times 240}$$

$$\boxed{I_m = 4.56\ A}$$

Stator resistance

Stator resistance per phase

$$r_s = \rho \frac{T_s L_{mts}}{a_s}$$

Rotor Resistance : Wound rotor :

Rotor resistance perphase : $r_r = \rho \dfrac{T_r L_{mtr}}{a_r}$

Rotor resistance per phase referred to stator $r_r' = \left(\dfrac{K_{ws}}{K_{wr}} \dfrac{T_s}{T_r}\right)^2 r_r'$

Cage rotor :

Resistance of each bar $r_b = \rho \dfrac{l_b}{a_b}$

Total Cu loss in bars $= I_b^2 r_b S_r$

$$= I_b^2 S_r \left(\rho \frac{l_b}{a_b}\right)$$

Resistance of each end ring $r_e = \rho \dfrac{\pi D_e}{a_e}$

Cu loss in two end rings $= 2 I_e^2 r_e$

$$= 2 I_e^2 \rho \frac{\pi D_e}{a_e}$$

Total Cu loss in in rotor = Cu loss in rotor bars + end rings

Equivalent resistance of rotor /phase in terms of stator

$$r_r' = 4 m_s T_s^2 K_{ws}^2 \rho \left[\frac{l_b}{S_r a_b} + \frac{2}{\pi} \frac{D_e}{P^2 a_e} \right]$$

(or)

$$r_r' = \frac{\text{Total rotor } I^2 R \text{ loss}}{m_s I_r'^2} \qquad I_r' = I_s \cos\phi$$

Jan 2011

Calculate the equivalent resistance of rotor per phase with respect to stator, the current in each bar and end ring and total rotor cu loss for a 415V., 50Hz, 4 Pole. 3ph. IM. having following data.

Stator slots = 48 cond / slot = 35, current in each cond = 10A

Rotor slots = 57, length of each bar = 0.12 m. area of each bar = (9.5 x 5.5) mm². mean diameter of end ring = 0.2 m. area of each end ring = 76 mm². resistivity of copper is 0.02 Ω/m/mm². Full load p.f = 0.85

<u>Given</u>:

$V = 415V$, $S_s = 48$, $l_b = 0.12m$, $\rho = 0.02\ \Omega/m/mm^2$

$f = 50Hz$, $Z_{ss} = 35$, $a_b = (9.5 \times 5.5) mm^2$, $p.f = 0.85$

$P = 4$, $I_s = 10A$, $d_e = 0.2m$

$m_s = 3$, $S_r = 57$, $a_e = 76 mm^2$

$r_r' = ?$

$I_b = ?$

$I_e = ?$

rotor cu loss = ?

$$T_s = \frac{Z_{ss} S_s}{6} = \frac{35 \times 48}{6}$$

$$= 280$$

$$I_b = \frac{6 T_s K_{ws} I_s \cos\phi}{S_r} = \frac{6 \times 280 \times 0.955 \times 10 \times 0.85}{57}$$

$$I_b = 239.3A.$$

$$I_e = \frac{S_r I_b}{\pi p} = \frac{57 \times 239.3}{\pi \times 4} = I_e = 1086\,A$$

$$r_b = \frac{\rho\, l_b}{a_b} = \frac{0.02 \times 0.12}{9.5 \times 55} = 46 \times 10^{-6}\,\Omega$$

I^2R loss in bars $= I_b^2\, r_b\, S_r$

$= 239.3^2 \times 46 \times 10^{-6} \times 57$

$= 150.15\,W$

$\pi D_e = l_e$

$$r_e = \rho \frac{\pi D_e}{a_e} = \frac{0.02 \times \pi \times 0.2}{76} = 165.3 \times 10^{-6}\,\Omega$$

I^2R loss in both end rings $= 2 I_e^2 r_e$

$= 2 \times 1086^2 \times 165.3 \times 10^{-6}$

$= 390\,W$

Total cu loss = Cu loss in rotor bars + end rings

$= 150.15 + 390$

Total cu loss $= 540.15\,W$.

Equivalent resistance of rotor /ph. in terms of stator:

$$r_r' = 4 m_s T_s^2 K_{ws}^2\, \rho \left[\frac{l}{S_r a_b} + \frac{2}{\pi}\frac{D_e}{p^2 a_e}\right]$$

$$r_r' = 4 \times 3 \times 280^2 \times 0.955^2 \times 0.02 \left[\frac{0.12}{57 \times 9.5 \times 55} + \frac{2}{\pi} \times \frac{0.2}{4^2 \times 76}\right]$$

$$\boxed{r_r' = 2.5\,\Omega}$$

or

$$r_r' = \frac{\text{Total rotor } I^2R \text{ loss}}{m_s I_r'^2} = \frac{540.15}{3 \times (10 \times 0.85)^2}$$

$$\boxed{r_r' = 2.5\,\Omega}$$

Leakage reactance

Various leakage fluxes responsible for the leakage reactance are as follows.

(i) Slot leakage flux (stator & rotor)
(ii) over hang leakage flux
(iii) Zigzag leakage flux
(iv) Differential leakage flux or Harmonic leakage flux.

Hence total leakage flux per phase

X = Slot reactance + overhang reactance + Zigzag reactance + Harmonic leakage reactance.

1) Slot leakage reactance is given by

$$x_{ss} = 8\pi f T_s^2 L \left(\frac{\lambda_{ss}}{P q_s}\right)$$

λ_{ss} : Specific slot permeance for stator

q_s : Stator slots / pole / phase.

Parallel sided slot.

$$\lambda_{ss} = \mu_0 \left[\frac{h_1}{3W_s} + \frac{h_2}{W_s} + \frac{2h_3}{W_s + W_0} + \frac{h_4}{W_0}\right]$$

Rotor specific slot permeance referred to stator

$$\lambda_{sr}' = \left(\frac{k_{ws}}{k_{wr}}\right)^2 \frac{S_s}{S_r} \lambda_{sr}$$

λ_{sr} = specific slot permeance of rotor

$$\lambda_{sr} = \mu_0 \left[0.66 + h/w_0\right]$$

$\therefore$ Rotor slot leakage reactance referred to stator

$$x_{sr}' = 8\pi f T_s^2 L \left(\lambda_{sr}' / p q_s\right)$$

2) overhang leakage reactance

$$x_o = 8\pi f T_s^2 L_o \left(\lambda_o / p q_s\right)$$

where $L_o \lambda_o = \mu_0 \dfrac{k_s \tau^2}{\pi y_{ss}}$

$\lambda_o \rightarrow$ Specific permeance for overhang leakage flux

$$\lambda_o = \mu_0 \frac{K L_o}{2\sqrt{2}\, y_{ss}}$$

K is constant

Concentric wound stator $\begin{cases} K = 0.35 \times 10^{-6} - \text{slip ring rotor} \\ K = 0.27 \times 10^{-6} \rightarrow \text{cage rotor} \end{cases}$

Barrel wound stator $\begin{cases} K = 0.5 \times 10^{-6} \rightarrow \text{slipring} \\ K = 0.37 \times 10^{-6} \rightarrow \text{cage rotor} \end{cases}$

3) Zig zag leakage reactance.

$$x_z = \frac{5}{6} \frac{X_m}{m_s^2} \left(\frac{1}{q_s^2} + \frac{1}{q_r^2}\right)$$

X_m = magnetic reactance = E_s / I_m

④ Harmonic or differential leakage reactance

$$x_h = x_m (k_{hs} + k_{hr})$$

k_{hs} & k_{hr} are constant.

Total leakage reactance of the machine referred to stator

$$\boxed{X_s = x_{ss} + x'_{sr} + x_o + x_z + x_h}$$

) Determine the leakage permeance per meter length of rectangular semiclosed slot having the following dimension in mm.

Slot width = 10.

Slot opening = 4.

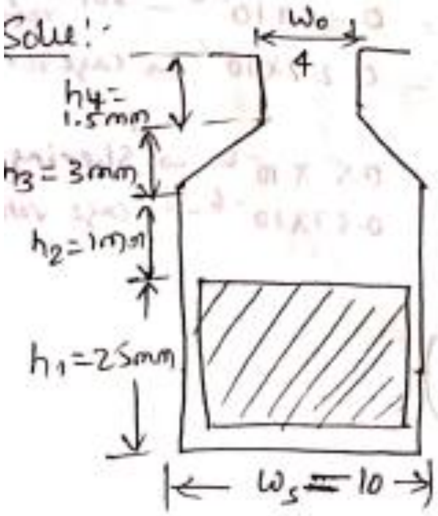
Height of conductor portion = 25

Height above conductor but below wedge = 1

wedge height = 3

Lip height = 1.5

Solu:



$$\lambda_s = \mu_0 \left[\frac{h_1}{3 w_s} + \frac{h_2}{w_s} + \frac{2h_3}{w_s + w_o} + \frac{h_4}{w_o} \right]$$

$$= 4\pi \times 10^{-7} \left[\frac{25}{3 \times 10} + \frac{1}{10} + \frac{2 \times 3}{10+4} + \frac{1.5}{4} \right]$$

$$= 4\pi \times 10^{-7} [0.833 + 0.1 + 0.428 + 0.37]$$

$$\lambda_s = \underline{2.18 \times 10^{-6}}$$

2) A 75 kW, 3000 V, 8 pole, 50 Hz, 3ph, star connected slipring induction motor has the following data. Stator bore = 0.66m, stator core length = 0.5m, $S_s = 96$, $S_r = 72$, $T_s = 286$, total specific permeance due to stator slots = $4.9\mu_0$; noload current per phase = 6.3 A, noload p.f = 0.095, harmonic leakage reactance per phase = 0.9Ω. Estimate the total standstill leakage reactance of motor referred to stator. The winding employs ~~per phase = 0.9Ω~~ full pitch coils.

Given: o/p = 75 kW, V = 3000 V, f = 50 Hz, 3ph.

$D = 0.66m$, $L = 0.5m$, $S_s = 96$, $S_r = 72$, $T_s = 286$.

$I_0 = 6.3A$, $Pf = 0.095$, $x_h = 0.9\,\Omega$, $\lambda_{ss} = 4.9\,\mu_0$

$\mu_0 = 4\pi \times 10^{-7}$ H/m. $X = ?$

Soln:
$$q_s = S_s/P/Ph$$
$$96/8/3 = 4$$
$$q_r = 72/8/3 = 3.$$

Slot leakage reactance $x_s = 8\pi f\, T_s^2\, L_s \left(\frac{\lambda_{ss}}{P q_{ss}}\right)$

$$x_s = 8 \times \pi \times 50 \times 286^2 \times 0.5 \times \frac{4.9 \times 4\pi \times 10^{-7}}{8 \times 4}$$

$$x_s = \underline{\underline{9.9\,\Omega}}$$

$\left\{ \lambda_{ss} = 4.9\,\mu_0 = 4.9 \times 4\pi \times 10^{-7} \right.$

No load p.f = $\cos\phi_0 = 0.095$

$\sin\phi_0 = 0.9954$

Magnetizing current $I_m = I_0 \sin\phi_0 = 6.3 \times 0.9954 = \underline{\underline{6.27A}}$

Stator voltage per phase $E_s = 3000/\sqrt{3} = 1732V$ (star).

Magnetizing reactance $X_m = E_s/I_m = \frac{1732}{6.27} = \underline{\underline{276.2\,\Omega}}$

Zigzag leakage reactance

$$x_z = \frac{5}{6}\frac{x_m}{m_s^2}\left(\frac{1}{q_s^2}+\frac{1}{q_r^2}\right)$$

$$= \frac{5}{6} \times \frac{276.2}{3^2}\left(\frac{1}{4^2}+\frac{1}{3^2}\right) = 4.4\,\Omega$$

Pole Pitch $\tau = \frac{\pi \times 0.66}{8} \quad \because \frac{\pi D}{P} = 0.26\,m$

Stator slot pitch $= y_{ss} = \frac{\pi D}{S_s} = \frac{\pi \times 0.66}{96} = 0.0216\,m$

Overhang Permeance.

$$L_o \lambda_o = \mu_0 \frac{K_s \tau^2}{\pi\, y_{ss}} = \mu_0 \frac{1 \times 0.26^2}{\pi \times 0.0216}$$

$K_s = 1$

$$L_o \lambda_o = 0.987\,\mu_0$$

Overhang leakage reactance $x_o = 8\pi f\, T_s^2\, L_o \frac{\lambda_o}{p\, q_{ss}}$

$$x_o = 8\pi \times 50 \times 286^2 \times \frac{0.987 \times 4\pi \times 10^{-7}}{8 \times 4}$$

$$x_o = 4\,\Omega$$

Total leakage reactance

$$X = x_s + x_z + x_o + x_h$$

$$= 9.9 + 4.4 + 4 + 0.9$$

$$X = 19.2\,\Omega$$

Circle diagram

It is possible to obtain graphically a considerable range of information from circle diagram. The construction gives estimate full load current and powerfactor, maximum power output, Pull out torque and the full load efficiency & slip.

The circle diagram is constructed from the following design data.

I_m = magnetizing current per phase

I_l = loss component of no load current per phase.

x_s = Total standstill leakage reactance per phase referred to stator.

R_s = Total resistance per phase referred to stator.

Z_s = Total short circuit impedance per phase referred to stator.

E_s = Stator voltage per Phase.

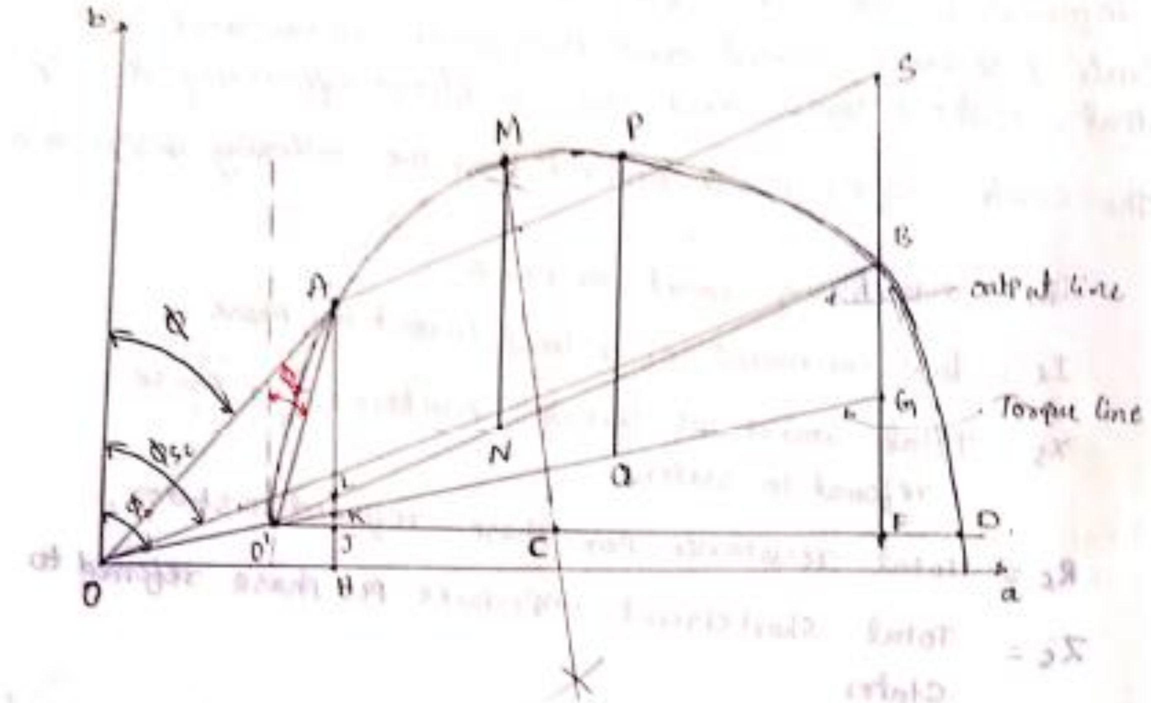
Procedure for drawing circle diagram

1. Draw Oa and Ob perpendicular to each other
2. Draw $OO' = I_0$ the no load current per phase at an angle ϕ_0 with Ob after choosing a suitable current scale.

$$\phi_0 = \tan^{-1}\frac{I_m}{I_l}$$

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

3. Draw $O'D$ passing through O' and parallel to Oa.
4. Draw $OB = I_{sc}$ short circuit current per phase at an angle ϕ_{sc}.



$$\phi_{sc} = \tan^{-1} \frac{X_s}{R_e}$$

$$I_{sc} = \frac{E_{s1}}{Z_e}$$

5. Join O' with B.
6. Construct the perpendicular bisector of O'B intersecting the line O'D at C. Point C is the centre of circle O'BD.
7. Draw circle O'BD.
8. Draw BF perpendicular to O'D and divide it at G in such a way that

$$\frac{BG}{GF} = \frac{\text{rotor resistance referred to stator}}{\text{Stator resistance}} = \frac{r_r'}{r_s}$$

9. Join O' to G. The line $O'G$ is known as torque line and line $O'B$ is the output line.

The diagram can be used to determine the characteristics for any current.

10. In design we are mainly interested in characteristics at rated output. The point A corresponding to rated output can be located.

The proper power scale can be choosen by

Power scale $= \frac{W_{sn}}{BF \text{ length}}$.

Current scale $=$ 1cm $= x$ Amps

$I_{sn} = I_{sc} \frac{V_o}{V_{sc}}$, $W_{sn} = W_{sc} \left(\frac{I_{sn}}{I_{sc}}\right)^2$. $W_{sc} = \frac{E_{s0}}{I_{sc}}$.

Where.

11. Extend the line FB till FS, BS = rated output per phase.

12. Draw SA parallel to output line $O'B$ cutting the circle at A. Then A is the operating point for rated output (full load condition).

13. Join O' to A. This gives ϕ_2 = rotor current phase angle.

Draw OAH perpendicular to OA

14. Label points J K L

Stator current per phase at full load $I_s = OA$.

Stator power factor at full load. $\cos\phi = \frac{AH}{OA}$.

Constant loss = 3 x JH.

Rotor copper loss at full load = 3 x LK.

Stator copper loss at full load = 3 x JK.

$$\text{slip } S = \frac{\text{rotor Cu loss}}{\text{rotor input}} = \frac{LK}{AK}$$

$$\text{Efficiency } \eta = \frac{\text{rotor output}}{\text{Stator input}} = \frac{AL}{AH}.$$

$$\text{Torque} = 3 \times AK. \text{ synch. watts. } \left\{ \frac{3AK}{\frac{2\pi N_s}{60}} = \text{in} \right.$$

~~Dro~~

The location of point M on circle for maximum power output is done by drawing a perpendicular on the output line from C. line MN represents maximum output.

Max. output = 3 x MN.

The location of point P on circle for maximum torque is done by drawing a perpendicular on torque line from. Line PQ represents the maximum torque.

Maximum torque = 3 x PQ. Synch watts.

UNTI 5
DESIGN OF SYNCHRONUS MACHINE AND COMPUTER AIDED DESIGN

Design of Synchronous Machine.

1> Salient pole machines
2> Non Salient Pole or Cylindrical rotor machines.

Synchronous machine operating on general power supply network may be divided into following categories.

a) Hydro generators :- 100 to 1000 rpm - upto 750 MW.
b) Turbo-alternators :- 3000 rpm - up to 1000 MW.
c) Engine driven :- 1500 rpm. - up to 20 MW
d) Motors :- wide ranging capacity provided damper winding
e) Compressors :- Synchronous motors runs at leading p.f to supply reactive power. upto 100 MVAR - 3000 rpm.

* **output equation** :-

The output equation of ac machine is given by

$$Q = C_0 D^2 L n_s.$$

$$C_0 = 11\, B_{av}\, ac\, K_{ws} \times 10^{-3}$$

ref:- The derivation is same as output equation of induction motor.

* **Choice of specific magnetic loading** (B_{av})

* Iron loss
* Voltage rating
* Stability
* Parallel operation
* Transient short circuit current.

Iron loss. The higher value of Bav. results in increase in ironloss & increases temperature rise & decreases efficiency.

Voltage: A lower value of Bav should be used in high voltage machines to avoid excessive value of flux density in teeth & core.

Stability:

$$P_{max} = \frac{EV}{X_s}$$

$X_s \rightarrow$ Synchronous reactance

$E \rightarrow$ induced Emf

$V \rightarrow$ Terminal Voltage.

Hence Pmax or steady state stability limit of a machine is inversely proportional to its synchronous reactance. Therefore use of High Bav increases the steady state stability limit.

Transient short circuit current: High value of Bav decreases the leakage reactance. Which results in higher short circuit currents. Hence low value of Bav is used to limit the initial emf under short circuit conditions.

Parallel operation:- The Satisfactory Parallel operation of Synchronous m/c. depends on the Synchronizing Power. Higher value of Pmax results in better stability of the machines in Parallel. The Pmax is $\propto \frac{1}{X_s}$ Therefore the machine with higher Bav operates satisfactory in Parallel.

The Bav lies in the range of 0.52 to 0.65 wb/m^2.

Choice of Specific Electric loading :- (ac)

* Copper loss
* Temperature rise.
* Voltage rating
* Synchronous reactance
* Stray load losses.

Copper loss & Temperature rise: A high value of ac gives higher copper loss resulting in lower efficiency & higher temperature rise. The value of ac used also depends on cooling co-efficient.

Voltage: A higher value of ac can be used for low voltage machine since the space required for insulation is small.

Synchronous reactance :- High value of ac results in higher value of synchronous reactance. Hence a machine designed with high value of ac has the following characteristics.

* Poor voltage regulation
* Low current under short circuit conditions
* Low value of steady state stability limit.
* Low value of synchronizing power.

Stray load losses: Increases steeply with an increase in 'ac'.

Usual values of ac are

Salient pole M/C :- 20,000 to 40,000 amp cond/m

Turbo alternators :- 50,000 to 75000 amp cond/m.

Design of Salient pole machines.

Main Dimensions:

D → Diameter depends on type of Pole.
L → length of Pole = width of Pole shoe (b_s).

Two types of Poles

1) Round Poles → L/τ ratio or (b_s/τ) is 0.6 to 0.7
2) Rectangular Poles. → L/τ ratio = 1 to 5.

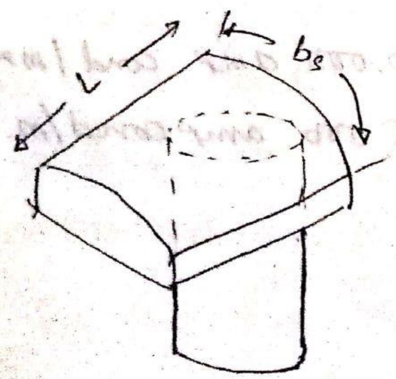
Under these conditions it is possible to use round poles with square pole shoes. Hence for round poles with square pole shoes are used.

Hence length of pole = length of stator core.

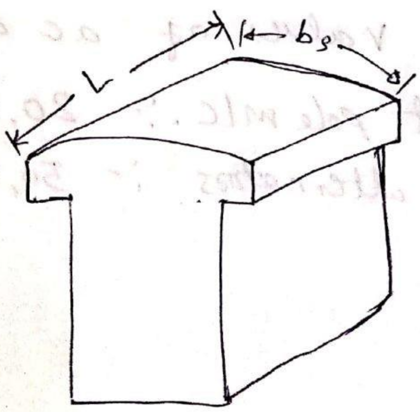
The L/τ ratio should not exceed 3 for normal machines. otherwise the design of field system becomes uneconomical.

Peripheral speeds depends on type of pole attachment.

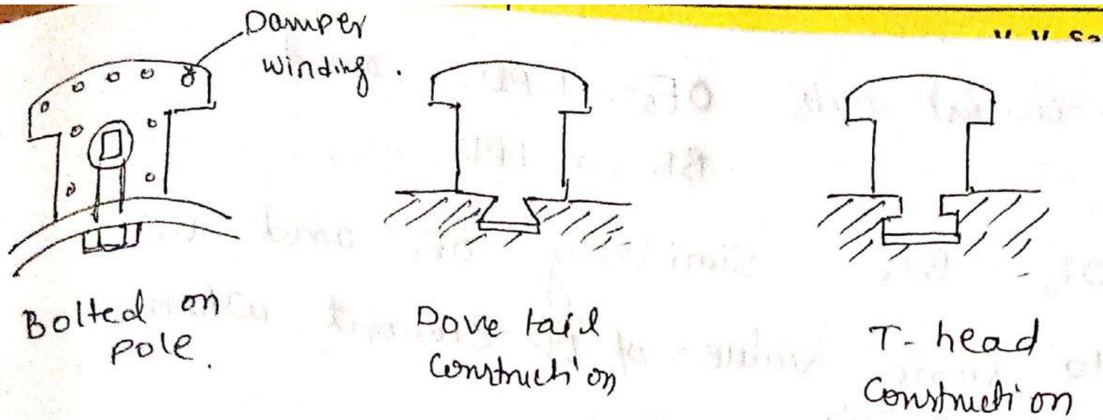
1) Bolted pole construction — 50 m/sec. (V_a → Peripheral speed)
2) Dovetail & T-head construction. — 80 m/sec (V_a)



Round pole.



Rectangular pole.



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Short circuit ratio (SCR)

The short circuit ratio (SCR) 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.

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

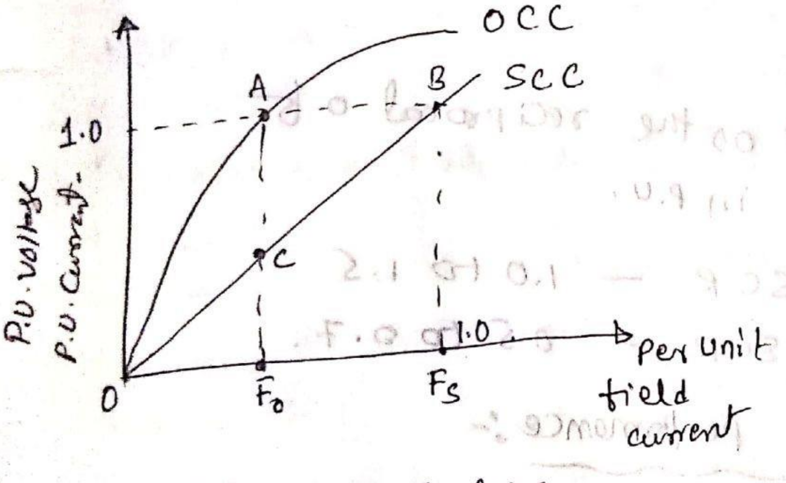


Fig. OCC & SCC characteristics of an alternator.

From fig. we can write

$$SCR = \frac{OF_o}{OF_s}$$

OF_o = P.U. field current required to develop rated voltage on open circuit.

OF_s = P.U. field current required to develop rated current on short circuit.

In fig both the axis are in P.U. Hence from characteristics we can conclude that

$$OF_o = CF_o \quad \text{and} \quad OF_s = BF_s = AF_o$$

Here in PU current axis $OF_s = 1$ PU and $BF_s = 1$ PU.

Hence $OF_s = BF_s$ Similarly OF_o and CF_o corresponds to same value of P.U. current when referred to current axis.

$$\therefore SCR = \frac{OF_o}{OF_s} = \frac{CF_o}{BF_s} = \frac{CF_o}{AF_o} = \frac{1}{\frac{AF_o}{CF_o}}$$

$$SCR = \frac{1}{\frac{\text{P.U. volt on open circuit}}{\text{P.U. SC current corresponding to PU volt}}}$$

Direct axis reactance $X_d = \frac{\text{PU volt}}{\text{PU SC current}}$

$$\therefore SCR = \frac{1}{X_d}.$$

Thus the SCR is defined as the reciprocal of synchronous reactance X_d in P.U.

Salient pole alternator – SCR – 1.0 to 1.5

Turbo alternator – SCR – 0.5 to 0.7.

* **Effect of SCR on machine performance:-**

1) Voltage regulation:- A low value of SCR means that the synchronous reactance has a large value. Thus synchronous machine with low value of SCR have greater changes in voltage under load fluctuations hence voltage regulation is poor.

2) Stability : A machine with low value of SCR has a lower stability limit as the maximum power output of machine is inversely proportional to X_d.

3) Parallel operation : Machine with a low value of SCR are also difficult to operate in parallel because a high value of X_s gives a small synchronizing power. This is responsible for keeping the machines in synchronism.

4) Short circuit current :- A small value of SCR indicates a smaller value of current under short circuit conditions owing to large value of synchronous reactance. But this is not a problem because the SC currents can be limited & thus the synchronous reactance.

5) Self excitation :- Machines feeding long transmission lines should not be designed with a small SCR as this would lead to large voltage on open circuit produced by self excitation owing to large capacitive currents drawn by the transmission lines.

The choice of SCR affects the performance of synchronous machine.

SCR → high → stability → High & regulation - low (good)

But SCR - high → SC current → high → longer air gap.

With longer airgap → MMF → high. → Field system → large. and the machine becomes costlier.

The modern design trend is to design the machine with low SCR.

* Length of Airgap:

The length of airgap greatly influences the Performance of synchronous machine

The advantages of large air gap are

* Reduction in armature reaction
* Small value of regulation
* Higher value of stability
* A Higher Synchronising Power
* Better cooling
* lower tooth pulsation loss
* less noise. Smaller unbalanced magnetic Pull.

Disadvantages are

* Required field mmf will increase, which results in larger field winding.
* Becomes costlier.

For Salient pole machines of normal construction and having open type slots.

$$\frac{\text{Length of airgap}}{\text{Pole pitch}} = \frac{l_g}{\tau} = 0.01 \text{ to } 0.015$$

l_g = length of airgap at centre of pole.

For Synchronous motors designed with maximum output equal to 1.5 times rated output.

$$\frac{\text{Length of airgap}}{\text{Pole pitch}} = \frac{l_g}{\tau} = 0.02$$

Estimation of Airgap using SCR

The airgap can also be estimated from short circuit ratio.

We know that, mmf required for airgap $= 8,00,000 B_g k_g l_g$

Also mmf required for airgap is approximately equal to 80% of no load field mmf.

Let AT_{fo} = Field mmf on no load.

$\therefore$ mmf required for airgap $= 0.8\, AT_{fo}$

On equating the two equations from mmf we get

$$8,00,000\, B_g k_g l_g = 0.8\, AT_{fo}$$

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

We know that

$$B_g = \frac{B_{av}}{k_f} \; ; \quad AT_{fo} = AT_a \times SCR$$

$$AT_a = 2.7 \frac{I_p T_{ph} k_{ws}}{P}$$

where AT_a = Armature mmf per pole
I_p = current per phase
T_{ph} = Turns per phase
k_{ws} = winding factor of stator
k_f = form factor.

On substituting the expression for AT_{fo} & B_g in the equation for l_g we get

$$\boxed{l_g = \frac{AT_a \times SCR \times k_f}{B_{av} \times k_g \times 10^6}}$$

Armature design

* Windings used may be single or double layer type.
* Modern practice is to employ double layer wave or lap winding.
* The coil span for the winding are choosen such that harmonics are reduced.

Number of armature slots:

The following factors are considered for selection of armature slots.

* The number of slots should result in balanced winding
* low cost. (Small slots)
* Small slots → hot spot temperature due to bunching of conductors.
* Small slots → leakage reactance is high
* large slots → reduced tooth ripples & losses
* large slots → B_{av} is high at teeth & hence iron losses.

The usual values of stator pitch y_{ss} are

$y_{ss} \leq 25$ mm for low voltage M/c

$y_{ss} \leq 40$ mm for 6 kV for low vtg m/c

$y_{ss} \leq 60$ mm for m/c upto 15 kV.

Salient pole m/c → no. of slots/pole/phase is 2 to 4.

Turns per phase;

The flux per pole, $\phi = B_{av} \tau L$.

If no. of Parallel Paths / phase = 1.

then

$$T_{ph} = \frac{E_{ph}}{4.44 \phi f K_{ws}}$$

If no. of Parallel paths per phase = a, then

$$T_{ph} = \frac{E_{ph} \times a}{4.44 \phi f K_{ws}}$$

Armature Conductors.

$$I_{ph} = \frac{KVA}{3 E_{ph} \times 10^{-3}}$$

If Parallel path = 1 then

Current through conductor $I_z = I_{ph}$

If Parallel Path / phase = a then

$$I_z = \frac{I_{ph}}{a}.$$

Area of c/s of armature conductors can be estimated by assuming suitable current density.

The range of δ_a = 3 to 5 A/mm².

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

Design of Turbo Alternator

In turbo-alternators the diameter is limited by the maximum Peripheral speed V_a

Peripheral speed, $V_a = \pi D n_s$

$\therefore$ Diameter, $D = \dfrac{V_a}{\pi n_s}$

The output equation of ac machine can be modified by using the above relation.

The KVA rating (or) output KVA,

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

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

Substitute $D = \dfrac{V_a}{\pi n_s}$ & the expression for C_o in Q

$$\therefore Q = 11 B_{av}\, ac\, K_w \times 10^{-3} \left(\frac{V_a}{\pi n_s}\right)^2 L n_s$$

$$Q = 1.11 B_{av}\, ac\, K_{ws} \frac{V_a^2}{n_s} L \times 10^{-3} \rightarrow (1)$$

The length of the armature, L can be estimated from equation (1).

The value of specific loading for conventionally cooled alternator are

$B_{av} = 0.54$ to 0.65 wb/m²

$ac = 50{,}000$ to $75{,}000$ Acond/m.

Length of airgap

The length of airgap can be estimated from the ratio $l_g / \tau = 0.02$ to 0.025 (or) it can be estimated from the value of SCR.

mmf for airgap $= 8,00,000\, K_g\, B_g\, l_g$

Also mmf for airgap $=$ 80% of no load field mmf (AT_{fo}).

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

$SCR = 0.5$ to 0.7 for turbo alternators $B_g = B_{av}/K_f$

On equating the two eqn. of mmf for airgap

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

$$= 0.8 \times SCR \times AT_a$$

$$= 0.8\, SCR\, ac\,(\tau/2)$$

$$l_g = \frac{0.8\, SCR\, ac\,(\tau/2)}{8,0,0000\, K_g\, B_g}$$

$$= \frac{0.5\, SCR\, ac\,\tau}{K_g\, B_g \times 10^6}$$

The armature slot, winding, turns per phase and conductors design of turbo alternator are same as that of Salient pole machines.

Slot dimensions

Minimum width of tooth $W_{t(min)} = \dfrac{\phi}{S/P \; L_i \times 1.8}$

Maximum possible width of slot $W_{s(max)} = y_s - W_{t(min)}$

length of mean turn

$$L_{mt} = 2L + 2.5\tau + 0.06\,KV + 0.2$$

KV = Voltage of machine in KV.

Stator core

Depth of armature core $d_c = \dfrac{\phi}{2 \times L_i \times B_c}$

$B_c \rightarrow$ value of flux density in armature core (1 to 1.2 Wb/m^2)

$\therefore$ outer diameter of stator core. $D_o = D + 2(d_s + d_c)$

Example :- 1:

A 3ϕ, 30 pole, 3.3 KV Y connected Salient pole alternator is designed to supply a rated current of 130A with average flux density of 0.55 Tesla and the specific electric loading of 3000 Amp cond./mt. If the conductor/slot is 9 and slot / pole / phase is 2, find KVA rating of alternator, main dimension, width of parallel slots. If Peripheral speed should be is less than [illegible] flux density in tooth is 1.8 Tesla.

Given :- 3Ph, $P = 30$, $V = 3.3\,KV$, $I = 130A$, $B_{av} = 0.55\,T$

$ac = 3000$ A cond /mt. $Z_{ss} = 9$. $q = 2$.

KVA rating $Q = ?$ $D = ?$ $L = ?$ $W_{tmin} = ?$ $W_{s(max)} = ?$

$K_{ws} = 0.955$

Soln: $Q = 3.3 KV \times 130 = 429 KVA.$

$C_0 = 11 B_{av}\, ac\, K_{ws} \times 10^{-3}$

$= 11 \times 0.55 \times 3000 \times 0.955 \times 10^{-3}$

$C_0 = \underline{17.33}$ KVA/m³ rps.

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{30} = 200 \text{ rpm}$$

$$n_s = \frac{200}{60} = 3.33 \text{ rps.}$$

$$D^2L = \frac{Q}{C_0 n_s} = \frac{429}{17.33 \times 3.33} = 7.434 \, m^3.$$

Assume

$L/\tau \doteq 0.65$

$L = 0.65\tau = 0.65 \frac{\pi D}{P}$

$= \frac{0.65 \times \pi D}{30}$

$L = 0.068 D.$

$\therefore D^2 (0.068 D) = 7.434$

$D^3 = 109.32$

$\boxed{D = 4.78 m}$

$L = 0.068 \times 4.78$

$\boxed{L = 0.325 m}$

Peripheral speed $V_a = \pi D n_s = \pi \times 4.78 \times 3.33$

$V_a = 50 \, m/s.$ $(< 60 \, m/s)$

Minimum width of tooth

$$W_t(min) = \frac{\phi}{S/p \times L_i \times 1.8}$$

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

$$\phi = \frac{0.55 \times \pi \times 4.78 \times 0.325}{30}$$

$$\phi = 0.0894 \text{ wb}$$

slot / pole / phase = 2

$$\text{slot / pole} = \frac{S}{P} = 2 \times 3 = 6.$$

Slot pitch $y_s = \frac{\pi D}{S_s} =$ $\quad S_s = 6 \times P$, $\quad S_s = 6 \times 30 = 180$ slots

$$y_s = \frac{\pi \times 4.78}{180}$$

$$y_s = 0.0834 \text{ m}$$

Net iron length $= L_i = K_i(L - n_v b_v)$

$n_v \rightarrow$ no. of ventilating ducts

$b_v =$ width of each duct

Assume 3 ventilating ducts each of 10mm wide is Provided. $K_i = 0.9$

$$\therefore L_i = 0.9\,(0.325 - 3 \times 10 \times 10^{-3})$$

$$L_i = 0.266 \text{ m}$$

$$W_t(min) = \frac{0.0894}{6 \times 0.266 \times 1.8} = 0.031\text{m}$$

Width of Slot $W_s(max) = y_s - W_t(min) = 0.0834 - 0.031$

$W_s(max) = 0.0524\text{m}$

Determine for 500 KVA, 6600 V, 12 Pole, 500 rpm, 3 ph alternator suitable values for (1) the diameter at airgap (2) the core length (3) the no. of stator conductors (4) the no. of stator slots. Assume a star connected stator winding. $B_{av} = 0.6 wb/m^2$ and $ac = 30,000$ A C/m. Assume $L/\tau = 1.5$.

Given:- $Q = 500$ KVA, $V = 6600$ V, $P = 12$, $N_s = 500$ rpm, 3Ph.

$L/\tau = 1.5$, $ac = 30,000$ AC/m, $B_{av} = 0.6 wb/m^2$.

$D = ?$, $L = ?$, $Z_s = ?$, $S_s = ?$, $K_{ws} = 0.955$.

Soln:-

$$n_s = \frac{500}{60} = 8.33 \text{ rps.}$$

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

$$= 11 \times 0.955 \times 0.6 \times 30,000 \times 10^{-3}$$

$$C_o = 189.09 \text{ KVA/m}^3\text{-rps.}$$

$$D^2L = \frac{Q}{C_o n_s} = \frac{500}{189.09 \times 8.33} = 0.317 \, m^3$$

Given $L/\tau = 1.5$

$$L = 1.5\tau = 1.5 \frac{\pi D}{P} = \frac{1.5 \times \pi \times D}{12}$$

$$L = 0.3924 \, D.$$

$$D^2 (0.3924 D) = 0.317.$$

$$D^3 = 0.808, \quad \boxed{D = 0.93 m}$$

$$L = 0.3925 \times 0.93 \quad \boxed{L = 0.366 m}$$

$$\phi = \frac{B_{av} \times \pi DL}{P} = \frac{0.6 \times \pi \times 0.93 \times 0.366}{12}$$

$$\phi = 0.053 \text{ Wb}$$

$$E_{ph} = \frac{6600}{\sqrt{3}} = \underline{\underline{3810.6V}}$$

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

$$= \frac{3810.6}{4.44 \times 50 \times 0.053 \times 0.955}$$

$$T_{ph} = \underline{\underline{339 \text{ turns}}}$$

The slot pitch should be nearly 45 mm for 6600 V M/c.

$$\text{Slot / pole / ph} = q = \frac{\pi D}{3 P y_s}$$

$$q = \frac{\pi \times 0.93}{3 \times 12 \times 45 \times 10^{-3}}$$

$$q = 1.8 \text{ slots} \approx 2 \text{ slots}$$

$$S_s = 3Pq = 3 \times 12 \times 2$$

$$S_s = 72 \text{ slots.}$$

$$Z_s = 6 T_{ph}$$

$$= 6 \times 334$$

$$Z_s = \underline{\underline{2034}}$$

$$Z_{ss} = \text{Cond / slot} = \frac{2016}{72} = \underline{\underline{28}}$$

3/4/2015

3) A 500 kVA, 3.3 kV, 50 Hz, 600 rpm, 3 ph salient pole alternator has 180 turns/ph. Estimate the length of airgap if the average flux density = 0.575 wb/m²; pole arc/pole pitch = 0.66. Short circuit ratio = 1.2; gap contraction factor 1.15. The mmf required for the gap is 82% of the no load field mmf. $K_w = 0.955$.

Given :- $Q = 500\,kVA$, $V = 3.3\,kV$, $N_s = 600\,rpm$, 3ph.

$T_{ph} = 180$, $B_{av} = 0.575\,wb/m^2$, $K_g = 1.15$, $K_f = \frac{\text{Pole arc}}{\text{Pole pitch}} = 0.66$

$K_w = 0.955$, $SCR = 1.2$, $AT_g = 0.82\,AT_{fo}$

Soln: $n_s = \frac{600}{60} = 10\,rps$.

$f = \frac{PN}{120} =$, $P = \frac{120 f}{N} = \frac{120 \times 50}{600}$

$P = 10$.

$$I_{ph} = \frac{kVA \times 10^3}{\sqrt{3}\, E_L} = \frac{500 \times 10^3}{\sqrt{3} \times 3300} = 87.4\,A$$

Armature mmf per pole

$$AT_a = \frac{2.7\, I_{ph}\, T_{ph}\, K_{ws}}{P} = \frac{2.7 \times 87.4 \times 180 \times 0.955}{10}$$

$$AT_a = 4060$$

$$AT_{fo} = AT_a \times SCR = 4060 \times 1.2 = 4872\,A$$

Field form factor $= \frac{\text{Pole arc}}{\text{Pole pitch}} = 0.66 = K_f \approx \psi$

Max flux density in the airgap

$$B_g = \frac{B_{av}}{K_f} = \frac{0.575}{0.66} = 0.87\,wb/m^2$$

MMF for airgap $= 800,000\, B_g\, K_g\, l_g$.

mmf for airgap = 82% of no load field mmf

$$800,000\, B_g\, l_g\, K_g = 0.82 \times 4872$$

Length of air gap $l_g = \dfrac{0.82 \times 4872}{800{,}000\ B_g\ k_g}$

$= \dfrac{0.82 \times 4872}{800{,}000 \times 0.87 \times 1.15}$

$l_g = 5.8 \times 10^{-3}$ mt.

$l_g = \underline{\underline{5.8 \text{ mm}}}$

4) Find the main dimensions of 100 MVA, 11 KV, 50 Hz, 150 rpm 3 ph. water wheel generators. Given $B_{av} = 0.65$ wb/m^2, ac = 40,000. The peripheral speed should not exceed 65 m/sec at normal running speed in order to limit the runway speed. Assume $K_w = 0.955$

Given :- 3 ph, Q = 100 MVA, V = 11 KV, f = 50 Hz, $N_s = 150$ rpm

$B_{av} = 0.65$ wb/m^2, ac = 40,000 A c/mt. $K_w = 0.955$.

$V_a < 65$ m/sec.

Soln:-

$n_s = \dfrac{150}{60} = 2.5$ rps

$P = \dfrac{120 f}{N_s} = \dfrac{120 \times 50}{150} = 40.$

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

$= 11 \times 0.65 \times 40{,}000 \times 0.955 \times 10^{-3}$

$C_o = 273.13 \approx 274$ KVA/m^3-rps

Trying circular poles $L/\tau = 0.6$ to 0.7

Taking $L/\tau = 0.65$, $L = 0.65\,\tau$

$0.65 \times \dfrac{\pi D}{P}$

$L = 0.65 \times \dfrac{\pi D}{40} = 0.051 D$

$\therefore D^2 (0.051D) = 146$

$D = 14.2 m$

$D^2 L = \frac{Q}{C_0 n_s}$

$= \frac{100 \times 10^3}{274 \times 2.5}$

$D^2 L = 145.98 \simeq 146$

Peripheral speed at synch. speed

$V_a = \pi D n_s$

$V_a = \pi \times 14.2 \times 2.5 = 111.52 \, m/s$

This is greater than the permissible limit of 65 m/s. Hence circular poles cannot be used.

For rectangular poles $L/\tau = 1$ to 5

Taking $\frac{L}{\tau} = 4$;

$L = 4\tau = 4\frac{\pi D}{P} = \frac{4 \times \pi \times D}{40}$, $L = 0.314 D$

$D^2 (0.314 D) = 146$ $\quad D = 7.747 m$

$V_a = \pi D n_s = 3.14 \times 7.747 \times 2.5 = 60.84 \, m/s.$

$V_a = 60.84 \, m/s \; (< 65 \, m/s)$.

Main Dimensions are

$D = 7.747 m$

$L = 0.314 D$

$L = 2.432 m$

Question Paper Solved Examples Design of Synchronous machines.

1) Determine the main dimensions for a 1000KVA, 50Hz, 3phase, 375 rpm alternator. The avg airgap flux density is 0.55 wb/m² and the ampere conductors per meter are 28,000. use rectangular poles and assume suitable value for ratio of core length to pole pitch in order that bolted on pole construction is used for which the maximum permissible peripheral speed is 50m/s The run away speed is 1.8 times synchronous speed. $K_{ws} = 0.955$, $L/\tau = 2$

Soln: Given:

$N = 375$ rpm, $f = 50$ Hz, $B_{avg} = 0.55$ wb/m²

$Q = 1000$ KVA, 3phase. $ac = 28000$ A cond/m

$D = ?$ $L = ?$ $K_{ws} = 0.955$, $L/\tau = 2$

$V_a \leq 50$ m/s.

Synchronous speed $n_s = \frac{\cancel{120} N_s}{60} = \frac{375}{60} = 6.25$ rps.

no. of poles $= P = \frac{2f}{n_s} = \frac{2 \times 50}{6.25} = 16.$

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

$= 11 \times 0.955 \times 0.55 \times 28{,}000 \times 10^{-3}$

$C_o = 161.77$ KVA/m³-rps

$D^2 L = \frac{Q}{C_o n_s} = \frac{1000}{161.77 \times 6.25} = 0.989\, m^3$

$\frac{L}{\tau} = 2$, $L = 2\frac{\pi D}{P} = \frac{2\pi D}{16} = 0.3926\, D$

$D^2 (0.3926 D) = 0.989$

$0.3926 D^3 = 0.989$

$\boxed{D = 1.36\, m}$ $\boxed{L = 0.534\, m}$

Peripheral Speed $V_a = \pi D n_s = \pi \times 1.36 \times 6.25$

$V_a = 26.7$ m/s.

peripheral Speed at runaway speed $= 1.8 \times V_a$

$= 1.8 \times 26.7$

$= 48$ m/s.

This is below 50 m/s and therefore a simple bolted on pole construction can be used.

(2) Calculate the stator core dimensions for a 10 MVA, 11 kV, 50 Hz, 3ph, 2 pole turbo alternator, based on the following information.

$B_{avg} = 0.63$ T, ac = 48,000 amp cond/mt. Limiting peripheral speed $V_a = 120$ m/sec, length of air gap $l_g = 2$ cm. $K_{ws} = 0.955$.

Given:-

$Q = \cancel{10 \times 10^6} \; 10 \times 10^3$ KVA $P = 2$, $B_{avg} = 0.63$ Wb/m²

$V = 11$ kV, $f = 50$ Hz, 3ph, ac, 48,000 Amp cond/mt.

$V_a \leq 120$ m/s. $l_g = 2$ cm, $K_{ws} = 0.955$

Sol:

$$n_s = \frac{2f}{P} = \frac{2 \times 50}{2} = 50 \text{ rps}.$$

$$Q = C_0 D^2 L n_s$$

$$\therefore C_0 = 11 B_{avg}\, ac\, K_{ws} \times 10^{-3}$$

$$= 11 \times 0.63 \times 48{,}000 \times 0.955 \times 10^{-3}$$

$$C_0 = 317.67 \text{ KVA/m}^3\text{.rps}.$$

$$Q = C_0 D^2 L n_s, \quad D^2 L = \frac{Q}{C_0 n_s}$$

$$= \frac{10 \times 10^3}{317.67 \times 50}$$

$$D^2 L = 0.629 \text{ m}^3.$$

The equation $\boxed{P_a = C_0 D^2 L n}$ → output equation

$D^2 L$ = Peripheral speed $V_a = \pi D . n_s$

$120 = \pi D \times 50$

outer diameter of rotor $D = 0.76\,m$

Internal diameter of stator $D = D_r + 2 l_g$

$= 0.76 + 2 \times 0.02$

$D = 0.8\,m$

Gross length of stator core, $L = \frac{D^2 L}{D^2} = \frac{0.631}{(0.8)^2}$

$L = 0.985\,m$

3) A 2500 KVA 225 rpm, 3 phase, 60 Hz, 2400 V, star connected salient pole alternator has the following design: Stator bore = 2.5 m, core length = 0.44 m; slot/pole/ph = 3.5, Conductor/slot = 4, circuit per ph = 2, Leakage factor = 1.2, winding factor = 0.95, $B_{avg} = 1.5\,wb/m^2$, winding depth = 30 mm, the ratio of full load field mmf to armature mmf = 2 the field winding space factor is 0.84 and the field winding dissi... field winding space factor is 0.84. and the field winding di... 1800 W/m² of inner & outer surface without the temperature rise exceeding the permissible limit. Leave 30 mm for insulation, flanges & height of pole shoe along the height of pole. Find (a) the flux/pole (b) length & width of pole (c) winding ... & (d) pole height.

Soln

$n_s = \frac{N}{60} = \frac{225}{60} = 3.75\,rps$

$P = \frac{2 \times f}{n_s} = \frac{2 \times 60}{3.75} = 32$

Total no of Slots = $3 \times 32 \times 3.5 = 336$

Total no. of Conductors $Z = 336 \times 4 = 1344$.

$T_{ph} = \frac{1344}{6} = 224$

$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{2400}{\sqrt{3}} = 1385.6V$

$E_{ph} = 4.44\, k_w\, \phi f \frac{T_{ph}}{a}$ $\quad a = 2$

Flux/pole $= \phi = \frac{1385.6 \times 2}{4.44 \times 224 \times 60 \times 0.95}$

$\phi = 48 \times 10^{-3}$ wb

Flux in pole body $\phi_p = C_L \phi$

$1.2 \times 48 \times 10^{-3}$

$\phi_p = 58.6 \times 10^{-3}$ wb

Area of Pole body $= A_p = \frac{\phi_p}{B_p} = \frac{58.6 \times 10^{-3}}{1.5} = 39.2 \times 10^{-3} m^2$

length of the Pole body L_p = length of armature core $= 0.44m$

width of the pole body $b_p = \frac{A_p}{L_p} = \frac{39.2 \times 10^{-3}}{0.44}$

$b_p = 0.088 m$

Current in each phase $I_{ph} = \frac{P}{\sqrt{3}\, V_L} = \frac{2500 \times 1000}{\sqrt{3} \times 2400}$

$I_{ph} = 601.4 A$.

Current in each Conductor $I_z = \frac{I_{ph}}{2} = \frac{601.4}{2} = 300.70 A$

(since there are two circuits)

Armature mmf per pole $AT_a = \frac{2.7\, I_z\, T_{ph}\, K_{ws}}{P}$

$$= \frac{2.7 \times 300 \times 224 \times 0.95}{32}$$

$$AT_a = 5386\,AT.$$

Field mmf as full load $AT_{fl} = 2 \times AT_a$

$$= 2 \times 5386$$

$$AT_{fl} = 10772\ AT.$$

Mmf per meter height of winding $= 10^4 \times \sqrt{q_f\, S_f\, d_f}$

$$= 10^4 \sqrt{0.84 \times 0.03 \times 1800}$$

$$= 67{,}349.8\,AT$$

depth = 30mm
= 0.03m
$S_f = 0.84$
$q_f = 1800$ W/m

Height of field winding $h_f = \frac{AT_{fl}}{\text{mmf per meter height of field winding}}$

$$h_f = \frac{10772}{67{,}349.8}$$

$$h_f = 0.159\,m$$

Height of Pole = height of winding + height of Insulation

$$= 0.159 + 0.03$$

(30mm for insulation = 0.03m)

Height of Pole $= 0.189\,m$

Magnetic circuit . Synchronous Machines :

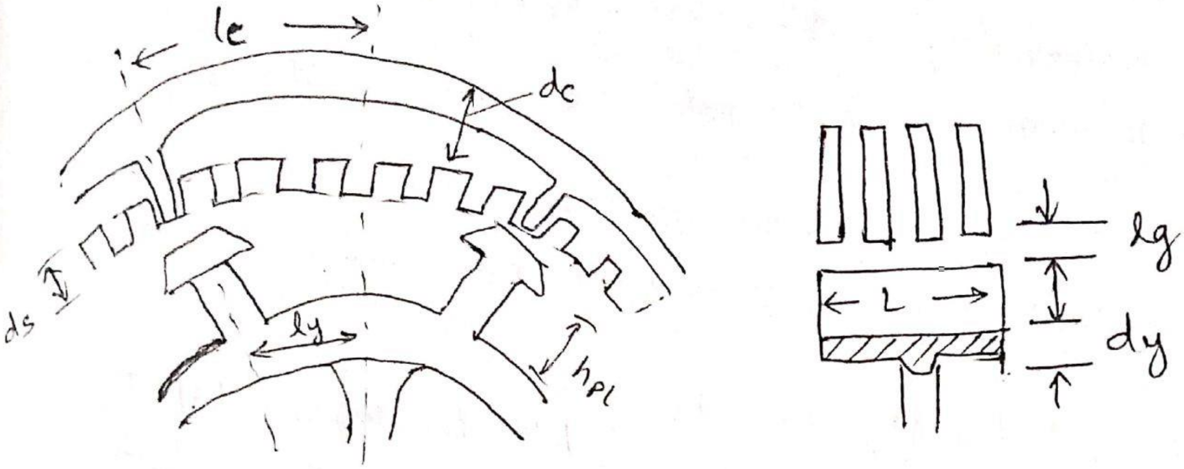


Fig. Magnetic circuit.

The calculation of magnetic circuit are discussed as follows.

1) mmf for air gap (AT_g)
2) mmf for armature teeth (AT_{at})
3) mmf for core. (AT_c)
4) mmf for poles. (AT_p)
5) mmf for yoke (AT_y)

1) mmf for air gap AT_g is given by

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

2) mmf for armature teeth is found by finding flux density $B_{t\,1/3}$ at 1/3 height from the narrow end.

The length of flux path in the teeth is equal to the depth of the slot.

3) mmf for core $AT_c = at_c\, l_c$

$$l_c = \frac{\pi (D + 2d_s + d_c)}{2P}$$

length of flux path in the core is taken equal to one half of the pole pitch on the mean diameter.

4) MMF for Poles

minimum flux in the poles $\phi_p(min) = \phi + \phi_{sl}$

maximum flux in the poles $\phi_p(max) = \phi + \phi_{sl} + \phi_{pl}$

$\phi_{sl} \rightarrow$ Total leakage flux from pole shoe.

$\phi_{pl} \rightarrow$ Total leakage flux from pole body

$$\phi_{sl} = 4 \mu_0 AT_l \left[\frac{L_s h_s}{c_s} + 1.47 h_s \log_{10}\left(1 + \frac{\pi b_s}{2c_s}\right)\right.$$

$$\phi_{pl} = 2 \mu_0 AT_l \left[\frac{L_p h_p}{c_p} + 1.47 h_p \log_{10}\left(1 + \frac{\pi b_p}{2c_p}\right)\right.$$

L_p = axial length of pole body.

L_s = axial lenght of pole shoe & b_s

$AT_l = AT_g + AT_t + AT_c$.

maximum flux density in the pole body $B_p(max) = \dfrac{\phi_p(max)}{A_p}$

min. flux density in the pole body $B_p(min) = \dfrac{\phi_p(min)}{A_p}$

Total mmf for body is

$$AT_p = at_p(max) \cdot \frac{h_{pl}}{3} + at_p(min) \cdot \frac{2h_{pl}}{3}$$

5) MMF for yoke

$$\phi_y = \frac{\phi + \phi_{sl} + \phi_{pl}}{2}$$

Area of yoke A_y = length of yoke x depth of yoke

$= L\, d_y$

Flux density in yoke $B_y = \dfrac{\phi_y}{A_y} = \dfrac{\phi + \phi_{pl} + \phi_{sl}}{2 L d_y}$

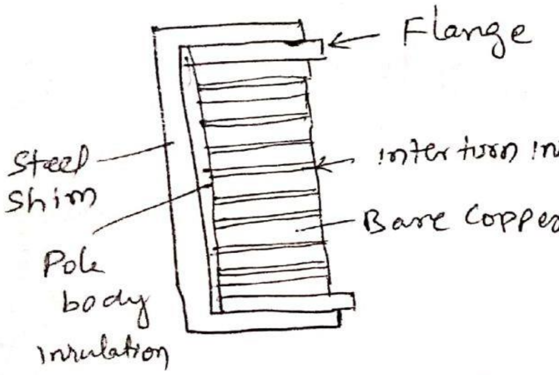
MMF for yoke $= AT_y = at_y \, l_y$.

$$l_y = \frac{\pi (D_r - 2h_{pl} - d_y)}{2p}$$

Total field mmf required at no load

$$AT_{fo} = AT_g + AT_t + AT_c + AT_p + AT_y.$$

Design of Field winding:

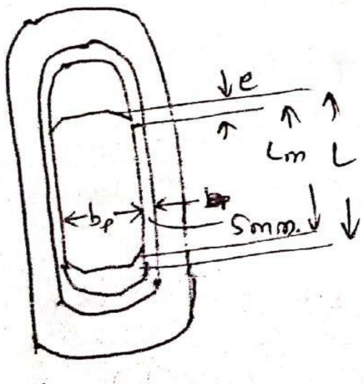


Field coil, with strip on edge conductors.

Length of mean turn $\quad L_{mt} = 2L_m + \pi (b_p + 0.01 + d_f)$

$L_m = 0.9L$

$e = 0.05L$



length of mean turn

① Voltage a/c field coil

$$E_f = \frac{(0.8 \text{ to } 0.85) V_e}{P}$$

② Height of the pole

$h_f = h_{pl} - h_1 -$ Space taken by spool, flanges etc..

(3) d_f & l_{mt} can be evaluated

(4) Voltage across the each field

$$E_f = I_f R_f = I_f \frac{T_f \rho l_{mtf}}{a_f}$$

$$I T_f = AT_{fl} \quad \text{Field mmf per pole at full load}$$

$$E_f = AT_{fl} \frac{\rho l_{mtf}}{a_f}.$$

$$a_f = \frac{AT_{fl} \rho l_{mtf}}{E_f}. \quad \text{area of field conductor}$$

(5) Current density δ_f is 3 to 4 A/mm^2

$$I_f = \delta_f a_f.$$

(6) Field Turns $T_f = \frac{AT_{fl}}{I_f}$

(7) resistance of winding calculated at 75°C

$$R_f = \frac{T_f \rho l_{mtf}}{a_f}$$

Copper loss in each field coil at 75°C

$$Q_f = I_f^2 R_f = I_f^2 T_f \frac{(\rho l_{mtf})}{a_f}.$$

Dissipating surface of the coil $S = 2 l_{mts} (h_f + d_f)$

Cooling co-efficient $C_f = \frac{0.08 \text{ to } 0.12}{1 + 0.1 V_a}$

Temperature rise $\theta = Q_f C_f / S$.

(8) Clearance b/w the field coil is 15 mm.

4) During the design of stator for a 3ϕ, 7.5 KVA, 6.6 KV, 50 Hz, 3000 rpm turbo alternator following information have been obtained.
Gross core length = 0.9 m, No. of stator slots/pole/ph = 7, D = 0.75 m
Sectional area of stator cond = 190 mm², No. of cond/slot = 4
Based on the above data calculate
1) flux/pole 2) specific loadings 3) current density for stator winding

Soln:

No. of Poles $= P = \frac{120f}{N} = \frac{120 \times 50}{3000} = P = 2$

No. of stator slots $S_s = 7 \times 2 \times 3 = 42$

Total no. of conductors $= 42 \times 4 = 168$

Turns per phase $T_{ph} = \frac{168}{2 \times 3} = 28$

Assume $k_{ws} = 0.955$

$$E_{ph} = \frac{6600}{\sqrt{3}} = 3810.6V$$

① $$\phi = \frac{E_{ph}}{4.44 f T_{ph} k_{ws}} = \frac{3810.6}{4.44 \times 50 \times 28 \times 0.955}$$

$$\phi = 0.642 wb$$

$$I_{ph} = \frac{P_{ph}}{E_{ph}} = \frac{7.5 \times 10^3}{3810}$$

$$I_{ph} = 1.96A$$

② Specific magnetic loading

$$B_{av} = \frac{P\phi}{\pi D L} = \frac{2 \times 0.642}{\pi \times 0.75 \times 0.9} = 0.606 wb/m^2$$

Specific electric loading

$$ac = \frac{6 I_z T_{ph}}{\pi D} = \frac{6 \times 1.97 \times 28}{\pi \times 0.75}$$

$$ac = \frac{6 \times 1.96 \times 28}{\pi \times 0.75} = 139.75 \text{ A cond/m}$$

5) Obtain the suitable values of diameter and core length for a 1500KVA, 3300V, 3ϕ, delta connected, 10 pole alternator which has specific magnetic loading 0.51 T. and specific electric loading 34,000 AT/m. The ratio of pole pitch to core length is 0.8. Assume winding factor as 0.955. f = 50Hz

Soln:

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

$$C_o = 11 B_{av}\, ac\, K_w \times 10^{-3}$$

$$= 11 \times 0.51 \times 34,000 \times 0.955 \times 10^{-3}$$

$$C_o = 182.16 \text{ KVA/m}^3\text{-rps}$$

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{10} = 600 \text{ rpm}, \quad n_s = \frac{600}{60} = 10 \text{ rps}$$

$$D^2 L = \frac{Q}{C_o n_s} = \frac{1500}{182.16 \times 10} = \underline{0.823 \text{ m}^3}$$

Given $\frac{\text{Pole pitch}}{\text{core length}} = 0.8$. $\quad \frac{\tau}{L} = 0.8 \Rightarrow 0.8L$

$$\tau = \frac{\pi D}{P}, \quad \frac{\tau}{L} = 0.8 = \frac{\pi D}{LP} = 0.8$$

$$L = \frac{\pi D}{0.8 \times 10} = 0.3925D, \quad \therefore D^2 L = 0.8.$$

$$0.3925 D^3 = 0.8$$

$$D^3 = 2.038$$

$$\boxed{D = 1.26 m} \qquad L = 0.3925 \times 1.26$$

$$\boxed{L = 0.497 m}$$