SCHOOL OF ELECTRICAL AND ELECTRONICS ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONICS

UNIT – I – Electrical Machine Design – SEEA1601

I. Introduction

Contents – Major considerations in Machine design Limitations in design Standard specifications Electrical Engineering materials High conductivity materials Insulating materials Magnetic circuit calculations mmf for airgap and iron path real and apparent flux densities in rotating machines- Choice of specific electric and magnetic loadings.

Introduction

The magnetic flux in all electrical machines (generators, motors and transformers) plays an important role in converting or transferring the energy. Field or magnetizing winding of rotating machines produces the flux while armature winding supplies either electrical power or mechanical power. In case of transformers primary wing supplies the power demand of the secondary. The basic design of an electrical machine involves the dimensioning of the magnetic circuit, electrical circuit, insulation system etc., and is carried out by applying analytical equations.

A designer is generally confronted with a number of problems for which there may not be one solution, but many solutions. A design should ensure that the products perform in accordance with the requirements at higher efficiency, lower weight of material for the desired output, lower temperature rise and lower cost. Also, they are to be reliable and durable.

A practical designer must effect the design so that the stock (standard frames, punching etc.,) is adaptable to the requirements of the specification. The designer must also affect some sort of compromise between the ideal design and a design which comply with manufacturing conditions.

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 (that deals with machine ratings, performance requirements etc., of the consumer)
c. Cost of material and labour
d. Manufacturing constraints etc.

As the design involves a number of assumptions and constraints, final design values can be obtained only by iterative methods. Computer plays a vital role in arriving at the final values. By Finite Element Method (FEM), the effect of a single parameter on the dynamical performance of the machine can be studied. Furthermore, some tests, which are not even feasible in laboratory setup, can be virtually performed by Finite Element Method.

Major considerations in Electrical Machine Design
The basic components of all electromagnetic apparatus are the field and armature windings supported by dielectric or insulation, cooling system and mechanical parts. Therefore, the factors for consideration in the design are,

Magnetic circuit or the flux path:
Should establish required amount of flux using minimum MMF. The core losses should be less.
Electric circuit or windings:
Should ensure required EMF is induced with no complexity in winding arrangement. The copper losses should be less.
Insulation:
Should ensure trouble free separation of machine parts operating at different potential and confine the current in the prescribed paths.
Cooling system or ventilation:
Should ensure that the machine operates at the specified temperature.
Machine parts:
Should be robust.
The art of successful design lies not only in resolving the conflict for space between iron, copper, insulation and coolant but also in optimization of cost of manufacturing, and operating and maintenance charges.
The factors, apart from the above, that requires consideration are
a. Limitation in design (saturation, current density, insulation, temperature rise etc.,)
b. Customer's needs
c. National and international standards
d. Convenience in production line and transportation e. Maintenance and repairs
f. Environmental conditions etc.

Limitations in design: The materials used for the machine and others such as cooling etc., imposes a limitation in design. The limitations stem from saturation of iron, current density in conductors, temperature, insulation, mechanical properties, efficiency, power factor etc.
a. 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.
b. Current density: Higher current density reduces the volume of copper but increases the losses and temperature.
c. Temperature: poses a limitation on account of possible damage to insulation and other materials.
d. Insulation (which is both mechanically and electrically weak): poses a limitation on account of breakdown by excessive voltage gradient, mechanical forces or heat.
e. Mechanical strength of the materials poses a limitation particularly in case of large and high-speed machines.
f. High efficiency and high-power factor poses a limitation on account of higher capital cost. (A low value of efficiency and power factor on the other hand results in a high maintenance cost).
g. Mechanical Commutation in dc motors or generators leads to poor commutation.
Apart from the above factors Consumer, manufacturer or standard specifications may pose a limitation.

Materials for Electrical Machines

The main material characteristics of relevance to electrical machines are those associated with conductors for electric circuit, the insulation system necessary to isolate the circuits, and with the specialized steels and permanent magnets used for the magnetic circuit.
Conducting materials
Commonly used conducting materials are copper and aluminium. Some of the desirable properties a good conductor should possess are listed below.

1. Low value of resistivity or high conductivity
2. Low value of temperature coefficient of resistance
3. High tensile strength
4. High melting point
5. High resistance to corrosion
6. Allow brazing, soldering or welding 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 shown in the table-1.

Table 1. Properties of copper and aluminium

Sl. No	Particulars	Copper	Aluminum
1	Resistivity at 20^0C	0.0172 ohm / m/ mm^2	0.0269 ohm / m/ mm^2
2	Conductivity at 20^0C	58.14 x 10^6S/m	37.2 x 10^6S/m
3	Density at 20^0C	8933kg/m^3	2689.9m^3
4	Temperature coefficient ($0\text{-}100^oC$)	0.393 % per ^0C	0.4 % per ^0C
		Explanation: If the temperature increases by 1^oC, the resistance increases by 0.4% in case of aluminum	
5	Coefficient of linear expansion ($0\text{-}100^oC$)	$16.8\text{x}10^{-6}$ per ^oC	23.5 x10^{-6} per ^oC
6	Tensile strength	25 to 40 kg / mm^2	10 to 18 kg / mm^2
7	Mechanical property	highly malleable and ductile	not highly malleable and ductile
8	Melting point	1083^0C	660^0C
9	Thermal conductivity ($0\text{-}100^oC$)	599 W/m ^0C	238 W/m ^0C
10	Jointing	can be 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. Though the aluminium reduces the cost of small capacity transformers, it increases the size and cost of large capacity transformers. Aluminium is being much used now a day's only because copper is expensive and not easily available. Aluminium is almost 50% cheaper than Copper and not much superior to copper.

Magnetic materials

The magnetic properties of a magnetic material depend on the orientation of the crystals of the material and decide the size of the machine or equipment for a given rating, excitation required, efficiency of operation etc.

The some of the properties that a good magnetic material should possess are listed below.

1. Low reluctance or should be highly permeable or should have a high value of relative permeability μr.
2. High saturation induction (to minimize weight and volume of iron parts)
3. High electrical resistivity so that the eddy EMF and the hence eddy current loss is less
4. Narrow hysteresis loop or low Coercivity so that hysteresis loss is less and efficiency of operation is high
5. A high curie point. (Above Curie point or temperature the material loses the magnetic property or becomes paramagnetic, that is effectively non-magnetic)

6. Should have a high value of energy product (expressed in joules / m3).

Magnetic materials can broadly be classified as Diamagnetic, Paramagnetic, Ferromagnetic, Antiferromagnetic and Ferrimagnetic materials. 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. The only exceptions are some alloys of manganese and some of the rare earth elements.

The relative permeability μr of ferromagnetic material is far greater than 1.0. When ferromagnetic materials are subjected to the magnetic field, the dipoles align themselves in the direction of the applied field and get strongly magnetized.
Further the Ferromagnetic materials can be classified as Hard or Permanent Magnetic materials and Soft Magnetic materials.

a) Hard or permanent magnetic materials- have large size hysteresis loop (obviously hysteresis loss is more) and gradually rising magnetization curve.
Ex: carbon steel, tungsten steal, cobalt steel, alnico, hard ferrite etc.

b) Soft magnetic materials- have small size hysteresis loop and a steep magnetization curve.
Ex: i) cast iron, cast steel, rolled steel, forged steel etc., (in the solid form).
Generally used for yokes poles of dc machines, rotors of turbo alternator etc., where steady or dc flux is involved.

ii) Silicon steel (Iron + 0.3 to 4.5% silicon) in the laminated 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 density. 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 or cold rolled. Cold rolled grain-oriented steel (CRGOS) is costlier and superior to hot rolled. CRGO steel is generally used in transformers.

c) Special purpose Alloys:
Nickel iron alloys have high permeability and addition of molybdenum or chromium leads to improved magnetic material. Nickel with iron in different proportion leads to
(i) High nickel permalloy (iron +molybdenum +copper or chromium), used in current transformers, magnetic amplifiers etc.,
(ii) Low nickel Permalloy (iron +silicon +chromium or manganese), used in transformers, induction coils, chokes etc.
(iii) Perminvor (iron +nickel +cobalt)
(iv) Pemendur (iron +cobalt +vanadium), used for microphones, oscilloscopes, etc.
(v) Mumetal (Copper + iron)

d) Amorphous alloys (often called metallic glasses):
Amorphous alloys are produced by rapid solidification of the alloy at cooling rates of about a million degrees centigrade per second. The alloys solidify with a glass-like atomic structure which is non-crystalline frozen liquid. The rapid cooling is achieved by causing the molten alloy to flow through an orifice onto a rapidly rotating water-cooled drum. This can produce sheets as thin as 10μm and a meter or more wide.
These alloys can be classified as iron rich based group and cobalt based group and is shown in table 2.

Table 2. Classification of alloys

Material	Maximum permeability $\mu \times 10^{-3}$	Saturation magnetization in tesla	Coercivity A/m	Curie temperature ^{o}C	Resistivity $\Omega m \times 10^{8}$
3% Si grain oriented	90	2.0	6-7	745	48
2.5% Si grain non -oriented	8	2.0	40	745	44
<0.5% Si grain non oriented	8	2.1	50-100	770	12
Low carbon iron	3-10	2.1	50-120	770	12
78% Ni and iron	250-400	0.8	1.0	350	40
50% Ni and iron	100	1.5-1.6	10	530	60
Iron based Amorphous	35-600	1.3-1.8	1.0-1.6	310-415	120-140

Insulating materials.

To avoid any electrical activity between parts at different potentials, insulation is used. An ideal insulating material should possess the following properties.

1) Should have high dielectric strength.
2) Should with stand high temperature.
3) Should have good thermal conductivity
4) Should not undergo thermal oxidation
5) Should not deteriorate due to higher temperature and repeated heat cycle
6) Should have high value of resistivity (like 1018 Ωcm)
7) Should not consume any power or should have a low dielectric loss angle δ
8) Should withstand stresses due to centrifugal forces (as in rotating machines), electro dynamic or mechanical forces (as in transformers)
9) Should withstand vibration, abrasion, bending
10) Should not absorb moisture
11) Should be flexible and cheap
12) Liquid insulators should not evaporate or volatilize

Insulating materials can be classified as Solid, Liquid and Gas, and vacuum. The term insulting material is sometimes used in a broader sense to designate also insulating liquids, gas and vacuum.

Solid: Used with field, armature, and transformer windings etc. The examples are:
1) Fibrous or inorganic animal or plant origin, natural or synthetic paper, wood, card board, cotton, jute, silk etc.,
2) Plastic or resins. Natural resins-lac, amber, shellac etc
Synthetic resins-phenol formaldehyde, melamine, polyesters, 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, alumina etc.,
6) Glass: soda lime glass, silica glass, lead glass, borosilicate glass
7) Non-resinous: mineral waxes, asphalt, bitumen, chlorinated naphthalene, enamel etc.,

Liquid: Used in transformers, circuit breakers, reactors, rheostats, cables, capacitors etc., & for impregnation. The examples are:
1) Mineral oil (petroleum by product)

2) Synthetic oil askarels, pyranols etc.,
3) Varnish, French polish, lacquer epoxy resin etc.,
Gaseous: The examples are:
1) Air used in switches, air condensers, transmission and distribution lines etc.,
2) Nitrogen use in capacitors, HV gas pressure cables etc.,
3) Hydrogen though not used as a dielectric, generally used as a coolant
4) Inert gases neon, argon, mercury and sodium vapours generally used for neon sign lamps.
5) Halogens like fluorine, used under high pressure in cables

No insulating material in practice satisfies all the desirable properties. Therefore, a material which satisfies most of the desirable properties must be selected.

Classification of insulating materials based on thermal consideration

The insulation system (also called insulation class) for wires used in generators, motors transformers and other wire-wound electrical components is divided into different classes according the temperature that they can safely withstand. As per Indian Standard (Thermal evaluation and classification of Electrical Insulation, IS.No.1271,1985, first revision) and other international standard insulation is classified by letter grades A, E, B, F, H (previous Y, A, E, B, F, H, C). The table 3 shows the different type of materials used for different insulation class.

Table 3. Materials for different insulation class

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

The maximum operating temperature is the temperature the insulation can reach during operation and is the sum of standardized ambient temperature i.e. 40 degree centigrade, permissible temperature rise and allowance tolerance for hot spot in winding. For example, the maximum temperature of class B insulation is (ambient temperature 40 + allowable temperature rise 80 + hot spot tolerance 10) = 130°C.

Insulation is the weakest element against heat and is a critical factor in deciding the life of electrical equipment. The maximum operating temperatures prescribed for different class of insulation are for a healthy lifetime of 20,000 hours. The height temperature permitted for the machine parts is usually about 2000C at the maximum. Exceeding the maximum operating temperature will affect the life of the insulation. As a rule of thumb, the lifetime of the winding insulation will be reduced by half for every 10 ºC rise in temperature. The present day trend is to design the machine using class F insulation for class B temperature rise.

MAGNETIC CIRCUITS

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

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

Mmf = NI (Ampere Turns)

Flux= mmf/Reluctance

$$\phi = AT / S$$

or $\phi = AT * \wedge$, where $\wedge$ = Permeance

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

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

where, μ = Permeability of the magnetic material

$\mu = \mu_r \mu_0$

μ_r = Relative permeability

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

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

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

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

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

AT = H x l = at x l

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

parts.

Total Reluctance S = S1 + S 2 + S 3

Where S1, S 2, S 3 ,… are reluctances of individual

Total mmf, AT = ØS1+ ØS2 +ØS3

= Ø(S1+S2+S3)

$= AT_1 + AT_2 + AT_3 + \ldots$
$= at_1 l_1 + at_2 l_2 + at_3 l_3 + \ldots$
$= \phi$ at l

The above equation represent the circuital law for magnetic circuits, where at1, at2, at3 are the mmf per meter for the individual part and l_1 , l_2 , l_3 are lengths of parts connected in series.

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

Total flux= Ø1+ Ø2+ Ø3

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

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

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

Where, S = Total reluctance of magnetic circuit.

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

$\wedge$- Total permeance of magnetic circuit.

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

The table 4 shows the comparison of Electrical and magnetic circuit.

Table 4. Electrical and Magnetic Circuit comparison

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

The figure 1 shows the flux path in various electrical machines.

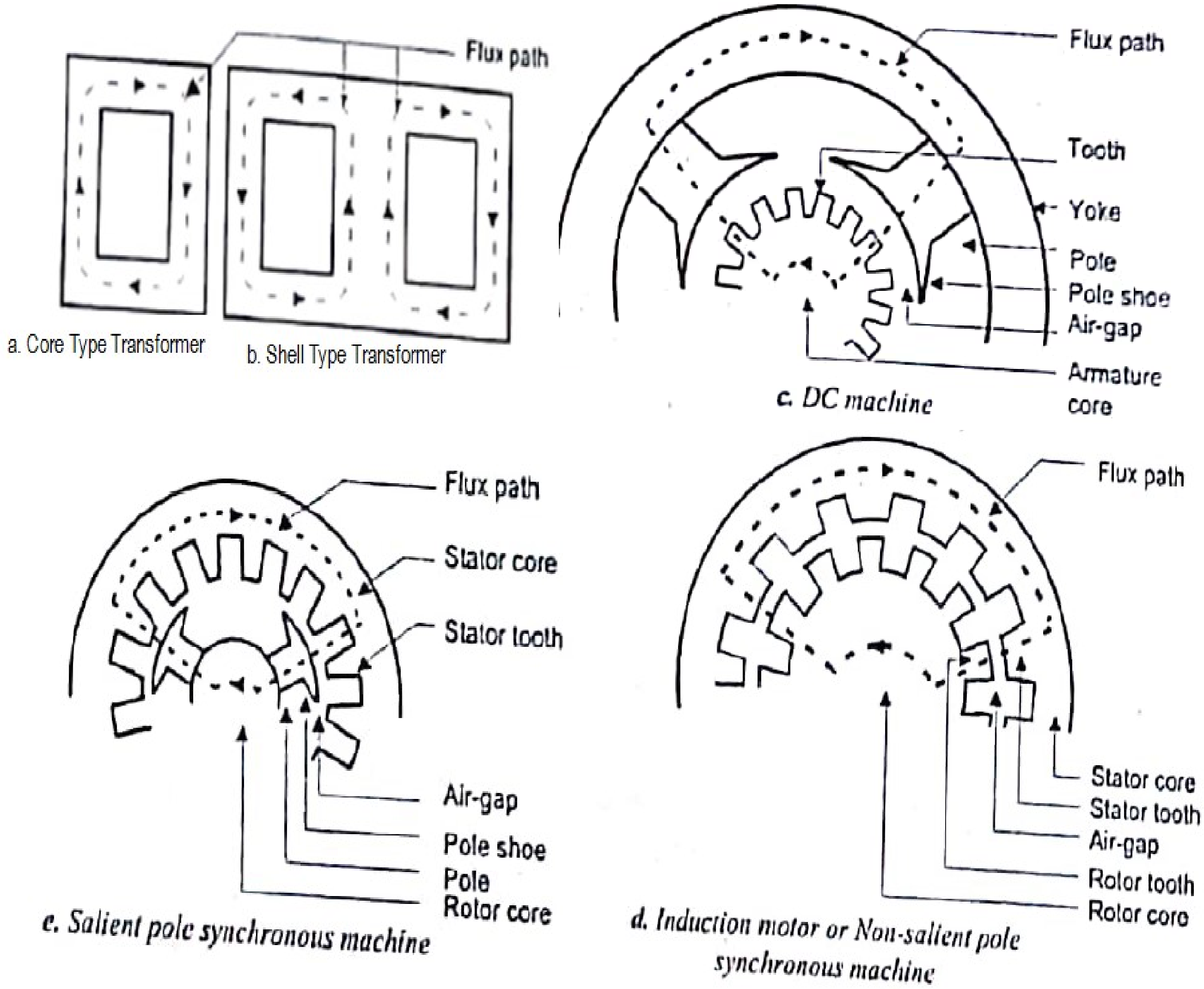

Figure 1. Flux path in various electrical machines

RELUCTANCE OF AIR GAP IN MACHINES

1. With Smooth Armature :

The rotating machines will have a small air-gap between armature and pole surface.

Smooth armature surfaces are possible only if the armature has closed slots.

L = Length of core

l_g = air gap length

y_s = slot pitch

W_s = width of slot

W_t = width of teeth

Consider the armature with closed slots, the flux is uniformly spread over the entire slot pitch and goes straight across the air gap. The figure 2 shows the reluctance of air gap with smooth armature

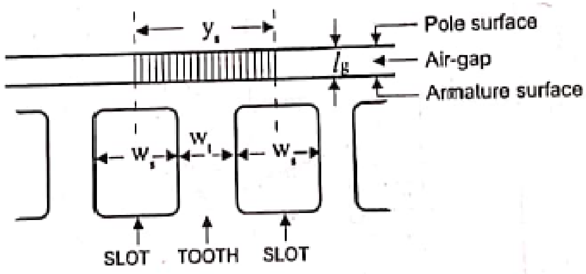

Figure 2. Reluctance of air gap with smooth armature

The reluctance, S of a magnetic path is given by = l / μA

Where, l = Length of magnetic path

μ = Permeability of the medium

A = Area of cross section of the magnetic path.

Consider the area of cross section of the magnetic path over one slot of the armature. It is given by the product of length of armature and slot pitch. Hence the reluctance of air gap can be given as,

Where S_g = reluctance of air gap

lg = length of air gap

μ_o = permeability of air

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

With Open Armature :

In armature with open and semi enclosed slots, the flux will flow through the teeth of the armature.

Hence the effective area of flux path is decreased, which results in increased reluctance in air gap.

Reluctance of air gap neglecting fringing effect:

In open type slots, consider the flux is only confined to the width of teeth.

Area of cross section of air gap through which the flux passes is $L(y_s - w_s)$ or Lw_t.

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

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

The figure 3 shows the open armature slots with neglecting fringing effect.

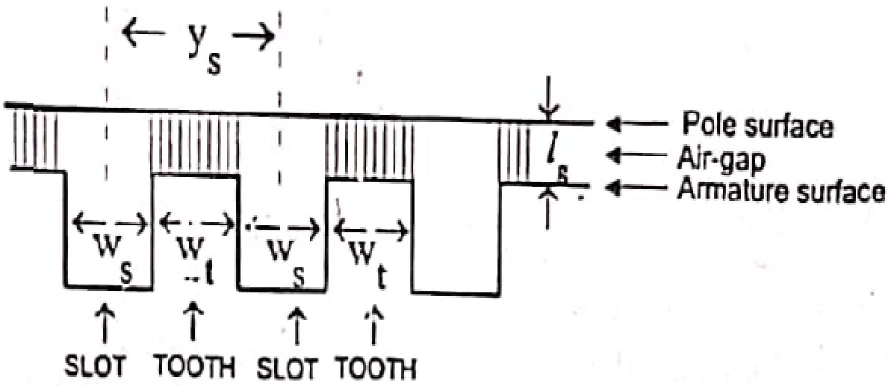

Figure 3. Reluctance of air gap of machines with open armature slots.

Reluctance of air gap including the effect of fringing

In the case of armature with open type slots, the flux would fringe around the teeth and this fringing would increase the area of cross section of flux path. Consider the open type slots of armature, the fringing of flux around the teeth increasing the area of cross section of flux path by δW_s. Assume the air gap flux is uniformly distributed over the whole slot pitch except for a fraction of slot width. The figure 4 shows the reluctance of air gap of machines with effect of fringing.

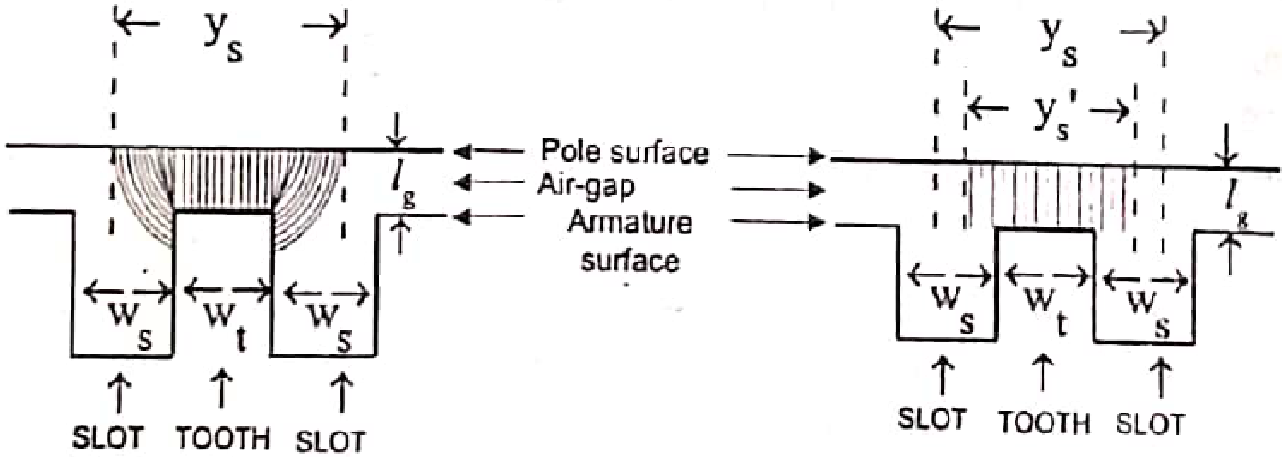

Figure 4. Reluctance of air gap of machines with effect of fringing.

i.e. flux distributed over one slot pitch is given by $\mathbf{W_t + \delta W_s}$.

Effective slot pitch, $\mathbf{y_s' = W_t + \delta W_s}$

By adding and subtracting $\mathbf{W_s}$,

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

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

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

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

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

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

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

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

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

GAP CONTRACTION FACTOR FOR SLOTS Kgs

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

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

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

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

$$= \frac{y_S}{y_S - K_{CS} W_S}$$

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

CARTERS GAP COEFFICIENT FOR SLOTS K_{CS}

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

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

Where W_0 = Slot opening. ($W_0 = W_s$ in open type slot).

EFFECT OF VENTILATING DUCTS IN RELUCTANCE OF AIR GAP

When the length of the armature is higher than the diameter or when the length is greater than 0.1 m, radial ventilating ducts are provided for better cooling of the armature core. The radial ventilating ducts are small gaps of width Wd in between the stacks of armature core. The core is normally divided into stacks of 40 – 80 mm thick, with ventilating ducts of width 10 mm in between two stacks.

The provision of radial ventilating ducts results in contraction of flux in the axial length of the machine is reduced and this results in an increase in the reluctance of air gap. The figure 5 shows the radial ventilating ducts.

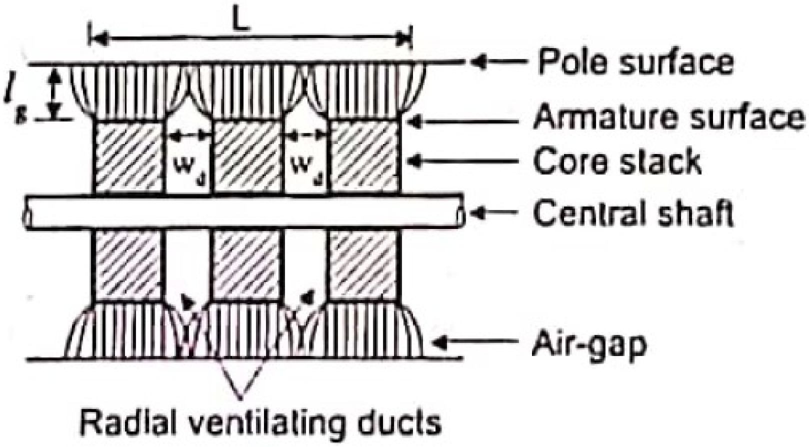

Figure 5. Radial ventilating ducts for cooling.

Axial Length $L' = L - K_{cd}\, n_d\, W_d$

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

n_d = number of ducts

W_d = width of ducts

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

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

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

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

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

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

Where W_d = Width of duct

GAP CONTRACTION FACTOR FOR DUCT Kgd

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

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

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

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

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

TOTAL GAP CONTRACTION FACTOR K_g

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

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

The gap contraction factor

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

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

$$= \frac{L}{L'} \frac{y_S}{y_S'}$$

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

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

TOTAL GAP CONTRACTION FACTOR FOR INDUCTION MOTOR

In Induction motor both the rotor and stator has slots.

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

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

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

K_{gss} = Gap contraction factor for stator slots

K_{gsr} = Gap contraction factor for rotor slots

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

MMF FOR AIR GAP

Non- magnetic materials have a constant value of permeability and so the B-H curve for them is a straight line passing through the origin. MMF per meter path in non- magnetic material

$$at_g = \frac{B}{\mu_0} = \frac{B}{4\pi \times 10^{-7}} = 800{,}000B \text{ in AT/ m}$$

Where, B = Flux density in the non magnetic material

μ_0 = Permeability of non magnetic material

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

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

$\mu = \mu_0 = 4\pi \times 10^{-7}$ H/m - Permeability of air gap

If l_g is the length of air gap, then

mmf per meter for air gap of length l_g in machines with smooth armature

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

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

The reluctance of air gap in machines with open armature slots is higher than with smooth armatures. The mmf required for air gap in machines with open armature slot is K_g times the mmf required for air gap in machines with smooth armature.

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

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

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

Effect of Saliency on the mmf for air gap

In the case of salient pole machines, the length of air gap is not constant over the whole pole pitch. To find the mmf in this case, we c of an consider the length of air gap as an effective gap given by K_{gsal} l_g, where K_{gsal} is the gap contraction factor for salient poles. The figure 6 shows the mmf for air gap influenced by the salient pole.

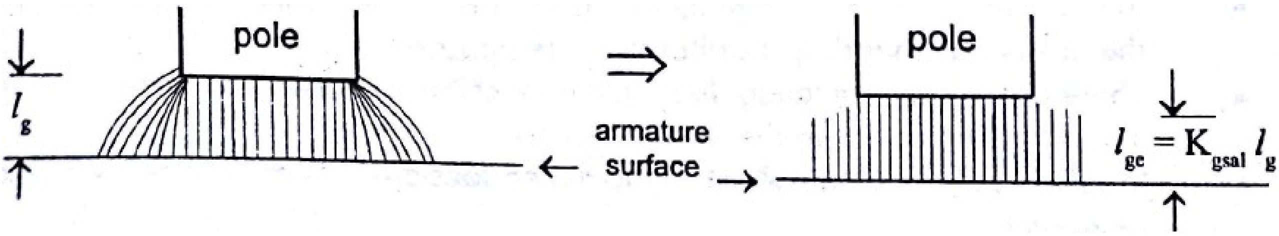

Figure 6. MMF for air gap for salient pole machines.

mmf required for air gap in salient pole machines

$$AT_g = 800{,}000 B_g K_g l_g$$

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

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

Field Form Factor K_f

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

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

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

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

MMF FOR TEETH

The mmf required for teeth depends on area of cross section of the tooth and flux passing through it. The area of cross section depends on dimensions of teeth. Dimension intern depends on the type of slot. The figure 7 shows the different dimensions of teeth.

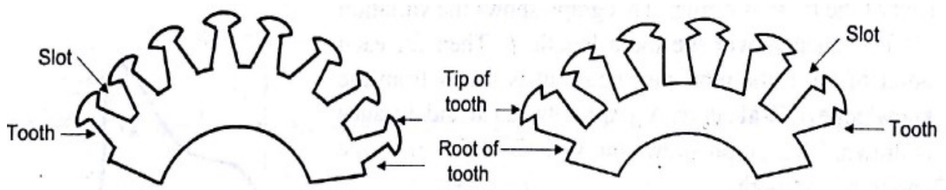

Figure 7. Different dimensions of teeth

Different method for calculation of mmf required for teeth

Graphical Method

Flux density at various sections of the teeth is determined. The flux density at any section of teeth,

Where B_t = Flux density of the teeth corresponding to A_t

ϕ = Flux per pole

n_t = number of teeth under a pole

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

A graph drawn between flux density and the distance from the root of the teeth. This graph shows the variation of flux density over the length of the teeth l_t. Then each point of the teeth mmf / m, at is found from BH curve. The figure 8 show the calculation of mmf for teeth using graphical method.

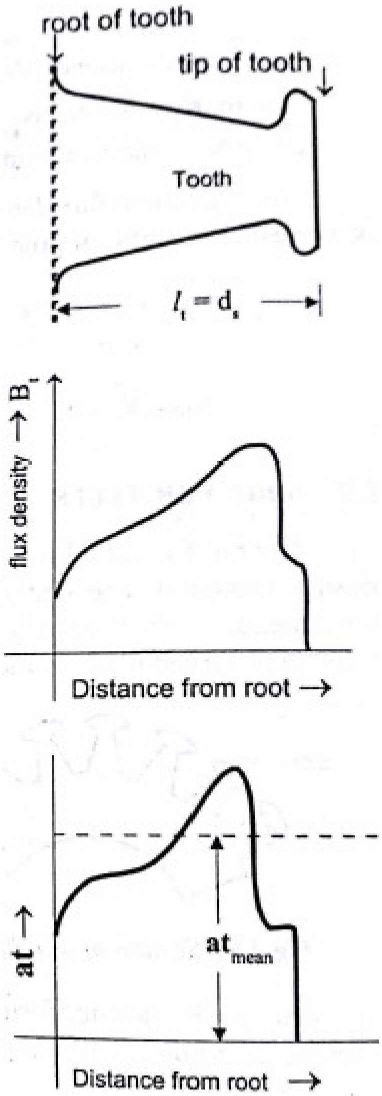

Figure 8. Calculation of mmf for teeth using graphical method

A graph drawn between mmf / m (at) and distance from the root of the teeth.

This graph shows the variation of at over the length of the teeth.

The mean ordinate of this graph gives the equivalent at for the whole teeth.

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

$At_t = at_{mean} \times l_t = at_{mean} \times d_s$

Where l_t = length of teeth

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

AT_t = total mmf for the teeth.

Three Ordinate Method (Simpson's Rule)

This method can be applied to teeth of very sinple form and of a small taper.

It is based on the assumption that the curve relating mmf per meter, at with flux density is a parabola.

Flux density and mmf / m, at are chosen at root, centre and tip of the teeth.

The flux density at any section of teeth,

Where B_t = Flux density of the teeth corresponding to A_t

ϕ = Flux per pole

n_t = number of teeth under a pole

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

Let at_1 = at for the root of teeth

at_2 = at for the centre of the teeth

at_3 = at for the tip of the teeth

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

$At_t = at_{mean} \times l_t = at_{mean} \times d_s$

Where l_t = length of teeth

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

AT_t = total mmf for the teeth

$B_{t1/3}$ Method

This method is applied to teeth of small tapper.

It is smple method

Assumption made : mmf / m, at is obtained for the flux density at a section 1/3 of teeth hight from the narrow ned is at_{mean}.

Calculate flux density at 1/3 height from narrow end using

$$B_t = \frac{\phi}{n_t A_t}$$

Where B_t = Flux density of the teeth corresponding to A_t

ϕ = Flux per pole

n_t = number of teeth under a pole

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

From the B H curve find at for this value of flux density.

This at is denoted as $at_{1/3}$

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

Where l_t = length of teeth

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

AT_t = total mmf for the teeth.

REAL AND APPARENT FLUX DENSITIES

The flux entering an armature from the air gap flows in teeth. If the flux density in the teeth is very high, then the mmf acting on the teeth is high. This mmf will act on the slots also (since the slots are parallel with teeth).Thus some of the fluxes pass through slots. At higher flux densities the flux passing through the slots becomes large and cannot be neglected.

The apparent flux density is defined as,

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

The real flux density is defined as,

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

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

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

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

y_s = slot pitch

L = Length of slot

L_i = Net iron length

A_a = Area of air path of slot

A_i = Area of iron path of teeth

W_t = Width of teeth

μ_0 = Permeability of air

$\mu_0 = 4\pi \times 10^{-7}$ H/m

ϕ_s = Flux over one slot pitch

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

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

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

$$B_{app} = B_{reeal} + B_a K$$

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

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

or

$$B_{real} = B_{app} - \mu_0 at_{real}(K_S - 1)$$

B_a = Flux density in air

$= \mu_o H$

$= \mu_o at_{real}$

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

A_i = Teeth width x net iron length

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

A_a = Total area - Teeth area

$$A_a = Ly_s - L_i W_t$$

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

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

$$\frac{A_a}{A_i} = K_S - 1 \quad where.K_S = \frac{Ly_s}{L_i W_t}$$

MAGNETIC AND ELECTRIC LOADINGS

Work done = Force x distance

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

$$workdone = BIL \times x$$

$$= B_{av} I_Z L \times x$$

$$= B_{av} Lx \times I_Z$$

$$= \phi \times I_Z$$

$$workdone = P\phi \times I_Z Z$$

$P\phi$ = Total magnetic loading

$I_z Z$ = total Electric loading

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

Total Magnetic Loading ($P\phi$)

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

Total Electric Loading ($I_Z Z$)

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

Specific Magnetic Loading (B_{av})

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

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

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

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

$$Polepitch.\tau = \frac{\pi D}{P}$$

Choice of Specific Electrical and Magnetic loadings

Specific magnetic loading:

Following are the factors which influences the performance of the machine.
(i) Iron loss: A high value of flux density in the air gap leads to higher value of flux in the iron parts of the machine which results in increased iron losses and reduced efficiency.

(ii) Voltage: When the machine is designed for higher voltage space occupied by the insulation becomes more thus making the teeth smaller and hence higher flux density in teeth and core.

(iii) Transient short circuit current: A high value of gap density results in decrease in leakage reactance and hence increased value of armature current under short circuit conditions.

(iv) Stability: The maximum power output of a machine under steady state condition is indirectly proportional to synchronous reactance. If higher value of flux density is used it leads to smaller number of turns per phase in armature winding. This results in reduced value of leakage reactance and hence increased value of power and hence increased steady state stability.

(v) Parallel operation: The satisfactory parallel operation of synchronous generators depends on the synchronizing power. Higher the synchronizing power higher will be the ability of the machine to operate in synchronism. The synchronizing power is inversely proportional to the synchronous reactance and hence the machines designed with higher value air gap flux density will have better ability to operate in parallel with other machines.

Specific Electric Loading (ac)

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

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

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

Specific Electric Loading:

Following are the some of the factors which influence the choice of specific electric loadings.
(i) Copper loss: Higher the value of q larger will be the number of armature of conductors which results in higher copper loss. This will result in higher temperature rise and reduction in efficiency.

(ii) Voltage: A higher value of q can be used for low voltage machines since the space required for the insulation will be smaller.

(iii) Synchronous reactance: High value of q leads to higher value of leakage reactance and armature reaction and hence higher value of synchronous reactance. Such machines will have poor voltage regulation, lower value of current under short

circuit condition and low value of steady state stability limit and small value of synchronizing power.

(iv) Stray load losses: With increase of q stray load losses will increase. Values of specific magnetic and specific electric loading can be selected from Design Data Hand Book for salient and non salient pole machines.
Separation of D and L: Inner diameter and gross length of the stator can be calculated from D2L product obtained from the output equation. To separate suitable relations are assumed between D and L depending upon the type of the generator. Salient pole machines: In case of salient pole machines

either round or rectangular pole construction is employed. In these types of machine the diameter of the machine will be quite larger than the axial length.

Problems

1. Calculate the mmf required for the air gap of a machine having core length = 0.32 m including 4 ducts of 10mm each, pole arc 0.19m, slot pitch = 65.4mm, slot opening = 12mm, air gap length = 6mm and useful flux per pole = 25 mwb. Take Carter's coefficient for slot as 0.03
2. Calculate the mmf required for the air gap of a DC machine with an axial length of 20cm (No ducts) and a pole arc of 18 cm. The slot pitch = 27mm, slot opening = 5mm, air gap length = 5mm, flux per pole = 52 mwb. Carter's coefficient for slot = 0.46 and Carters coefficient for duct = 0.65
3. Calculate the mmf required for the air gap of a DC machine with an axial length of 200mm having 2 ducts of 10 mm wide, pole arc of 18 mm. The slot pitch = 65mm, slot opening = 3mm, air gap length = 1mm, flux per pole = 40 mwb. Carter's coefficient for slot = 0.3 and Carters coefficient for duct = 0.25
4. Calculate the mmf required for the air gap of a DC machine having core length = 0.25m, including 4 ducts of 10mm each, pole arc = 0.19mm, slot pitch = 64mm, slot opening = 3mm, air gap length = 0.95mm, flux per pole = 52 mwb. Given carter's coefficient is 0.18 for opening /gap = 1, and is 0.28 opening /gap = 2
5. Estimate the mmf for air gap of a three phase slip ring induction motor from the following data. Stator bore = 637 mm, core length = 250 mm, number of stator slots = 90, slot opening = 2 mm, rotor slot = 120, rotor slot opening = 2 mm, air gap length = 1mm, K_{gd} = 1.07, air gap density = 0.62 wb/m^2.
6. Calculate the mmf required for air gap of a dc machine from the following data. Length = 170 mm, width of duct = 10mm, number of duct = 4, pole are / pole pitch = 0.67, slot pitch = 28 mm, length of air gap = 5mm, average air gap density = 0.71 wb/m^2. Slot opening = 13mm.
7. Determine the air-gap length of a dc machine from the following particulars.

   Gross length of core – 0.14 mm

   Number of ducts – 1 and is 10mm wide,

   Slot pitch – 25mm, slot width – 10mm

   Carter's coefficient for slots and ducts – 0.32

   Gap density at pole centre – 0.7wb/m^2

   mmf for air-gap, AT_g - 3300 AT

   mmf for iron parts of magnetic circuit = 800 AT

8.A 15 KW, 230V, 4 pole dc machine has the following data : armature diameter = 0.25 m, armature core length = 0.125m, length of air-gap at pole centre = 2.5 mm, flux per pole = 11.7 x10^{-3} Wb. (pole arc / pole pitch) = 0.66. Calculate the mmf required for air gap (i) if the armature surface is treated as smooth (ii) if the armature is slotted and the gap contraction factor is 1.18

QUESTION BANK

1. What are the considerations to be made while designing a electrical machines?

1 Cost

2.Durability

3.Compliance with the performance specification and consumer requirement

2. **List some limitation of the design**

1. Magnetic Saturation 2. Temperature rise3. Efficiency4. Standard specifications 5.Insulation 6.Mechanical parts 7.commutation

8.powerfactor 9.Consumer's specification

3. Define total magnetic loading.

The total magnetic load is defined as the total flux around the armature periphery and is given by pϕ Weber's

4. Define total electric loading

The total armature ampere conductors around the armature periphery is known as the total electric loading and is given by IzZ

5. Define specific magnetic loading

The specific magnetic loading is defined as the total flux per unit area over the surface of the armature periphery and is denoted by Bav also known as average flux density.

6. Define specific electric loading

It is defined as the number of armature conductors per meter of armature

periphery at the air gap.

Specific electric loading=total number ampere conductors/armature periphery at air gap.

7. What are the factors that decide the choice of specific magnetic loading?

1. Maximum flux density in iron parts of machine
2. Magnetizing current
3. Core losses

8. What is the factors that decide the choice of specific electric loading.

1. Permissible temperature rise
2. Voltage rating of machine
3. Size of machine
4. Current density.

9. How the design problems of electrical machines can be classified?

1. Electromagnetic design

2. Mechanical design

3. Thermal Design

4. Dielectric design

10. What are the major considerations to evolve a good design of electrical machine?

The major considerations to evolve a good electrical machine are the specific magnetic loading, specific electric loading, temperature rise, efficiency, length of air gap and power factor.

11. Write short notes on standard specifications.

The standard specifications are the specifications issued by the standards

organization of a country. The standard specification serves as guidelines for the manufacturers to produce quality products at economical prices.

The standard specifications for the electrical machines include Ratings, Types of Enclosure, Dimensions of the conductors, Name plate details, performance indices ,permissible temperature rise, permissible loss, efficiency etc.,

12. What is a magnetic circuit?

The magnetic circuit is the path of magnetic flux. The mmf of the circuit creates flux in the path against the reluctance of the path. The equation which relates flux, mmf and the reluctance is given by,

Flux = mmf/reluctance

13. What are the constituents of magnetic circuit in rotating machine?

The various elements in the flux path of the rotating machine are poles, pole shoe, air gap, rotor teeth and rotor core.

14. Write ant two similarities between magnetic and electric circuits.

1. In electric circuit the emf circulates current in a closed path. Similarly in a

magnetic circuit the mmf creates the flux in a closed path.

2. In electric circuit the flow of current is opposed by resistance of the circuit. Similarly in magnetic circuit the creation of flux is opposed by

reluctance of the circuit.

15. Write any two essential differences between magnetic and electric circuit.

1. When the current flows in electric circuit the energy is spent continuously, whereas in magnetic circuit the energy in needed only to create the flux but not to maintain it.

2. Current actually flows in the circuit, whereas the flux does not flow in a

magnetic circuit but is only assumed to flow.

16. What is magnetization curve?

The curve shows the relation between the magnetic field intensity (H) and the flux density (B) of a magnetic material. It is used to estimate the mmf required for the flux path in the magnetic material and it is supplied by the manufacturer of stampings or laminations

17. What is meant by magnetic circuit calculations?

The calculations of reluctance, flux density and mmf for various sections of magnetic circuit are commonly referred as magnetic circuit calculations.

18. How the mmf of a magnetic circuit is determined?

The magnetic circuit split into convenient parts (Sections) which may be

connected in series or parallel. Then the reluctance, flux density and mmf for every section of the magnetic circuit is estimated. The summation of mmf of all sections in series gives the total mmf for the magnetic circuit.

19. Define gap contraction factor for the slots.

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

20. Define gap contraction factor for the ducts.

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

21. Define total gap contraction factor, Kg.

The total gap contraction factor Kg, is defined as the ratio of reluctance of air gap of machines with slotted armature & ducts to the reluctance of air gap in machines with smooth armature and without ducts. The total gap contraction factor is equal to the product of gap contraction factors for slots and ducts.

22. What is carter's coefficient?

The carter's coefficient is a parameter that can be used to estimate the contracted or effective slot pitch in case of armature with open or semi enclosed slots. It is the function of the ratio W_0/l_g where W_0 is slot opening and l_g is air gap length.

23. Write the expression for the gap contraction factor for slots and ducts

Gap contraction factor for slots$K_{gs} = y_s / (y_s - K_{cs}W_s)$

Gap contraction factor for ducts , $K_{gd} = L / (L - K_{cd}n_dw_d)$

24. Write down the formula for computing the mmf for the air gap length.

Mmf for the air gap = $800000BK_gl_g$ in AT

25. Write the expressions for reluctance of air gap in machines with smooth armature and slotted armature.

Reluctance of air gap in machines with smooth armature and without ducts

$= l_g / \mu_0 L y_s$

Reluctance of air gap in machines with open armature slots and ducts

$= l_g / \mu_0 L' y_s'$

26. Define field form factor.

The filed form factor Kf is defined as the ratio of average gap density over the pole pitch to maximum flux density in the air gap.

$K_f = B_{av} / B_g$

$K_f \approx \psi$ = pole arc/pole pitch

27. List the methods used for estimating the mmf for the teeth(tapered teeth)

1. Graphical method

2. Three ordinate method (Simpson's rule)

3. Bt1/3 method

28. What is real flux density and apparent flux density?

The real flux density is due to actual flux through a tooth. The apparent flux density is due to total flux that has to be passed through the tooth. Since some of the flux passes through slot, the real flux density is always less than the apparent flux density

29. Define real flux density.

The real flux density is defined as the ratio of actual flux in the teeth to the area of the teeth

30. Define apparent flux density

The apparent flux density is defined as the ratio of the total flux in the slot pitch to the area of the teeth.

31. State the relation between real and apparent flux density.

Breal = Bapp - μ0

atreal

(K

s – 1)

32. Define leakage coefficient

The leakage coefficient is defined as the ratio of total flux to the useful flux.

33. What is fringing flux?

The bulging of magnetic path at the air gap is called fringing. The fluxes in the bulged portion are called fringing flux.

34. List some leakage fluxes available in the rotating machine.

1. Slot leakage flux
2. Zig-zag leakage flux
3. Harmonic or differential leakage flux
4. Peripheral leakage flux
5. Tooth to leakage flux
6. Skew leakage flux

35. Define permeance.

Permeance is the inverse of reluctance. The reluctance of magnetic path is given by the reluctance $S = l/A\mu$.

36. Define specific permeance of a slot.

Specific permeance of a slot is defined as the paermeance per unit length of slot or depth of field.

37. What is unbalanced magnetic pull?

The unbalanced magnetic pull is the radial force acting on the rotor due to non uniform air gap around the armature periphery.

38. What do you understand by slot pitch?

The slot pitch is defined as the distance between centres of two adjacent slots measured in linear scale.

39. Define slot space factor or slot insulation factor.

The slot space factor is defined as the ratio of conductor area to slot area.

40. List the different types of slots that are used in rotating machines.

1. Parallel sided slots with flat bottom
2. Tapered slots with flat bottom
3. Parallel sided slots with circular bottom
4. Tapered sided slots with circular bottom
5. Circular slot

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SCHOOL OF ELECTRICAL AND ELECTRONICS ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONICS

UNIT – III – Electrical Machine Design – SEEA1601

II. DC MACHINES

Contents- Output equation - Main Dimensions - Choice of number of poles - Armature design - Estimation of number of conductors / turns – Coil armature slots- Conductor dimensions - Slot dimension - Design of field poles and field coil (shunt field) - Design of Commutators and Brushes

Introduction

The size of the DC machine depends on the main or leading dimensions of the machine viz., diameter of the armature D and armature core length L. As the output increases, the main dimensions of the machine D and L also increases. The figure 1 shows armature, yoke and pole arrangement of DC machine

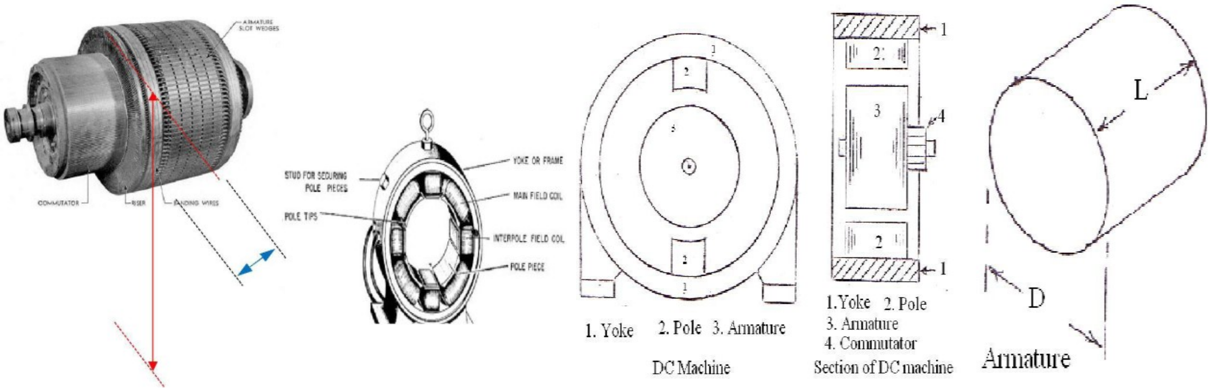

Figure 1. Armature, yoke and pole arrangement of DC machine

Output Equations and Main Dimensions of DC Machine

Note: Output equation relates the output and main dimensions of the machine. Actually, it relates the power developed in the armature and main dimensions.

E : EMF induced or back EMF
I_a : armature current
φ : Average value of flux / pole
Z : Total number of armature conductors
N : Speed in rpm
P : Number of poles
A : number of armature paths or circuits
D : Diameter of the armature
L : Length of the armature core
Power developed in the armature in kW = E Ia x 10-3
$= (\varphi\ Z\ N\ P/60\ A) \times Ia \times 10^{-3}$
$= (P\varphi) \times (I_a\ Z/A) \times N \times 10^{-3}/60$ .... (1)
The term P φ represents the total flux and is called the magnetic loading. Magnetic loading/unit area of the armature surface is called the specific magnetic loading or average value of the flux density in the air gap Bav. That is,
$Bav = P\varphi / \pi\ DL$ Wb/m^2 or tesla denoted by T
Therefore $P\varphi = B_{av}\pi\ DL$ .... (2)

The term (I_a Z/A) represents the total ampere-conductors on the armature and is called the electric loading. Electric loading/unit length of armature periphery is called the specific electric loading ac. That is,
Therefore, $I_a Z/A = ac \pi D$ .... (3)
Substitution of equations 2 and 3 in 1, leads to
$kW = Bav \pi DL \times ac \pi D \times (N/60)\times 10^{-3}$
$= \pi^2 Bav\, ac\, D^2 L\, n_s * 10^{-3}$
$Q = C0\, D^2 L\, n_s$
Where C0 is called the output co-efficient of the DC machine and is equal to $\pi^2 Bav\, ac 10^{-3}$
$Q = C0\, D^2 L\, n_s$
The above equation is called the output equation. The D^2L product represents the size of the machine or volume of iron used. In order that the maximum output is obtained /kg of iron used, D^2L product must be as less as possible. For this, the values of ac and Bav must be high.

Effect of higher value of ac

Note: Since armature current I_a and number of parallel paths A are constants and armature diameter D must be as less as possible or D must be a fixed minimum value, the number of armature conductors increases as $q = I_a Z / A \pi D$ increases.
a. As ac increases, number of conductors increases, resistance increases, I^2R loss increases and therefore the temperature of the machine increases. Temperature is a limiting factor of any equipment or machine.
b. As ac increases, number of conductors increases, conductors/slot increases, quantity of insulation in the slot increases, heat dissipation reduces, temperature increases, losses increases and efficiency of the machine reduces.
c. As ac increases, number of conductors increases, armature ampere-turns per pole ATa / pole = (Ia Z / 2 A P) increases, flux produced by the armature increases, and therefore the effect of armature reaction increases. In order to overcome the effect of armature reaction, field MMF has to be increased. This calls for additional copper and increases the cost and size of the machine.
d. As ac increases, number of conductors and turns increases, reactance voltage proportional to (turns)2 increases. This leads to sparking commutation.

Effect of higher value of B_{av}
a. As B_{av} increases, core loss increases, efficiency reduces.
b. As B_{av} increases, degree of saturation increases, mmf required for the magnetic circuit increases. This calls for additional copper and increases the cost of the machine.
It is clear that there is no advantage gained by selecting higher values of ac and B_{av}. If the values selected are less, then D^2L will be large or the size of the machine will unnecessarily be high. Hence optimum value of q and B_{av} must be selected.
In general ac lies between 15000 and 50000 ampere-conductors/m.
Lesser values are used in low capacity, low speed and high voltage machines. In general B_{av} lies between 0.45 and 0.75 T.

SEPARATION OF D^2L PRODUCT
Knowing the values of kW and N and assuming the values of q and Bav, a value for
$D^2 L = Q/ \pi^2 Bav\, ac 10^{-3} n_s$ can be calculated.

Since the above expression has two unknowns namely D and L, another expression relating D and L must be known to find out the values of D and L.

Usually a value for the ratio armature core length L to pole pitch is assumed to separate D^2L product. The pole pitch τ refers to the circumferential distance corresponding one pole at diameter D. In practice L /τ lies between 0.55 and 1.1.
Therefore $L = (0.55 \text{ to } 1.1)\ \tau$
$= (0.55 \text{ to } 1.1)\ \pi D / P$
If $L/\tau = 1.0$ and $P = 4$, then $L = 1.0 \times \pi D / P$
$= 1.0 \times \pi D / 4 = 0.785D$.
Therefore $D^2 \times 0.785\ D = 0.1$ or $D = 0.5$m. Thus $L = 0.785 \times 0.5 = 0.395$ m.
Note: The D^2 L product can also be separated by assuming a value for the peripheral velocity of the armature.

Selection of number of poles

As the armature current increases, cross sectional area of the conductor and hence the eddy current loss in the conductor increases. In order to reduce the eddy current loss in the conductor, cross-sectional area of the conductor must be made less or the current / path must be restricted.
For a normal design, current / parallel path should not be more than about 200A. However, often, under enhanced cooling conditions, a current / path of more than 200A is also being used. By selecting a suitable number of paths for the machine, current / path can be restricted and the number of poles for the machine can be decided. While selecting the number of poles, the following conditions must also be considered as far as possible. In order to decide what number of poles (more or less) is to be used, let the different factors affecting the choice of number of poles be discussed based on the use of more number of poles.
Frequency

Weight of the iron used for the yoke

Weight of iron used for the armature core (from the core loss point of view)

Weight of overhang copper

Armature reaction

Overall diameter

Length of the commutator

Flash over

Labour charges

Frequency
As the number of poles increases, frequency of the induced EMF increases core loss in the armature increases and therefore efficiency of the machine decreases.

Weight of the iron used for the yoke
Since the flux carried by the yoke is approximately $\varphi/2$ and the total flux $\varphi T = p\varphi$ is a constant for a given machine, flux density in the yoke
It is clear that is $\propto 1/P$
As is also almost constant for a given iron. Thus, as the number of poles increases,
And hence the weight of iron used for the yoke reduces.

Weight of iron used for the armature core (from the core loss point of view)
Since the flux carried by the armature core is φ /2, eddy current loss in the armature core

is independent of the number of poles.

Weight of overhang copper: For a given active length of the coil, overhang $\propto$ pole pitch goes on reducing as the number of poles increases. As the overhang length reduces, the weight of the inactive copper used at the overhang also reduces.

Overall diameter

When the number of poles is less, ATa / pole and hence the flux, produced by the armature is more. This reduces the useful flux in the air gap. In order to maintain a constant value of air gap flux, flux produced by the field or the field ampere-turns must be increased. This calls for more field coil turns and size of the coil defined by the depth of the coil df and height of the coil hf increases. In order that the temperature rise of the coil is not more, depth of the field coil is generally restricted. Therefore, height of the field coil increases as the size of the field coil or the number of turns of the coil increases. As the pole height, is proportional to the field coil height, height of the pole and hence the overall diameter of the machine increases with the increase in height of the field coil. Obviously as the number of poles increases, height of the pole and hence the overall diameter of the machine decreases.

The armature winding can broadly be classified as concentrated and distributed winding.In case of a concentrated winding, all the conductors / pole is housed in one slot. Since the conductors / slot is more, quantity of insulation in the slot is more, heat dissipation is less, temperature rise is more and the efficiency of operation will be less. Also emf induced in the armature conductors will not be sinusoidal. Therefore

a. design calculations become complicated (because of the complicated expression of non-sinusoidal wave).

b. Core loss increases (because of the fundamental and harmonic components of the non-sinusoidal wave) and efficiency reduces.

c. Communication interference may occur (because of the higher frequency components of the non-sinusoidal wave).

Hence no concentrated winding is used in practice for a DC machine armature.

In a distributed winding (used to overcome the disadvantages of the concentrated winding), conductors / pole is distributed in more number of slots. The distributed winding can be classified as single layer winding and double layer winding.In a single layer winding, there will be only one coil side in the slot having any number of conductors, odd or even integer depending on the number of turns of the coil. In a double layer winding, there will be 2 or multiple of 2 coil sides in the slot arranged in two layers. Obviously conductors / slot in a double layer winding must be an even integer. The figure 2 shows the single layer and double layer winding.

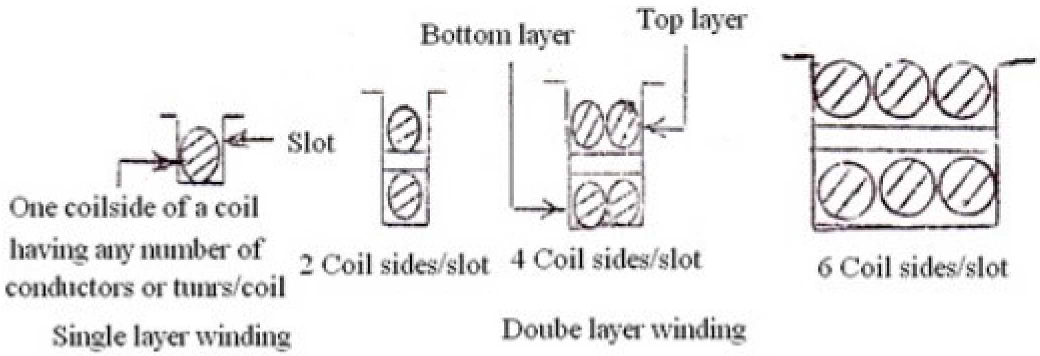

Figure 2. Single layer and double layer winding.

Since for a given number of conductors, poles and slots, a single layer winding calls for less number of coils of more number of turns, reactance voltage proportional to (turn)2 is high. This decreases the quality of commutation or leads to sparking commutation. Hence a single layer winding is not generally used in DC machines. However, it is much used in alternators and induction motors where there is no commutation involved.

Since a double layer winding calls for more, number of coils of less numbers of turns/coil, reactance voltage proportional to (turn)2 is less and the quality of commutation is good. Hence double layer windings are much used in DC machines.

Unless otherwise specified all DC machines are assumed to be having a double layer winding.

A double layer winding can further be classified as simplex or multiplex and lap or wave winding. In order to decide what number of slots (more or less) is to be used, the following merits and demerits are considered.

NUMBER OF ARMATURE SLOTS

1. As the number of slots increases, cost of punching the slot increases, number of coils increases and hence the cost of the machine increases.

2.As the number of slots increases, slot pitch

λs = (slot width bs + tooth width bt)

= πD/ number of slots S

decreases and hence the tooth width reduces. This makes the tooth mechanically weak, increases the flux density in the tooth and the core loss in the tooth. The figure 3 shows the slot dimensions. Therefore, efficiency of the machine decreases.

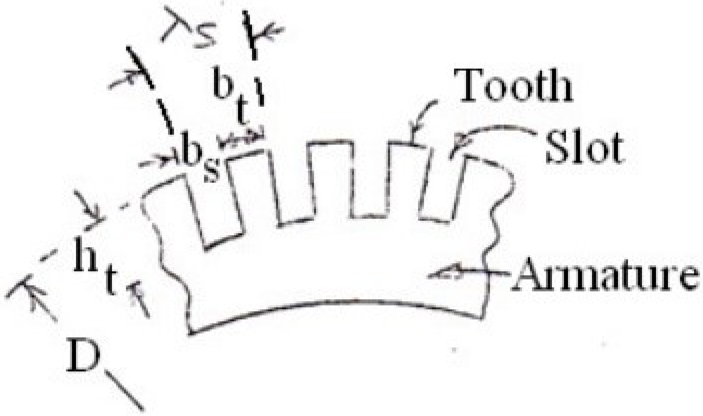

Figure 3. Slot dimensions

If the slots are less in number, then the cost of punching & number of coils decreases, slot pitch increases, tooth becomes mechanically strong and efficiency increases, quantity of insulation in the slot increases, heat dissipation reduces, temperature increases and hence the efficiency decreases. It is clear that not much advantage is gained by the use of either too a less or more, number of slots. As a preliminary value, the number of slots can be selected by considering the slot pitch. The slot pitch can assume to be between (2.5 and 3.5) cm. (This range is applicable to only to medium capacity machines and it can be more or less for other capacity machines).

The selection of the number of slots must also be based on the type of winding used, quality of commutation, flux pulsation etc. When the number of slot per pole is a whole number, the number slots embraced by each pole will be the same for all positions of armature. However, the number teeth per pole will not be same.

This causes a variation in reluctance of the air gap and the flux in the air gap will pulsate. Pulsations of the flux in the air gap produce iron losses in the pole shoe and give rise to magnetic noises. On the other hand, when the slots per pole is equal to a whole number plus half the reluctance of the flux path per pole pair remains constant for all positions of the armature, and there will be no pulsations or oscillations of the flux in the air gap.

To avoid pulsations and oscillations of the flux in the air gap, the number of slots per pole should be a whole number plus half. When this is not possible or advisable for other reasons, the number of slots per pole arc should be an integer. The figure 4 shows the flux distributed.

Figure 4. Flux distribution in Pole shoe

Number of teeth/pole shoe = 5 and flux passes through 5 teeth.

The reluctance of the air gap is inversely proportional to the area corresponding to 5 teeth.

Number of teeth/pole shoe = 5 and flux passes through 6 teeth when the armature is moved half-tooth pitch to the right. The reluctance of the air gap is inversely proportional to the area corresponding to 6 teeth. The reluctance in this case is less and the flux is more compared to the former case. Therefore, the flux pulsates i.e. Varies in magnitude.

Number of teeth/pole shoe = (5+ 0.5) and flux passes through 6 teeth. The reluctance of the air gap is inversely proportional to the area corresponding to 6 teeth.

Number of teeth/pole shoe = (5+0.5) and flux passes through 6 teeth when the armature is moved half tooth pitch to the right. The reluctance of the air gap is inversely proportional 6 teeth as before. The reluctance and the flux in both the cases remains the same in all positions of the armature. However, the reluctance and the flux under the tips of the pole are not the same for all the positions of armature. Therefore, when the armature rotates the flux under the pole oscillates between the pole tips. This produces ripple in the voltage induced in the conductors moving under poles. The flux pulsation under inter pole causes the sparking. A small tooth pitch helps to reduce the effect of armature slots upon the inter poles.

To obtain good commutation, the flux density in the air gap must decrease gradually from maximum value under the center of the pole to zero on the center line between two poles, and the flux densities near the neutral point must be low. A field form that drops off rapidly from maximum value to zero not only leads to commutation difficulties but may also give rise to noises in machines with slotted armatures. In order to achieve good commutation, the pole shoe is designed to cover only certain percentage of the pole pitch. The circumferential distance covered by the pole shoe on the armature surface is called the pole arc. The ratio of the pole arc to pole pitch is called per unit embrace or enclosure. That is, per unit enclosure

$$\psi = \frac{\text{Pole arc}}{\text{Pole pitch}} \leq 1.0.$$

In practice ψ lies between 0.6 and 0.7.

In general, the slots between pole tips of two adjacent pole tips i.e. $(1-\psi)\frac{S}{P}$ should be at least 3, or

$$(1-\psi)\frac{S}{P} \geq 3$$

If Ψ=0.66,the number of slots per pole,

$$\frac{S}{P} \geq \frac{3}{(1-0.66)} \geq 8.82 \text{ or say } 9$$

Design of commutator and brushes

The Commutator is an assembly of Commutator segments or bars tapered in section. The segments made of hard drawn copper are insulated from each other by mica or micanite, the usual thickness of which is about 0.8 mm. The number of commutator segments is equal to the number of active armature coils.

The diameter of the commutator will generally be about (60 to 80) % of the armature diameter. Lesser values are used for high-capacity machines and higher values for low-capacity machines.

Higher values of commutator peripheral velocity are to be avoided as it leads to lesser commutation time dt, increased reactance voltage and sparking commutation.

The commutator peripheral velocity $v_c = \pi$ DC N / 60 should not as for as possible be more than about 15 m/s. (Peripheral velocity of 30 m/s is also being used in practice but should be avoided whenever possible.)

The commutator segment pitch τC = (outside width of one segment + mica insulation between segments) = π DC / Number of segments should not be less than 4 mm. (This minimum segment pitch is due to 3.2 mm of copper + 0.8 mm of mica insulation between segments.) The outer surface width of commutator segment lies between 4 and 20 mm in practice.

The axial length of the commutator depends on the space required

1)by the brushes with brush boxes

2)for the staggering of brushes
3) for the margin between the end of commutator and brush and
4) for the margin between the brush and riser and width of riser.

If there are nb brushes / brush arm or spindle or holder, placed one beside the other on the commutator surface, then the length of the commutator LC = (width of the brush wb + brush box thickness 0.5 cm) number of brushes / spindle + end clearance 2 to 4 cm + clearance for risers 2 to 4 cm + clearance for staggering of brushes 2 to 4 cm.

If the length of the commutator (as calculated from the above expression) leads to small dissipating surface π DC LC, then the commutator length must be increased so that the temperature rise of the commutator does not exceed a permissible value say 55°C.

The temperature rise of the commutator can be calculated by using the following empirical formula.

$$\theta^{\circ}C = \frac{120 \quad \text{watt loss / cm}^2 \text{ of dissipating surface} \quad D_c \; L_c}{1 + 0.1 \; v_c}$$

The different losses that are responsible for the temperature rise of the commutator are
a) Brush contact loss and
b) Brush frictional loss.
Brush contact loss = voltage drop / brush set × Ia
The voltage drop / brush set depend on the brush material – Carbon, graphite, electro graphite or metalized graphite. The voltage drop / brush set can be taken as 2.0 V for carbon brushes. Brush frictional loss (due to all the brush arms)

= frictional torque in Nm × angular velocity

= frictional force in Newton x distance in meter × 2 π N/60

= 9.81 μPbAball ×DC /2×2π N/60
= 9.81μPbAball vC
whereμ = coefficient of friction and depends on the brush material. Lies between 0.22 and 0.27 for carbon brushes
Pb = Brush pressure in kg / m^2 and lies between 1000 and 1500 Aball = Area of the brushes of all the brush arms in m^2
= Ab × number of brush arms

= Ab × number of poles in case of lap winding

= Ab × 2 or P in case of wave winding
Ab = Cross-sectional area of the brush / brush arm

Brush Details

Since the brushes of each brush arm collets the current from two parallel paths, current collected by each brush arm is 2 I/2 I_a and the cross-sectional area of the brush or brush arm or holder or spindle Ab. The current density δp depends on the brush material and can be assumed between 5.5 and 6.5 A/cm^2 for carbon.

In order to ensure a continuous supply of power and cost of replacement of damaged or worn out brushes is cheaper, a number of subdivided brushes are used instead of one single brush. Thus if

i) tb is the thickness of the brush
ii) wb is the width of the brush and
iii) nb is the number of sub divided brushes
then Ab = tb wb nb

As the number of adjacent coils of the same or different slots that are simultaneously undergoing commutation increases, the brush width and time of commutation also increases at the same rate and therefore the reactance voltage (the basic cause of sparking commutation) becomes independent of brush width.

With only one coil undergoing commutation and width of the brush equal to one segment width, the reactance voltage and hence the sparking increases as the slot width decreases. Hence the brush width is made to cover more than one segment. If the brush is too wide, then those coils which are away from the commutating pole zone or coils not coming under the influence of inter pole flux and undergoing commutation leads to sparking commutation.

Hence brush width greater than the commutating zone width is not advisable under any circumstances. Since the commutating pole zone lies between (9 and 15) % of the pole pitch, 15% of the commutator circumference can be considered as the maximum width of the brush.

It has been found that the brush width should not be more than 5 segments in machines less than 50 kW and 4 segments in machines more than 50 kW.

The number of brushes / spindle can be found out by assuming a standard brush width or a maximum current / sub divided brush. Standard brush width can be 1.6, 2.2 or 3.2 cm Current/subdivided brush should not be more than 70A.

Problems

1. Determine the main dimensions, number of poles and the length of airgap of a 600kw, 500v, 900 rpm generator. Assume average gap density as 0.6 wb/m2 and ampere conductors per metre as 35,000. The ratio of pole arc to pole pitch is 0.75 and the efficiency is 91%. The following are the design constraints: peripheral speed 40 m/s, frequency of flux reversals 50 HZ, current per brush arm 400 A and armature mmf per pole 7500A. The mmf required for air gap is 50% of armature mmf per pole and gap contraction factor is 1.15.

2. The commutator of a 50 rpm machine is 0.3m in diameter. The brush friction loss is 100 w. If at full load the commutator loss is twice the brush friction loss, calculate the length of commutator which will give a final temperature rise of 40□C. Assume that a commutator of this diameter and 75mm in length running at 700 rpm gives a temperature length running at 700 rpm gives a temperature rise of 40□C with a commutator loss of 300W.

3.Find the main dimensions and the number of poles of a 37 kW, 230V, 1400 r.p.m. shunt motor so that a square pole face is obtained. The average gap density is 0.5 Wb/m2 and the ampere conductors per meter are 22,000. The ratio of the pole arc to pole pitch is 0.7 and the full load efficiency is 90 percent.

4. 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 meter 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 is 0.75.

5. A 4 pole, 400 V, 960 rpm, shunt motor has an armature diameter of 0.3m in diameter and 0.2m in length. The commutator diameter is 0.22m. Give full details of a suitable winding including the number of slots, number of commutator segments and number of conductors in each slots for an average flux density of approximately 0.55 wb/m2 in the air gap.

6.A 5 KW, 250V, 4 pole, 1500 rpm dc shunt generator is designed to have a square pole face. The average magnetic flux density in the air gap is 0.42 Web/m2 and ampere conductors per metre = 15,000.Compute the main dimensions of the machine. Assume full load efficiency = 87%. The ratio of pole to pole pitch = 0.66.

7.A 4 pole, 400V, 960 rpm, shunt motor has an armature of 0.3 diameter and 0.2 m in length. The commutator diameter is 0.22 m. Give full details of a suitable winding including the number of slots, number of commutator segments and number of conductors in each slot for an average flux density of approximately 0.55 Wb/m2 in the air-gap.

8. Design a suitable commutator for a 350 KW, 600 rpm, 440 V, 6 pole DC generator having an armature diameter of 0.75 m. The number of coils is 288. Assume suitable values wherever necessary.

9. Calculate the main dimensions of a 200 KW, 250 V, 6 pole 1000 rpm generator. The maximum value of the flux density in the air gap is 0.87Wb/m2 and the ampere conductors per metre of armature periphery are 31000. The ratio of pole arc to pole pitch is equal to 0.67 and the efficiency is 0.91. Assume the ratio of length of core to pole pitch = 0.75.

10. Find the following details for 10 HP. 1450 rpm, 220V d.c shunt motor?(i) Output coefficient(ii) Diameter of armature

11.Find the main dimensions of a 200 kW, 250 volts, 6 pole, 1000, rpm DC generator. The maximum value of flux density in the air gap is 0.87 wb/m2 and the ampere conductors per meter length of armature periphery are 31000; The ratio of pole arc to pole pitch is 0.67 and the efficiency is 91 percent. Assume that the ratio of length of core to pole pitch = 0.75.

12.Design a suitable commutator for a 350 KW, 700 rpm, 440V, 6 pole dc generator having an armature diameter of 0. 75m. The number of coil is 288, Dc=0.62D. Assume suitable values wherever necessary.

QUESTION BANK

UNIT II

1. What is the relation between the power developed in armature and the output in the dc machine?

Output for generators = $P_a = P/\eta$

Output for motors = $P_a = P$

2. Write the expression for the power developed an the armature of dc machine in terms of the maximum gap density.

Power developed by armature $P_a = C_0 D^2 L n$
Where $C_0 = \pi^2 B_{av}\, ac * 10^{-3}$
B_{av}-specific magnetic loading in wb/m^2
ac-specific electric loading in ampere conductors per metre
D-armature diameter or stator bore in m
L-stator core length in m
n-speed in rps

3. What is the range of specific magnetic loading in a dc machine?

The usual range of specific magnetic loading in dc machine is 0.4 to 0.8 wb/m2

4. What are the factors to be considered for the choice of specific magnetic loading?

1. Flux density in the teeth
2. Frequency of flux reversals
3. Size of the machine

5. What is the range of specific electric loading in dc machine?

The usual range of specific electric loading in dc machine is 15000 to 50000 amp.cond/m

6. What are the factors to be considered for the choice of specific electric loading?

1. Temperature rise 2. Speed of the machine 3. Size of the machine

4. voltage 5. Armature reaction 6. Commutation

7. What is the purpose of constructing the pole body by laminated sheets?

The laminated pole offers the homogeneous construction, (Because while casting internal blow holes may develop and while forging internal cracks may develop) Also the laminated poles offers the flexibility of increasing the length by keeping the diameter fixed, in order to increase the power output (or capacity) of the machine.

8. What are the factors to be considered for the selection of number of poles in dc machine?

1. Frequency

2. Weight of iron parts

3. Weight of copper parts

4. Length of commutator

5. Labour charges

6. Flash over and distortion of filed form.

9. List the advantages of large number of poles

The large number of poles results in reduction of the following

1. Weight of armature core and yoke

2. Cost of armature and field conductors

3. Overall length and diameter

4. Length of Commutator

5. Distortion of field form under load condition

10. List the disadvantages of large number of poles

The large number of poles results in increase of the following

1. Frequency of flux reversals

2. Labour charges

3. Possibility of lash over between brush arms.

11. Why square pole is preferred?

If the cross section of the pole body is square then the length of the mean turn of

field winding is minimum. Hence to reduce the copper requirement a square cross section is preferred for the poles of the dc machines.

12. What is square pole and square pole face?

In square pole, the width of the pole body is made equal to the length of the

armature. In square pole face, the pole arc is made equal to the length of the

armature.

13. Mention guiding factors for the selection of number of poles

1. The frequency of flux reversals should lie between 25 to 50 Hz.

2. The value of current per parallel path is limited to 200 A. thus the current

per brush arm should not be more than 400A

3. The armature mmf should not be too large. The mmf per pole should be in

the range 5000 to 12500 AT.

4. Choose the largest value of poles which satisfies the above three conditions.

14. What are the advantages of large length of air gap in dc machine?

In dc machines a larger value of air gap length results in lesser noise, better cooling, reduced pole face losses, reduced circulating currents, less distortion of field form and lesser armature reaction.

15. What are the factors to be considered for estimating the length of air gap in dc machine?

The factors to be considered for estimating the length of air gap are armature reaction, cooling, iron losses, distortion of filed form and noise.

16. Mention the factors governing the choice of number of armature slots in a dc machine.

The factors governing the choice of number of armature slots are,

Slot pitch

Slot loading

Flux pulsations

Commutation

Suitability for winding

17. What is the purpose of slot insulation?

The conductors are placed on the slots in the armature. When the armature rotates the insulation the insulation of the conductors may damage due to vibrations. This may lead to a short circuit with armature core if the slots are not insulated.

18. What are the factors to be considered for deciding the slot dimensions?

1. Flux density in the tooth

2. Flux pulsations

3. Eddy current loss in conductors

4. Reactance voltage

5. Fabrication difficulties

19. What factor decides the minimum number of armature coils?

The maximum voltage between adjacent commutator segments decides the minimum number of coils.

20. Mention the two types of winding used in the dc machines.

1.Simplex

a. simplex Lap winding

b. simplex Wave winding

2.Multiplex

21. What is meant by equalizer connections?

In lap winding, due to the difference in the induced emf in various parallel paths, there may be circulating currents in brushes and winding. The connections that are made to equalize the difference in induced emf and to avoid circulating currents through brushes are called equalizer connections.

22. What is the length of mean turn of filed coil?

Length of mean turn $L_{mt} = 2(L_p + b_p + 2d_f)$

L_{mt}-length of mean turn of field coil

L_P- length of pole

b_p-width of the pole

d_f –depth of the winding

23. Mention the factors to be considered for the design of shunt field coil?

1. MMF per pole and flux density
2. Loss dissipated from the surface of field coil
3. Resistance of the field coil
4. Current density in the field conductors

24. Define copper space factor of the coil.

The copper space factor of a coil is defined as the ratio of conductor area and the area of the cross section of the coil.

Copper space factor = Conductor area/Area of cross section of the coil

Conductor area = Number of turns x area of cross section of conductor

25. How the ampere turns of the series field coil is estimated?

In compound machines the ampere turns to be developed by the series field coil is estimated as 15 to 25% of full load armature mmf.

In series machines the ampere turns to be developed by the series field is

estimated as 1.15 to 1.25 times the full load armature mmf.

26. What is meant by commutation?

The process of current reversal in a coil is called commutation.

27. Discuss the parameters governing the length of commutator.

The length of the commutator depends upon the space required by the brushes and upon the surface required to dissipate the heat generated by the commutator losses.

$L_C=n_b(w_b+c_b)+C1+C2$

L_C-length of the commutator

n_b-number of brushes per spindle

w_b-width of each brush

c_b-clearance between the brushes

C1-clearance allowed for staggering the brushes

C2-clearance for allowing the end play

28. What are the factors that influence the choice of commutator diameter?

1. The peripheral speed

2. The peripheral voltage gradient should be limited to 3 V/mm

3. Number of coils in the armature.

29. What is the purpose of mica strip between two adjacent commutator segments?

Mica is placed in between two commutator segments in order to insulate the segments from each other.

30. What are the factors to be considered for the design of commutator?

1. Peripheral speed

2. Voltage between adjacent segments

3. Number of coils in the armature

4. The number of brushes

5. Commutator losses.

31. What type of copper is used for commutator segments?

The commutator segments are made of hard drawn copper or silver copper (0.05% silver)

32. What is the need for brushes in dc machine?

The brushes are used in dc machines to collect or draw current from the rotating armature.

33. What are the materials used for brushes in dc machines?

1. Natural graphite

2. Electro graphite

3. Hard carbon

4. Metal graphite

34. How to design the number of brushes for a dc machine?

The numbers of brush locations are decided by the type of winding. In lap winding the number of brush locations is equal to number of poles and in wave winding it is always two.

In each location there may be more than one brush mounted on a spindle, whenever the current per brush location is more than 70A. Hence the number of brushes in a spindle is selected such that each brush does not carry more than 70A.

35. What are the effects of armature reaction?

The various effect of armature reaction are reduction in induced emf, increase in iron loss, delayed commutation, sparking and ring firing.

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS

UNIT – III – Electrical Machine Design – SEEA1601

III. TRANSFORMERS

Contents – Output equation - Design of core and winding of single- phase shell and core type transformer and three phase transformers -Temperature rise in transformers - Design of tank, cooling tubes and Ducts

Introduction

A transformer is defined as a passive electrical device that transfers electrical energy from one circuit to another through the process of electromagnetic induction. It is most commonly used to increase ('step up') or decrease ('step down') voltage levels between circuits. The classification of transformer is show in figure1.

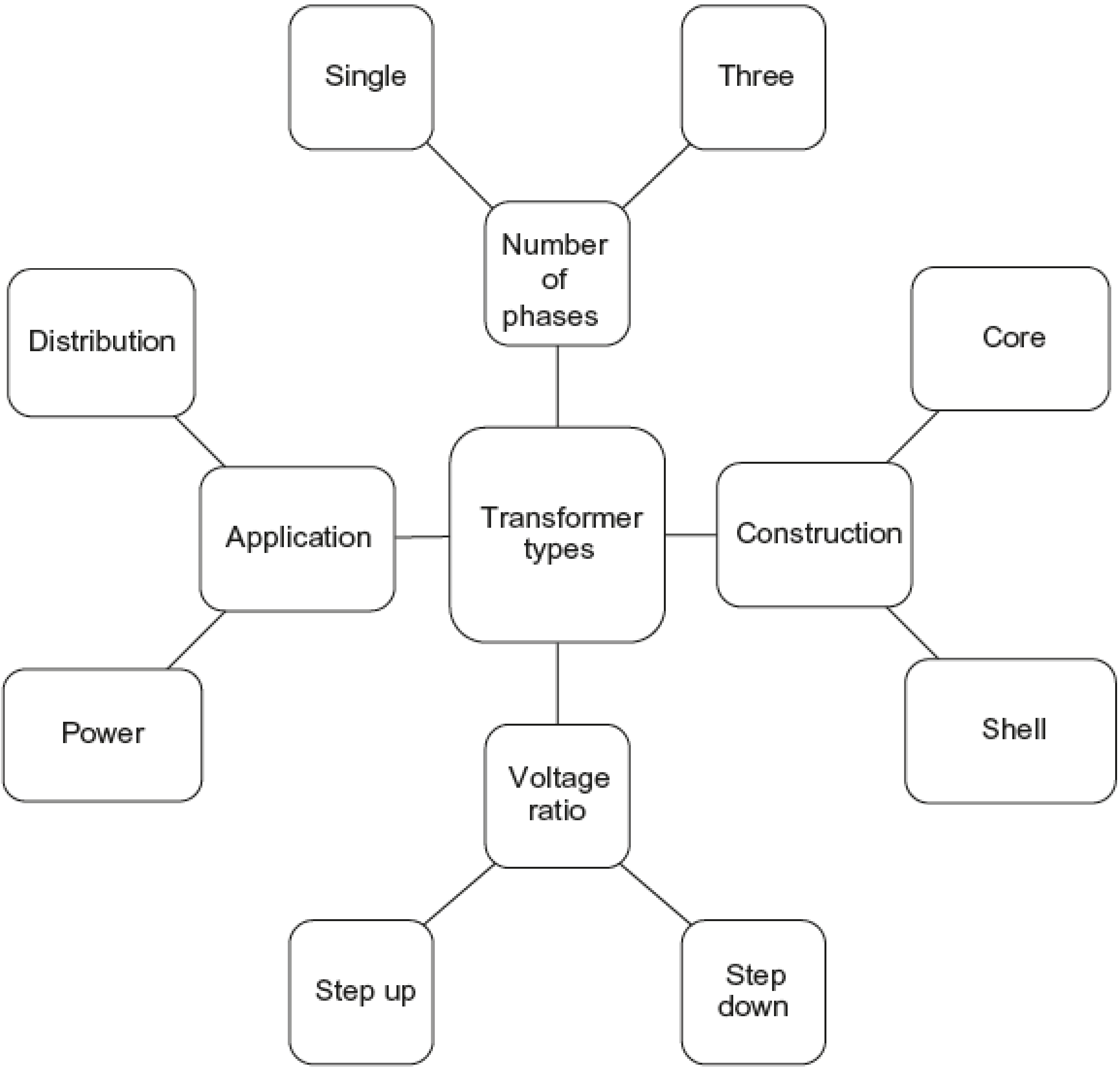


Figure 1. Classification of transformer

OUTPUT EQUATION OF SINGLE- PHASE TRANSFORMER

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

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

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

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

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

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

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

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

The current density δ is same in both the windings.

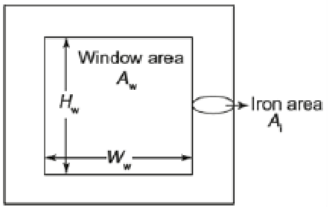
$\therefore$ Current density, $\delta = \frac{I_P}{a_P} = \frac{I_S}{a_S}$

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

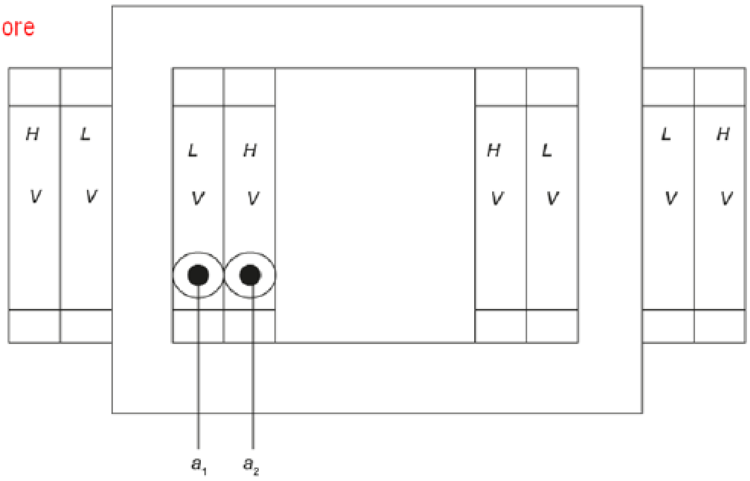
Area of cross section of secondary conductor, $a_S = \frac{I_S}{\delta}$

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

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



Cross section of single phase core type transformer



Winding arrangement of single phase core type transformer

Figure 2. Cross section and winding arrangement of single- phase core type transformer

The figure 2 shows the cross section and winding arrangement of single- phase core type transformer.

Total copper area in window A_c = Copper area in Primary winding + Copper area in secondary winding

= (Number of turns in primary x Area of cress section of primary conductor) + (Number of turns in secondary x Area of cress section of secondary conductor)

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

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

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

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

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

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

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

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

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

Multiple and divided by E_p,

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

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

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

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

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

is called output equation of single phase transformer

OUTPUT EQUATION OF THREE- PHASE TRANSFORMER

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

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

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

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

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

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

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

Conductor area in window, $A_c = K_w A_w$ ---- (1)

The current density δ is same in both the windings.

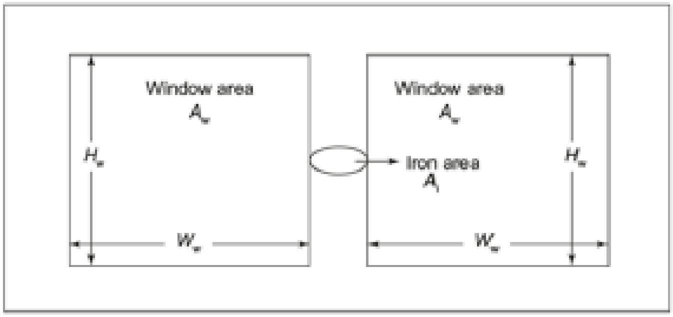
$\therefore$ Current density, $\delta = \frac{I_P}{a_P} = \frac{I_S}{a_S}$

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

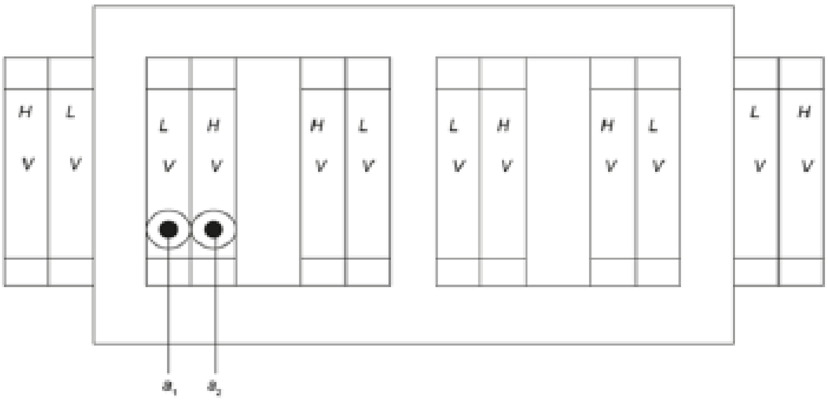
Area of cross section of secondary conductor, $a_S = \frac{I_S}{\delta}$

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

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



Cross section of three phase core type transformer



Winding arrangement of three phase core type transformer

Figure 3. Cross section and winding arrangement for three phase transformer.

The figure 3 shows the cross section and winding arrangement for three phase transformer.

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

$$= (2 \times T_P \times a_p) + (2 \times T_s \times a_s)$$

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

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

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

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

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

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

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

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

Multiple and divided by E_P,

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

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

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

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

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

is called output equation of three phase transformer

DESIGN OF CORES

The figure 4 shows the different type of core s of transformer.

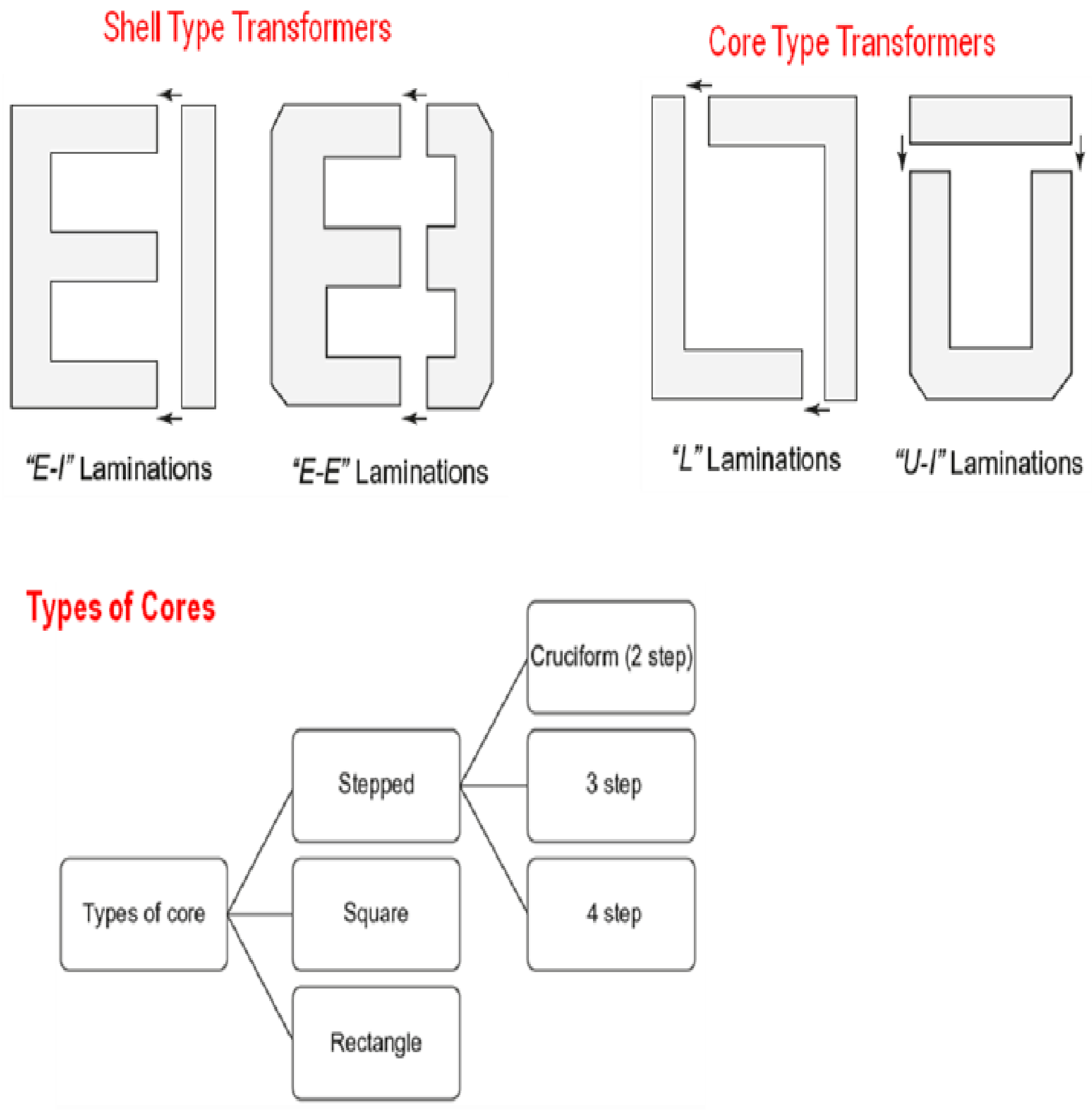


Figure 4. Different types of cores available for transformer

For core type transformers, the cross section may rectangular, square or stepped.
When circular coils are used for distribution and power transformer. The square and stepped cores are used. For shell type transformer, the cross section may be rectangular. Coils are also rectangular in shape.

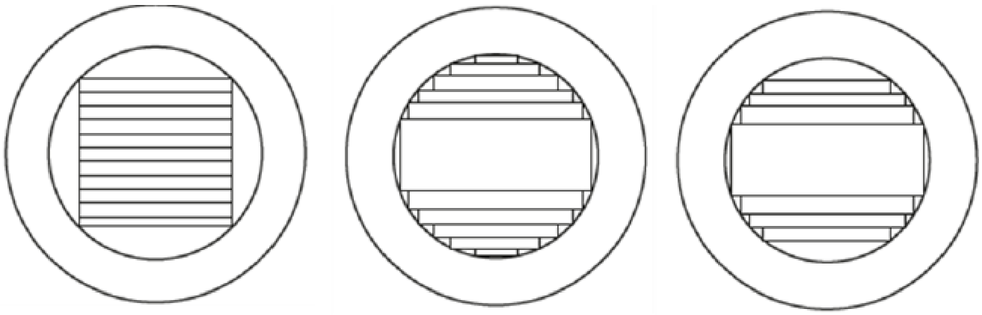


Figure 5. Cross section of square, 4stepped core and multi stepped core

The figure 5shows the cross section of square, 4stepped core and multi stepped core.

Merits and demerits of Stepped core

In square cores, the diameter of the circumscribing circle is larger than the diameter of stepped cores of same area of cross section.
Stepped cores are used the length of mean turn of winding is reduced. Results in reduction of cost of copper and hence copper loss.
However, with large number of steps, a large number of different sizes of laminations have to used. This results in higher labour charges for assembling different types of laminations.

OPTIMUM DESIGN

The design involves,

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

The ratio, Flux$_m$ / AT is high value, If Flux m is large, it requires large cross section, results in higher volume, increased weight, increased cost of iron, higher iron loss. If decreased in Flux$_m$ / AT, Number of turns reduced, results in volume reduced, weight reduced, cost of copper reduced, copper loss reduced.

TYPES OF WINDING

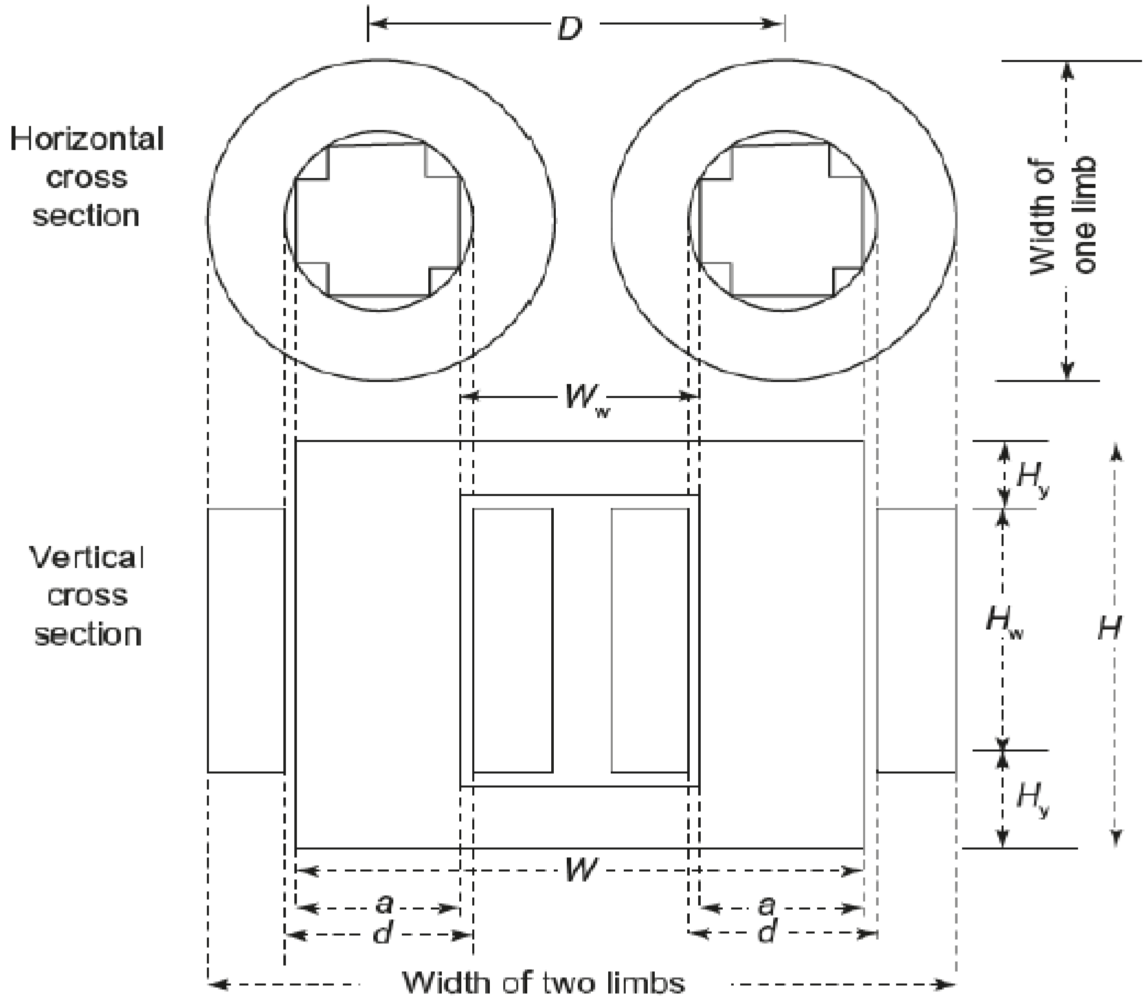
1.Cylindrical winding 2. Helical winding 3. Double helical winding 4. Multi- layer helical winding 5. Cross over winding6. Disc & continuous disc winding

FACTORS TO BE CONSIDERED TO CHOOSE TYPE OF WINDING FOR A CORE TYPE TRANSFORMER

1. Current density 2. Short circuit ratio 3. Temp rise 4. Surge voltage5. Impedance 6. Transport facilities

Overall Dimensions of Transformer

Single phase Core type Transformer



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

$$H = H_w + 2H_y$$

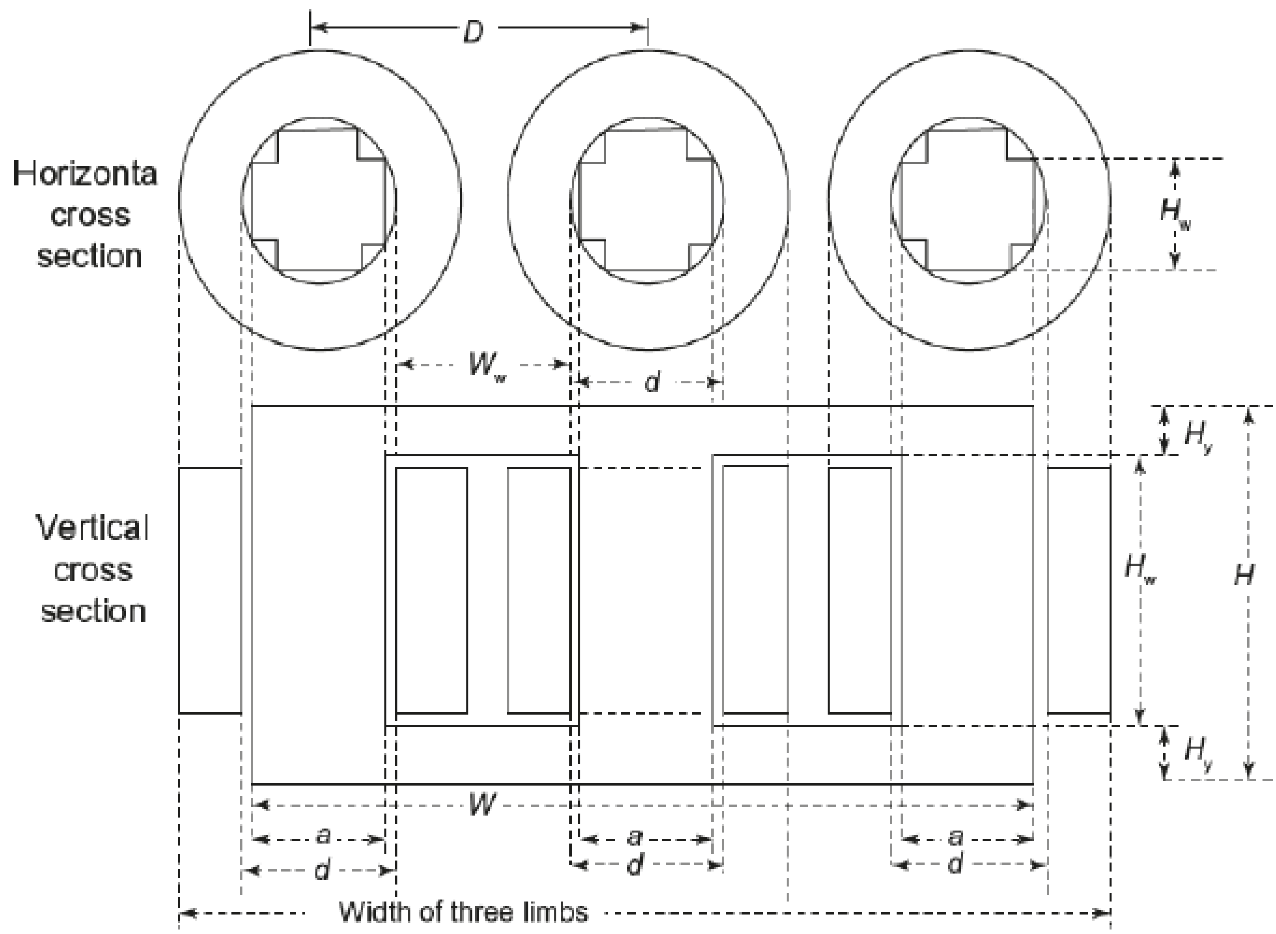
$$D = W_w + d$$

$$W = D + a$$

$$D_y = a$$

Figure 6. Overall dimensions of single- phase core type transformer

Three phase Core type Transformer



H - Overall height

W – Overall width

D – Distance between core centers

d – diameter of circumscribing circle

W_W – Width of the window

H_W – Height of window

H_Y – Height of Yoke

D_Y – Depth of yoke

$H = H_w + 2\ H_y$

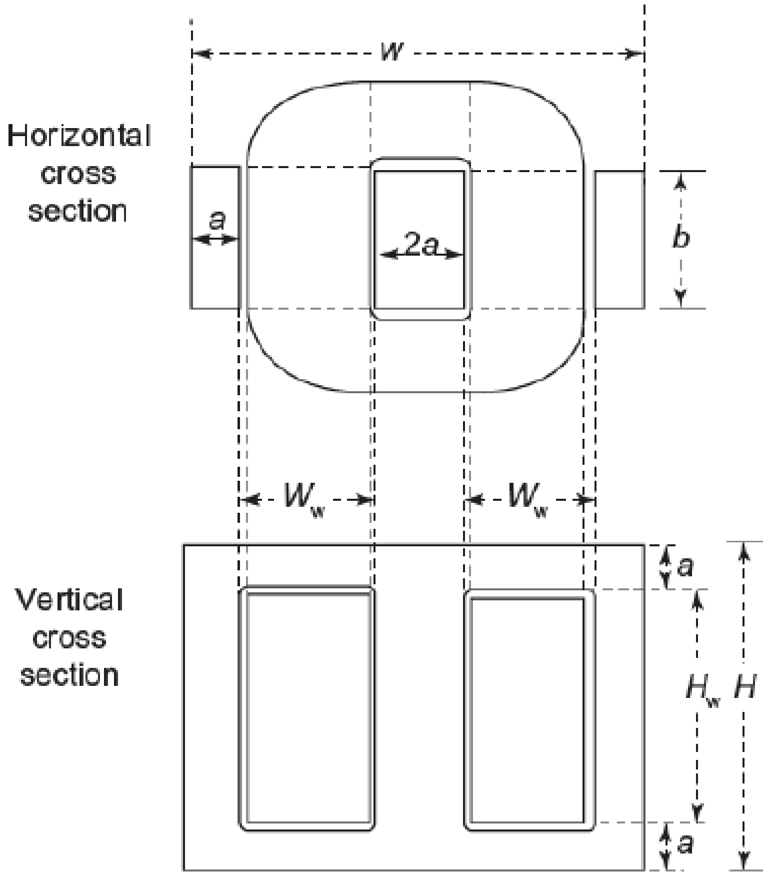
$D = W_w + d$

$W = 2D + a$

$D_y = a$

Figure 7. Overall dimensions of Three- phase core type transformer

Single phase Shell type Transformer



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

$H = H_w + 2\,H_y$

$W = 2\,W_w + 4a$

$D_y = b$

$H_y = a$

Figure 8. Overall dimensions of single- phase shell type transformer

The figure 6,7,8 shows the overall dimensions of different types of transformer.

STEPS INVOLVED IN DESIGN OF TRANSFORMER TANK AND TUBES

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

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

Let, Dissipating surface of tank = S_t

Dissipating surface of tube = xS_t

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

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

= $12.5\ S_t$

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

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

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

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

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

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

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

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

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

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

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

Where d_t = diameter of tube

l_t = length of tube

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

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

PROBLEMS

1.Determine the dimensions for core and yoke for a 5KVA, single phase core type transformer. A rectangular core is used with long side twice as long side twice as long as short side. The window height is 3 times the width. Voltage per turn is 1.8 V. Space factor 0.2, current density 1.8 A/mm^2 flux density 1wb/m^2.

2.The tank of a 1250 KVA natural oil cooled transformer has the dimensions of length, width and height as 1.55m x 0.65m x 1.85m respectively. The full load loss is 13.1 kw. Find the number of tubes for this transformer assuming: W/m^2°C due to radiation = 6 and due to convection = 6.5. Improvement in convection due to provision of tubes = 40% temperature rise = 40°C. Length of each tube = 1m and diameter of tubes. Neglect the top and bottom surfaces of the tank as regards cooling.

3.A 250 kVA, 6600/400V, 3 phase core type transformer has a total loss of 4800W at full load. The transformer tank is 1.25m in height and 1 m X 0.5 m in plan. Design a suitable scheme for tubes if the average temperature rise is to be limited to 35°C. The diameter of tubes is 50mm and are spaced 75mm from each other. The average height of tubes is 1.05m. Specific heat dissipation due to radiation and convection is respectively 6 and 6.5 W/m^2-^{0}C. Assume that convection is improved by 35% due to provision of tubes.

4.Calculate the approximate overall dimensions for a 200KVA,6600/440V,50HZ,3Φ core type transformer. The following data may be assumed: emf per turn = 10v, Max. flux density = 1.3 Web/m^{2,} current density =2.5 A/mm^2,window space factor=0.3,overall height = overall width, slacking factor = 0.9. use a 3 stepped core. For a three stepped core, width of largest stamping = 0.9d and net iron area = 0.6 d^2 where d is the diameter of circumscribing circle.

5.Estimate the main dimensions including winding conductor area of a 3-phase, delta to star core type transformer rated at 300 KVA, 6600/440 V, 50 Hz. A suitable core with three steps having a circumscribing circle of 0.25 m diameter and a leg spacing of 0.4 m is available. δ = 2.5A/mm^2, EMF per turn = 8.5 V, K_w = 0.28, S_f =0.9 (Stacking factor)

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 100 KVA, 2300/400 V, 50 Hz, 1 phase, shell type transformer. Ratio of magnetic and electric loading = 480 x 10^{-8} (i.e. flux and secondary mmf at full load) B_m = 1.1 Wb/m^{2,} δ = 2.2 A/mm^2, K_W = 0.3; Stacking factor = 0.9,

$$\frac{Depth\ of\ Stacked\ Core}{Width\ of\ Central\ Limb} = 2.6 \ , \ \frac{Height\ of\ Window}{Width\ of\ Window} = 2.5.$$

7.Determine the main dimensions of the core of a 5 KVA, 11000/1400 volts, 50 Hz, single phase core type distribution transformer having the following data: The net conductor area in the window is 0.6 times the net cross- sectional area of iron in the core. The core is of square cross section, maximum flux density is 1 wb/m^2. Current density is 1.4 A/mm^2. Window space' factor is 0.2. Height of the window is 3 times its width.

8.Calculate approximate overall dimensions for a 200KVA, 6600/440V, 50Hz, 3 phase core type transformers. The following data may be assumed: emf per turn = 10V, maximum flux density = 1.3 Wb/m^2, current density = 2.5 A/mm^2, window space factor = 0.3, overall height = overall width, staking factor = 0.9. use a 3 stepped core for which net iron area is 0.6d^2, width of the largest stamping is 0.9d.

9.Determine the main dimensions for the core and the yoke for a 250 KVA, 50 Hz, single phase core type transformer having the following data: Emf per turn is 15v, window space factor is 0.33, current density is 3A/mm^2 and B_{max} is 1.1 T. The distance between the centre of the square section core is twice the width of the core. The distance between the centre of the square section of the core is twice the width of the core.

QUESTION BANK

UNIT III

1.What are the various types of Transformers?
Based on construction
1. Core Type
2. Shell Type
Based on the applications
1. Distribution transformer
2. Power transformer
3. Special transformers
4. Instrument transformer
5. Electronics Transformers

2. What is the range of efficiency of transformers?
The efficiency of the transformer will be in the range of 94% to 99%. Among the available electrical machine the transformer has the highest efficiency.

3. What is transformer bank?
A transformer bank consists of three independent single- phase transformers with their primary and secondary windings connected either in star or delta.

4.What is the purpose of constructing the pole body by laminated sheets?
The laminated pole offers the homogeneous construction, (Because while casting internal blow holes may develop and while forging internal cracks may develop) Also the laminated poles offer the flexibility of increasing the length by keeping the diameter fixed, in order to increase the power output (or capacity) of the machine

5.Distinguish between core and shell type transformer.
In core type transformer the coil surrounds the core, while in shell type transformer the core surrounds the coil. In shell type transformers the coils are well supported on the all sides and so they can withstand higher mechanical stresses developed during short circuit conditions. Also the leakage reactance will be less in shell type transformers compared to core type transformers.

6. In transformers, why the low voltage winding placed near the core?
The winding & Core are both made of metals and so an insulation have to be placed in between them, the thickness of insulation depends on the voltage rating of the winding. In order to reduce the insulation requirement the low voltage winding place near the core.

7.What do you meant by stacking factor (iron space factor)?
In transformers, the core is made of laminations and the laminations are insulated from each other by a thin coating of varnish. Hence when the laminations are stacked to the form the core, the actual iron area will be less than the core area. The ratio of iron area and total core area is called stacking factor. The value is usually 0.9.
8.What are the factors to be considered for choosing the type winding for a core type transformer?
1. Current density

2. Short circuit current
3. Temperature rise
4. Surge voltage
5. Impedance
6. Transport facilities

9. What is tertiary winding?
Some three phase transformers may have a third winding called tertiary winding apart from primary and secondary. It is also called auxiliary winding or stabilizing winding.

10. What is the purpose of tertiary winding?
1. To supply small additional loads at a different voltage
2. To give supply to phase compensating devices such as capacitors which work at different voltage.
3. To limit the short circuit current
4. To indicate voltage in high voltage testing transformer.

11.How the tertiary winding is connected?
The tertiary winding is normally connected in delta. When the tertiary is connected in delta, the unbalance in phase voltage during unsymmetrical faults in primary and secondary is compensated by the circulating currents flowing in the closed delta.

12.What are the factors to be considered for choosing the method of cooling?
The choice of cooling method depends on KVA rating of transformer, size, application and the site conditions where it will be installed.

13.How the heat dissipates in a transformer?
The heat dissipation of a transformer occurs by convection, conduction and radiation.

14.Why transformer oil is used as a cooling medium?
When transformer oil is used as a coolant the heat dissipation by convection is 10 times more than the convection due to air. Hence transformer oil is used as a cooling medium.

15.Why cooling tubes are provided?
Cooling tubes are provided to increase the heat dissipating area of the tank.

16.What is a breather?
The breather is a device fitted in the transformer for breathing. In small oil cooled transformers some air gap is provided between the oil level and tank top surface. When the oil is cooled, it shrinks and air is drawn from the atmosphere through breather. This action of transformer is called breathing.

17.Why silica gel is used in breather?
The silica gel is used to absorb the moisture when the air is drawn from the atmosphere in to the transformer.

18.What is conservator?
A conservator is a small cylindrical drum fitted just above the transformer

main tank. It is used to allow the expansion and contraction of oil without contact with surrounding atmosphere. When conservator is fitted in a transformer, the tank is fully filled with oil and the conservator is half filled with oil.

19.How the leakage reactance of the transformer is reduced?
In transformers the leakage reactance is reduced by interleaving the high voltage and low voltage winding.

20.State the advantages of stepped core in transformers.
For same area of cross section the stepped cores will have lesser diameter of the circumscribing circle than square cores. This results in length of mean turn of the winding with consequent reduction in both cost of copper and copper loss.

21.Name the different types of winding used in transformer.
i)cylindrical winding with circular conductors.
ii)cross over winding with circular or rectangular conductors
iii)continuous disc type winding with rectangular conductors
iv)helical winding

22.How will you select the Emf per turn of a transformer?
The equation of emf per turn in terms of KVA rating, flux frequency and
ampere turn is given by,
Emf per turn, $E_t = K\sqrt{Q}$
Where $K = \sqrt{4.44f\,(\phi m/AT)} \times 103$

23.The voltage per turn of a 500 kVA, 11 kV/415 V, delta/star, 3-phase transformer is 8.7 V, calculate the number of turns per phase of LV and HV
Windings
$E_t = 8.7v$
$E_{ph} = 11*10^3$(primary)
$T_s = (415/\sqrt{3})/8.7 = 28$ turns
$T_p = (28 * 11*10^3)/(239.6) = 1286$ turns

24.Why the core of transformer is laminated?
The core of the transformer is laminated to minimize the eddy current loss.

25..Name the different methods of cooling of transformers.
Air natural, Air blast, Oil Natural, Oil natural air forced, Oil natural water forced, Oil forced, Oil forced air natural, Oil forced air natural, Oil forced water forced.

26.What are the advantages of having circular coil in a transformer?
The excessive leakage fluxes produced during short circuit and over loads, develop severe mechanical stresses on the coil. On circular oils these forces are radial and there is no tendency to change its shape. But on rectangular coils the force are perpendicular to the conductors and tends to deform the coil in circular form.

27.State the merits of three phase transformer over single phase transformer.
i)It occupies less space for same rating ,compared to bank of a three single phase transformers
ii)it is economical to use three phase transformers for transmission and distribution
iii)it weighs less

iv)the cost is also low
v)easy to handle

28.Define window space factor with respect to transformer
The window space factor is defined as the ratio of copper area in window to total area of window.

$$K_w = \frac{A_c}{A_w} = \frac{\text{copper area in window}}{\text{total area of the window}}$$

29.How the heat dissipation is improved by the provision of cooling tubes?
The cooling tubes will improve the circulation of oil. The circulation of oil is due to effective pressure heads produced by columns of oil in tubes. The improvement in cooling is accounted by taking the specific heat dissipation due to convection as 35% more than that without tubes.

30.Why is stepped core generally preferred in transformer core design?
When stepped cores are used the diameter of the circumscribing circle is minimum for a given area of the core. This helps in reducing the length of mean turn of the winding with consequent reduction in both cost of copper and copper loss.

31.Write down the output equation for the1phase and 3 phase transformer.
Output KVA of single- phase transformer $Q = 2.22 f B_m A_i K_w A_w \delta \times 10^{-3}$
Output KVA of three phase transformer, $Q = 3.33 f B_m A_i K_w A_w \delta \times 10^{-3}$
f-frequency in HZ,
B_m-maximum flux density in wb/m^2
A_i-Net core area in m^2
K_w-window space factor
A_w-total area of the window m^2
δ – current density A/m^2

32.What are the advantages of shell type transformer over core type transformers?
In shell type transformers the coils are well supported on the all sides and so they can withstand higher mechanical stresses developed during short circuit conditions. Also, the leakage reactance will be less in shell type transformers

33.Why cooling tubes are provided in transformer?
Cooling tubes are provided to increase the heat dissipating area of the tank.

34.Write the output equation of single- phase transformer?
Output KVA of single- phase transformer $Q = 2.22 f B_m A_i K_w A_w \delta \times 10^{-3}$
f-frequency in HZ,
B_m-maximum flux density in wb/m^2
A_i-Net core area in m^2
K_w-window space factor
A_w-total area of the window m^2
δ – current density A/m^2

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UNIT – IV – Electrical Machine Design – SEEA1601

IV. INDUCTION MOTORS

Contents – Output equation, Main dimensions, Design of stator, Choice of L/D ratio - Air gap length - Design of rotor - squirrel cage and slip ring rotor.

Introduction

Induction motors are the ac motors which are employed as the prime movers 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, and drilling machines etc.

Constructional Details:

Similar to DC machines an induction motor consists of a stationary member called stator and a rotating member called rotor. However, the induction motor differs from a dc machine in the following aspects.

1. Laminated stator
2. Absence of commutator
3. Uniform and small air gap
4. Practically almost constant speed

The AC induction motor comprises two electromagnetic parts:

• Stationary part called the stator
• Rotating part called the rotor

The stator and the rotor are each made up of

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

The stator

The stator is the outer stationary part of the motor, which consists of

• The outer cylindrical frame of the motor or yoke, which is made either of welded sheet steel, cast iron or cast aluminium alloy.
• The magnetic path, which comprises a set of slotted steel laminations called stator core pressed into the cylindrical space inside the outer frame. The magnetic path is laminated to reduce eddy currents, reducing losses and heating.
• A set of insulated electrical windings, which are placed inside the slots of the laminated stator. The cross-sectional area of these windings must be large enough for the power rating of the motor. For a 3-phase motor, 3 sets of windings are required, one for each phase connected in either star or delta. Fig 1 shows the cross-sectional view of an induction motor. Details of construction of stator are shown in Figs

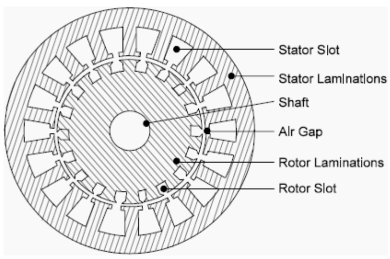

Figure 1. Stator and rotor laminations

The rotor

Rotor is the rotating part of the induction motor. The rotor also consists of a set of slotted silicon steel laminations pressed together to form of a cylindrical magnetic circuit and the electrical circuit. The electrical circuit of the rotor is of the following nature

Squirrel cage rotor consists of a set of copper or aluminium bars installed into the slots, which are connected to an end-ring at each end of the rotor. The construction of this type of rotor along with windings resembles a 'squirrel cage'. Aluminium rotor bars are usually die-cast into the rotor slots, which results in a very rugged construction. Even though the aluminium rotor bars are in direct contact with the steel laminations, practically all the rotor current flows through the aluminium bars and not in the lamination

Wound rotor consists of three sets of insulated windings with connections brought out to three slip rings mounted on one end of the shaft. The external connections to the rotor are made through brushes onto the slip rings as shown in fig 7 and 8. Due to the presence of slip rings such type of motors is called slip ring motors. Sectional view of the full induction motor is shown in Fig. 8

Some more parts, which are required to complete the constructional details of an induction motor, are:

Two end-flanges to support the two bearings, one at the driving-end and the other at the non- driving end, where the driving end will have the shaft extension.

• Two sets of bearings to support the rotating shaft,
• Steel shaft for transmitting the mechanical power to the load
• Cooling fan located at the non-driving end to provide forced cooling for the stator and rotor
• Terminal box on top of the yoke or on side to receive the external electrical connections

Figure 2 to 5 show the constructional details of the different parts of induction motor.

Fig. 2 Stator laminations

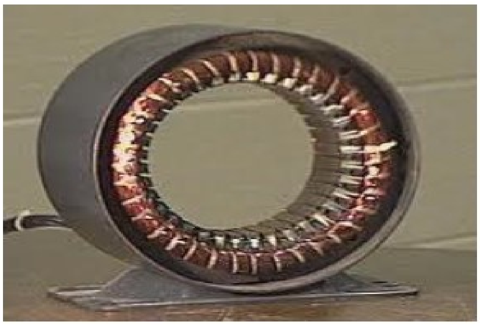

Fig. 3 stator core with smooth yoke

Fig.4 Stator with ribbed yoke

Fig 5. Squirrel cage rotor

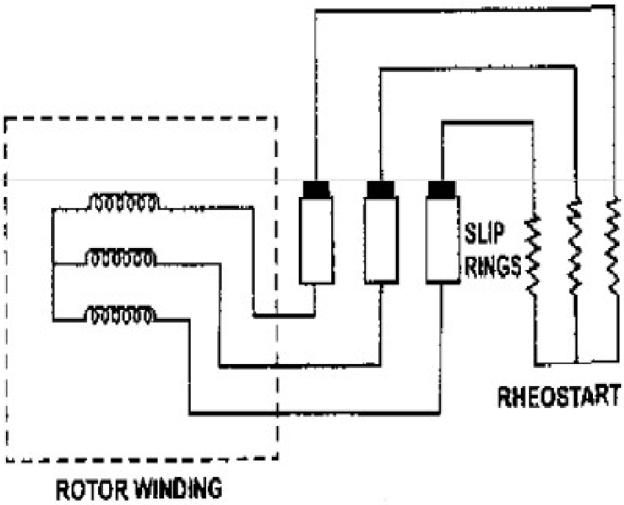

Fig. 6. Slip ring rotor

Fig 7. Connection to slip rings

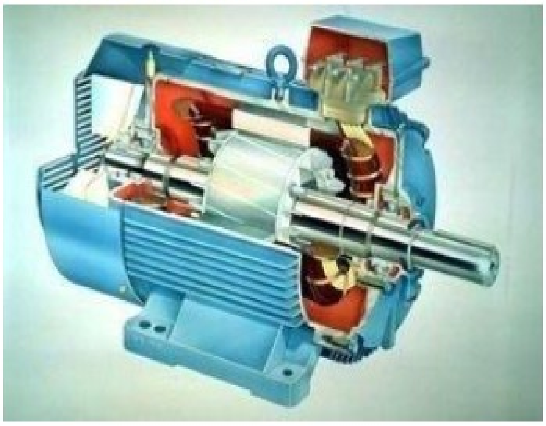

Fig. 8 Cut sectional view of the induction motor.

Introduction to Design

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

1. The main dimensions of the stator.
2 Details of stator windings.
3. Design details of rotor and its windings
4. Performance characteristics.

In order to get the above design details, the designer needs the customer specifications Rated output power, rated voltage, number of phases, speed, frequency, connection of stator winding, type of rotor winding, working conditions, shaft extension details etc.

In addition to the above the designer must have the details regarding design equations based on which the design procedure is initiated, information regarding the various choice of various parameters, information regarding the availability of different materials and the limiting values of various performance parameters such as iron and copper losses, no load current, power factor, temperature rise and efficiency

OUTPUT EQUATION OF INDUCTION MACHINES

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

In an induction motor the out put equation can be obtained as follows

Consider an 'm' phase machine, with usual notations

Out put Q in kW = Input x efficiency

Input to motor = $mV_{ph}\ I_{ph} \cos \Phi \times 10^{-3}$ kW For a 3 Φ machine m = 3

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

$V_{ph} = E_{ph}$, $V_{ph} = E_{ph} = 4.44\ f\ \Phi\ T_{ph}Kw$

$= 2.22\ f\ \Phi ZphKw$

$f = PN_S/120 = Pn_s/2$,

Output = $3 \times 2.22 \times Pn_s/2 \times \Phi ZphKw\ I_{ph}\ \eta \cos \Phi \times 10^{-3}$ kW

Output = $1.11 \times P\Phi \times 3I_{ph}\ Zph \times ns\ Kw\ \eta \cos \Phi \times 10^{-3}$kW

$P\Phi = Bav\pi DL$, and $3Iph\ Zph/\ \pi D = q$

Output to motor = $1.11 \times B_{av}\pi DL \times \pi D_q \times n_s\ Kw\ \eta \cos \Phi \times 10^{-3}$ kW

$Q = (1.11\ \pi^2\ B_{av}\ q\ Kw\ \eta \cos \Phi \times 10^{-3})\ D^2L\ ns$ kW

$Q = (11\ B_{av}\ q\ Kw\ \eta \cos \Phi \times 10^{-3})\ D^2L\ ns$ kW

Therefore Output $Q = Co\ D^2L\ n_s$ kW

where $Co = (11\ B_{av}\ q\ Kw\ \eta \cos \Phi \times 10^{-3})$

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

Z_{ph} = no of conductors/phase

T_{ph} = no of turns/phase

Ns = Synchronous speed in rpm

ns = synchronous speed in rps

p = no of poles,

q = Specific electric loading

Φ = air gap flux/pole;

B_{av} = Average flux density

kw = winding factor

η = efficiency

$\cos\Phi$= power factor

D = Diameter of the stator,

L = Gross core length

Co = Output coefficient

MAIN DIMENSIONS

The operating characteristics of an induction motor are mainly influenced by ratio

ration L / τ for various design factors are,

for minimum cost, $L / \tau = 1.5$ to 2

for good power factor, $L / \tau = 1.0$ to 1.25

for good efficiency, $L / \tau = 1.5$

for good overall design, $L / \tau = 1$

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

PERIPHERAL SPEED

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

VENTILATING DUCTS

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

SELECTION OF STATOT SLOTS Ss

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

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

Step 2 : Stator slots should be a multiple of "q"
Where q is slots per pole per phase
q = 2, 3, 4 ….
Ss = number of phase x poles x q
Ss = m x P x q
Step 3 : Select the choice of stator slots which are common between the values obtained in step 1 and step 2.
Step 4 : Slot loading = Iz x Zss
Iz = current through stator conductor, Zss – conductor per slot

LENGTH OF AIR GAP

The length of air gap in induction motor is decided by
- Power factor
- Overload capacity
- Pulsation loss
- Unbalanced magnetic pull
- Cooling
- Noise

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

or

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

DESIGN OF SQUIRREL CAGE ROTOR

The squirrel cage rotor is shown in figure 9 and steps involved in its design are discussed.

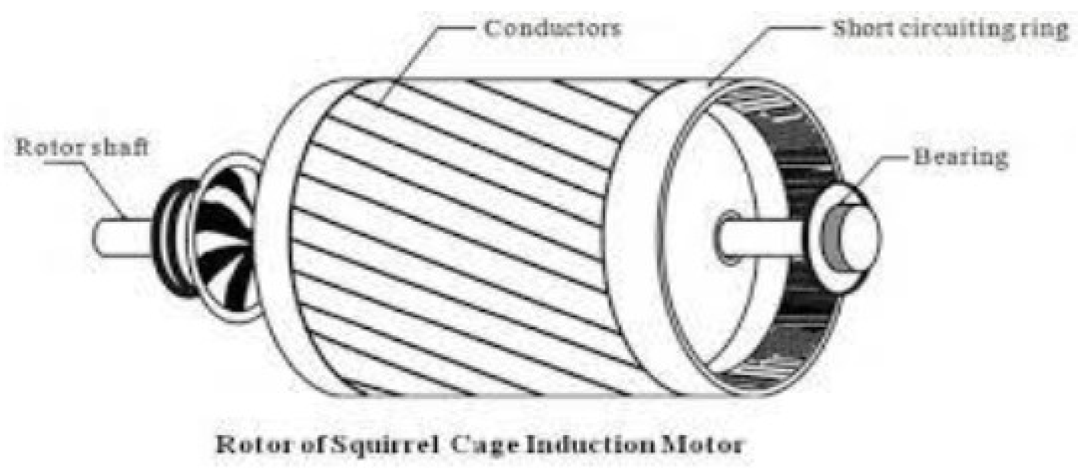

Figure 9. Squirrel cage rotor

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

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

Where I_s = Stator current per phase

T_s = Stator turns per phase

S_r = number of rotor slots

Area of cross section of each rotor bar, $\boxed{a_b = \frac{I_b}{\delta_b}}$ in mm²

Where I_b = Rotor bar current

δ_b = Current density in rotor bars

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

Where S_r = number of rotor slots

I_b = Rotor bar current

p = number of poles

Area of cross section of end ring, $\boxed{a_e = \frac{I_e}{\delta_e}}$ in mm²

Where I_e = Rotor end ring current

δ_e = Current density in rotor end ring

Current density
Stator conductors δ = 3 to 5 A/mm²
Rotor bars δ = 4 to 7 A/mm²

RULES FOR SELECTION OF ROTOR SLOTS

- The number of stator slots should never be equal to rotor slots.
- The difference ($S_s \sim S_r$) should not be equal to $\pm$ P, $\pm$ 2 P or $\pm$ 5 P
  - to avoid synchronous cusps
- The difference ($S_s \sim S_r$) should not be equal to $\pm$ 3 P
  - to avoid magnetic locking
- The difference ($S_s \sim S_r$) should not be equal to $\pm$ 1, $\pm$ 2, $\pm$ (P $\pm$ 1), $\pm$ (P $\pm$ 2)
  - to avoid noise and vibrations

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

DESIGN OF WOUND ROTOR (SLIP RING IM)

The wound rotor has the facility of adding external resistance to rotor circuit in order to improve the torque developed by the motor.
The motor consists of laminated core with semi enclosed slots and carries a three- phase winding. The figure 10 shows the wound rotor.

Figure 10. Wound rotor of IM

NUMBER OF ROTOR TURNS

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

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

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

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

Rotor ampere turns = 0.85 stator ampere turns

$$T_r I_r = 0.85 I_s T_s$$

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

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

Current density In rotor conductors δ = 3 to 5 A/mm^2

Area of cross section of rotor conductor $\boxed{a_r = \frac{I_r}{\delta_r}}$ in mm^2

PROBLEMS

1.Estimate the stator core dimensions, number of stator slots and number of stator conductors per slot for a 100 kw, 3300v, 50 Hz, 12 pole star connected slip ring induction motor. Assume average gap density = 0.4 wb/m^2; Conductors per metre = 25,000 A/m efficiency = 0.9, power factor = 0.9 and winding factor = 0.96 choose main dimensions to give overall design.

2.A 3 phase, 6 pole, 50Hz, 10kw, 220v star connected Induction motor has 54 stator slots each containing 6 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 power factor of 0.85. The rotor mmf may be assumed as 85% of stator mmf. Also find the bar and end ring sections if the current density is 5A/mm^2.

3.Determine the approximate diameter and length of stator core, the number of stator slots and the number of stator conductors for an 11kW, 400V, 3 phase, 4 pole, 1425 rpm, and delta connected induction motor. B_{av} = 0.45 Wb/ m^2, ac = 23000 amp.cond/m, full load efficiency = 0.85, power factor = 0.88, L / τ = 1. The stator employs a double layer winding.

4. A 11kW, 3 phase, 6 pole, 50Hz, 220V, Star Connected induction motor has 54 stator 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 power factor of 0.85. The rotor mmf may be assumed as 85 percent of stator mmf. Also find the bar and end ring sections if the current density is 5 A/mm^2.

5.Determine the main dimensions, number of radial ventilating ducts, number of stator slots of a 3.7 kW, 400V, 3 φ, 4 pole, 50 Hz squirrel cage induction motor to be started by Y-Δ starter. Assume average flux density in air gap is 0.45 Wb/m^2; Ampere conductors/m is 23,000; Efficiency = 85% & p.f.=0.84; winding factor = 0.955, stacking factor = 0.9. Choose the main dimensions to give a cheaper design.

6.Calculate , (i) length (ii) length (iii) number of turns per phase (iv) full load current and cross section of conductors, and (v) total I^2R loss of stator of three phase,120 kW, 2200V,50 Hz, 750 rpm (synchronous speed), stator connected slip ring induction motor from the following particulars: B_{av} = 0.48T, ac = 26000 amp.cond.per meter, efficiency = 92 %, power factor = 0.88, L = 1.25, ζ, K_w = 0.955 ,current density = 5 A/mm^2, mean length of stator conductors = 75 cm , ρ = 0.021ohm/m. and mm^2 section.

7.Estimate the stator core dimensions, number of stator slots and number of stator conductors per slot for a 100 kw, 3300v, 50 Hz, 12 pole star connected slip ring induction motor. Assume average gap density = 0.4 wb/m^2; Conductors per metre = 25,000 A/m efficiency = 0.9, power factor = 0.9 and winding factor = 0.96 choose main dimensions to give overall design.

8.Find the main dimension of a 15KW, 3Φ, 400V, 50HZ, 2810 rpm squirrel cage induction motor having an η of 88% and full load pf of 0.9. Specific magnetic loading is 0.5Web/m^2.Specific electric loading = 25000 A/M. Take rotor peripheral Speed as approximately 20m/sec at synchronous speed.**13/4/2013**

9.A 90KW, 500V, 50HZ, 3Φ, 8 pole Slip-ring induction motor has star connected stator accommodating 6 conductors per slot. The number of stator slots=63. If the slip ring voltage on open circuit is to be about 400V, find the number of rotor slots and the number of conductors in each slot.

10.Estimate the stator core dimensions, number of stator slots, number of stator conductors per slots for a 3 phase, 100 KW, 3300 V, 12 pole, 50 Hz, star connected slip ring Induction motor. B_{av} = 0.4 Wb/ m^2 and Specific electric loading = 25000 amp. cond./m., p.f. =0.9, η = 0.9. Choose the main dimensions to give best power factor. The slot loading should not exceed 500 amp. cond.

11.Estimate the main dimensions, number of stator slots, stator turns per phase and for a 3 phase, 70 HP, 415 V, 6 pole, 50 Hz, 975 rpm Induction motor. The motor is star connected. B_{av} = 0.51 Wb/ m^2 and Specific electric loading = 30000 amp. cond./m. L/Γ = 1, p.f. =0.91, η = 0.9. Estimate the number of stator conductors required for a winding in which the conductors are connected in two parallel paths. Choose a suitable number of conductors per slot, so that the slot loading does not exceed 750 amp. cond.

12.A 90 KW, 500 V, 50 Hz, 3 phase, 8 pole induction motor has a star connected stator winding accommodated in 63 slots with 6 conductors per slot. If the slip ring voltage on open circuit is not to exceed 400 V, find a suitable rotor winding by estimating the number of slots, number of conductors per slot, coil span, slip ring voltage on open circuit, approximate full load current per phase in rotor. Assume η =0.9 and power factor = 0.86

13. Find the values of diameter and length of stator core of a 7.5 Kw, 220 V, 50 Hz. 4 pole. 3 phase induction motor for best power factor. Given: specific magnetic loading = 0.4 wb/m^2; Specific electric loading – 22000 ac/m; Efficiency = 0.86; Power factor = 0.87. Also find the main dimensions if the ratio of core length to pole pitch is unity. (8)

14.Determine the main dimension for a 15hp, 400V, 3 phase, 4 pole and 1425 rpm induction motor. Adopt of a specific magnetic loading of 0.45 Weber/m^2 and specific electric loading of 230 ac/cm. Assume that a full load efficiency of 85% and a full load power factor of 0.88 will be obtained.

QUESTION BANK
UNIT– IV

1.What are the different types of induction motor and how differ from each other?
The two different types of induction motor are squirrel cage and slip ring induction motor. The stator is identical for both but they differ in construction of rotor.

2. Why wound rotor construction is adopted?
The wound rotor has the facility of increasing the rotor resistance through slip rings. High value of rotor resistance is need during starting to get a high value of starting torque.

3.What is rotating transformer?
The principle of operation of induction motor is similar to that a transformer. The stator winding is equivalent to primary of the transformer and the rotor winding is equivalent to short circuited secondary of a transformer. In transformer the secondary is fixed but in induction motor it is allowed to rotate. Hence the induction motor also called rotating transformer.

4.How the slip ring motor is started?
The slip ring motor is started by using rotor resistance starter. The starter consists of star connected to slip rings. While starting the full resistance is included in the rotor circuit to get high starting torque. Once the rotor starts rotating the resistance is gradually reduced in steps. At running condition the slip rings are shorted and so it is equivalent to squirrel cage rotor.

5.What are the materials used to manufacture the brushes for slip rings of an induction motor?
The slip rings are made of brass and phosphor bronze. The brushes are made of metal graphite which is an alloy of copper and carbon.

6.What are the advantages of cage rotor over slip ring induction motor?
1. It is cheaper than slip ring motor
2. In does not have any wear and tear parts like slip rings, brush gear and short circuiting devices. Hence the construction will be rugged.
3. No over hang therefore copper loss is less.
4. Better power factor, and over load capacity

7.Name the materials used to insulate the laminations of the core of induction motor.
The materials used to insulate the laminations are kaolin and varnish.

8.What are the advantages of slip ring motor over squirrel cage motor?

1. The starting torque can be varied by adding resistance to rotor.

2. The speed of the machine can be varied by injecting an emf through slip rings to the rotor.

9.Write the expression for the output equation and out coefficient of induction motor.

.$Q = C_0 D^2 L n_s$ in KVA

$C_0 = 11 K_w ac B_{av} * 10^{-3}$

10. What are the factors to be considered for choosing the specific magnetic loading?

The choice of specific magnetic loading depends on power factor, iron loss and over load capacity.

11.What are the factors to be considered for the choice of specific electric loading?

The choice of specific loading depends on copper loss, temperature rise, voltage rating and over load capacity.

12.What are the main dimensions of an induction motor?

The main dimensions of induction motor are stator core internal diameter and stator core length.

13.How the induction motor can be designed for best power factor?

For best power factor the pole pitch, τ is chosen such that, $\tau = \sqrt{0.18L}$

14.What are the different types of stator winding in induction motor?

The different types of stator windings are mush winding, lap winding and wave winding.

15.Where mush windings are used?

The mush windings are used in small induction motors of ratings below 5 HP.

16.What types of slots are preferred for the induction motor?

Semi enclosed slots are preferred for induction motor. It results in less air gap contraction factor giving a small value of magnetizing currents, low tooth pulsation loss and much quieter operation(less noise)

17. What is slot space factor?

The slot space factor is the ratio of conductor (or copper) is per slot and slot area. It gives an indication of the space occupied by the conductors and the space available for insulation. The slot space factor for induction motor varies from 0.25 to 0.4.

18. What is the minimum value of slot pitch in induction motor?

The minimum value of slot pitch in three phase induction motor is 15mm.

19. What are the factors to be considered for selecting number of slots in

induction machine stator?

The factors to be considered for selecting the number of slots are tooth pulsation loss, leakage reactance, magnetizing current, iron loss and cost. Also the number of slots should be multiple of slots per pole per phase for integral slot winding.

20.Which part of induction motor has the maximum flux density? What is the maximum flux density in that part?

The teeth of the stator and rotor core will have maximum flux density. The maximum value of flux density in the teeth is 1.7 wb/m2

21.What are the factors to be considered for estimating the length of air gap.

1. Power factor, 2. Unbalanced magnetic pull, 3. Overload capacity

4. Pulsation loss, 5. Cooling, 6. Noise.

22.What are the advantages and disadvantages of large air gap length in

induction motor?

Advantage: A large air gap length results in higher overload capacity, better cooling, reduction in noise and reduction in unbalanced magnetic pull.

Disadvantages: The disadvantage of large air gap length is that it results in high value of magnetizing current.

23.What happens if the air gap length is doubled?

If the air gap of an induction motor is doubled then the mmf and magnetizing current approximately doubles. Also increase in air gap length increases the overload capacity, offers better cooling, reduces noise and reduces unbalanced magnetic pull.

24.List out the methods to improve the power factor of the induction motor.

The power factor of the induction motor can be improved by reducing the magnetizing current and leakage reactance. The magnetizing current can be reduced by reducing the length of air gap. The leakage reactance can be reduced by the depth of stator & rotor slots, by providing short chorded winding and reducing the overhang in stator winding.

25.Why the air gap of an induction motor is made as small as possible?

The mmf and the magnetizing current are primarily decided by length of air gap. If air gap is small then mmf and magnetizing current will be low, which in turn increase the value of power factor. Hence by keeping small air gap, high power factor is achieved.

26.Write the formula for air gap in case of three phase induction motor in terms of length and diameter.

The length of air gap, $l_g = 0.2 + 2\sqrt{DL}$ in mm

Where D, L are expressed in metre.

27.Discuss the relative merits and demerits of open and closed slots for

induction motor.

The closed slots will not increase reluctance of air gap and has lesser noise but it has difficulty in casting the rotor bars.

The open slots increase the reluctance of air gap and has high noise but it offers flexibility in casting rotor bars.

28.List the undesirable effects produced by certain combination of rotor and stator slots.

1. The motor may refuse to start (cogging)

2. The motor may run at sub synchronous speed (Crawling)

3. Severe vibrations may develop and the noise will be excessive.

29.What are the different types of windings used for the rotor of induction motor?

The different types of windings employed in induction motor rotor are mush winding and double layer winding.

30.What is crawling and cogging?

Crawling is a phenomenon in which the induction motor runs at a speed lesser than the sub synchronous speed.

Cogging is a phenomenon in which the induction motor refuse to start.

31. What are the methods adopted to reduce harmonic torques?

The methods used for reduction or elimination of harmonic torques are chording, integral slot winding, skewing and increasing the length of air gap.

32. What is skewing?

Skewing is twisting either the stator or rotor core. The motor noise, vibrations, cogging and synchronous cusps can be reduced or even entirely eliminated by skewing.

33.Define dispersion coefficient.

The dispersion coefficient is defined as the ratio of magnetizing current to ideal short circuit current.

34.What is the condition for obtaining the maximum torque in case of 3 phase induction motor?

The maximum torque occurs in induction motor when rotor reactance is

equal to rotor resistance.

34.What are the advantages of selecting smaller length of airgap in the induction motor design? Or Why the air gap of an Induction motor is made as small as possible motor?

The mmf and the magnetizing current are primarily decided by length of air gap. If air gap is small then mmf and magnetizing current will be low, which in turn increase the value of power factor. Hence by keeping small air gap, high power factor is achieved.

35.List the different factors that affect the choice of number of stator slots.

The factors to be considered for selecting the number of slots are tooth pulsation loss, leakage reactance, magnetizing current, iron loss and cost. Also the number of slots should be multiple of slots per pole per phase for integral slot winding.

36.What type of slots are prefered in induction motor?

Semi enclosed slots are preferred for induction motor. It results in less air gap contraction factor giving a small value of magnetizing currents, low tooth pulsation loss and much quieter operation(less noise)

37.Write the formula for air gap in case of three phase induction motor in terms of length and diameter.

The length of air gap,

For small IM $l_g = 0.2 + 2\sqrt{DL}$ in mm

Where D, L are expressed in metre.

38.What are the different components of leakage flux in poly phase induction motor?

The different components of leakage flux are slot leakage flux, zigzag leakage flux, overhang leakage flux, harmonic leakage flux, skew leakage flux, peripheral leakage flux.

39.What are the different shapes of stator slots in three phase induction motor?

Semi enclosed slots and open slots are the different shapes of stator slots in three phase induction motor.Semi enclosed slots are preferred for induction motor. It results in less air gap contraction factor giving a small value of magnetizing currents, low tooth pulsation loss and much quieter operation(less noise).In open slots it is easier to replace individual coils and avoids excessive slot leakage there by reducing the leakage reactance.

40.State the effect of change of airgap length in a three phase induction motor.

If air gap is small then mmf and magnetizing current will be low, which in turn increase the value of power factor. Hence by keeping small air gap, high power factor is achieved. A large air gap length results in higher overload capacity, better cooling, reduction in noise and reduction in unbalanced magnetic pull.

41.Define Dispersion co-efficient in an induction motor.

The dispersion coefficient is defined as the ratio of magnetizing current to ideal short circuit current.

Dispersion co-efficient=I_m/I_{sci}

I_m-Magnetising current

I_{sci}-Ideal short circuit current

42.What are the main dimensions of induction motor?

The main dimensions of induction motor are stator core internal diameter and stator core length.

43.List the advantages and disadvantages of large air gap length in induction motor.

Advantage: A large air gap length results in higher overload capacity, better cooling, reduction in noise and reduction in unbalanced magnetic pull.

Disadvantages: The disadvantage of large air gap length is that it results in high value of magnetizing current.

44.List the factors to be considered for estimating the length of air gap in induction motor.

1. Power factor, 2. Unbalanced magnetic pull, 3. Overload capacity

4. Pulsation loss, 5. Cooling, 6. Noise

45.Differentiate slip ring and squirrel cage induction motor.

Cage IM

1. It is cheaper than slip ring motor

2. In does not have any wear and tear parts like slip rings, brush gear and

short circuiting devices. Hence the construction will be rugged.

3. No over hang therefore copper loss is less.

4. Better power factor, and over load capacity

Slip ring IM

1. The starting torque can be varied by adding resistance to rotor.

2. The speed of the machine can be varied by injecting an emf through slip rings to the rotor.

46.Why wound rotor construction is adopted?

The wound rotor has the facility of increasing the rotor resistance through slip rings. High value of rotor resistance is need during starting to get a high value of starting torque.

47.Which part of induction motor has maximum flux density? What is the maximum value of flux density in that part?

The teeth of the stator and rotor core will have maximum flux density. The maximum value of flux density in the teeth is 1.7 wb/m^2

48.Write the expression for output equation and output coefficient of Induction motor.

$Q = C_0 D^2 L n_s$ in KVA

$C_0 = 11 K_w ac B_{av} * 10^{-3}$

C_0 -output coefficient

Q-KVA rating

D-diameter of stator bore in m

L-length of stator core in m

n_s-synchronous speed

K_w-Winding factor

Ac-specific electric loading in ampere conductor per metre

B_{av}- specific magnetic loading in wb/m^2

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS

UNIT – V– Electrical Machine Design – SEEA1601

V. SYNCHRONOUS MACHINES

Contents – Output equation - Design of salient pole rotor machine - Dimensions - Short circuit ratio - Effect of Short Circuit ratio – Air gap length - Armature design - Slot dimensions - Rotor design - Design of damper winding - Design of cylindrical rotors

Introduction

Synchronous machines are AC machines that have a field circuit supplied by an external DC source. Synchronous machines are having two major parts namely stationary part stator and a rotating field system called rotor. In a synchronous generator, a DC current is applied to the rotor winding producing a rotor magnetic field. The rotor is then driven by external means producing a rotating magnetic
field, which induces a 3-phase voltage within the stator winding. Field windings are the windings producing the main magnetic field (rotor windings for synchronous machines); armature windings are the windings where the main voltage is induced (stator windings for synchronous machines).

Types of synchronous machines

1.Hydrogenerators: The generators which are driven by hydraulic turbines are called hydro generator. These are run at lower speeds less than 1000 rpm.
2. Turbogenerators: These are the generators driven by steam turbines. These generators are run at very high speed of 1500rpm or above.
3. Engine driven Generators: These are driven by IC engines. These are run at a speed less than 1500 rpm. Hence the prime movers for the synchronous generators are Hydraulic turbines, Steam turbines or IC engines
Hydraulic Turbines: Pelton wheel Turbines: Water head 400 m and above
Francis turbines: Water heads up to 380 m
Keplan Turbines: Water heads up to 50 m
Steam turbines: The synchronous generators run by steam turbines are called turbogenerators or turbo alternators. Steam turbines are to be run at very high speed to get higher efficiency and hence these types of generators are run at higher speeds.
Diesel Engines: IC engines are used as prime movers for very small rated generators.

Construction of synchronous machines

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

Non-salient pole or Cylindrical rotor or Round rotor Machines: These machines are having cylindrical smooth rotor construction with distributed field winding in slots. This type of rotor construction is employed for the machine driven by steam turbines.

Construction of Hydro-generators: These types of machines are constructed based on the water head available and hence these machines are low speed machines. These machines are constructed based on the mechanical consideration. For the given frequency the low speed demands large number of poles and consequently large diameter. The machine should be so connected such that it permits the machine to be transported to the site. It is a normal to practice to design the rotor to withstand the centrifugal force and stress produced at twice the normal operating speed.

Stator core:

The stator is the outer stationary part of the machine, which consists of the outer cylindrical frame called yoke, which is made either of welded sheet steel, cast iron.

The magnetic path, which comprises a set of slotted steel laminations called stator core pressed into the cylindrical space inside the outer frame. The magnetic path is laminated to reduce eddy currents, reducing losses and heating. CRGO laminations of 0.5 mm thickness are used to reduce the iron losses.

A set of insulated electrical windings are placed inside the slots of the laminated stator. The cross-sectional area of these windings must be large enough for the power rating of the machine. For a 3-phase generator, 3 sets of windings are required, one for each phase connected in star. Fig. 1 shows one stator lamination of a synchronous generator.

In case of generators where the diameter is too large stator lamination can not be punched in on circular piece. In such cases the laminations are punched in segments. A number of segments are assembled together to form one circular laminations. All the laminations are insulated from each other by a thin layer of varnish.

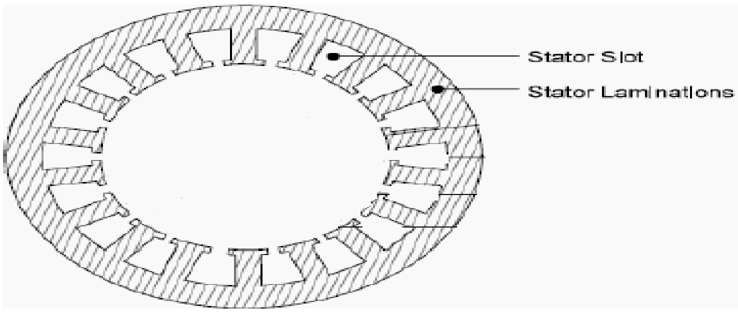


Fig. 1. Stator lamination

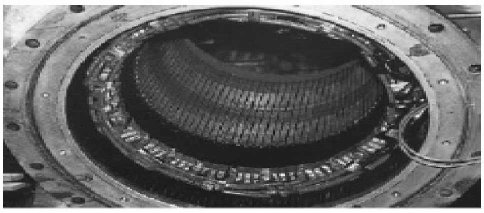


Fig 2. (a) Stator and (b) rotor of a salient pole alternator

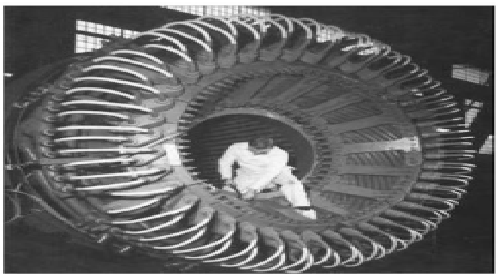


Fig 3. (a) Stator of a salient pole alternator

Details of construction of stator are shown in Figs 2 – 8

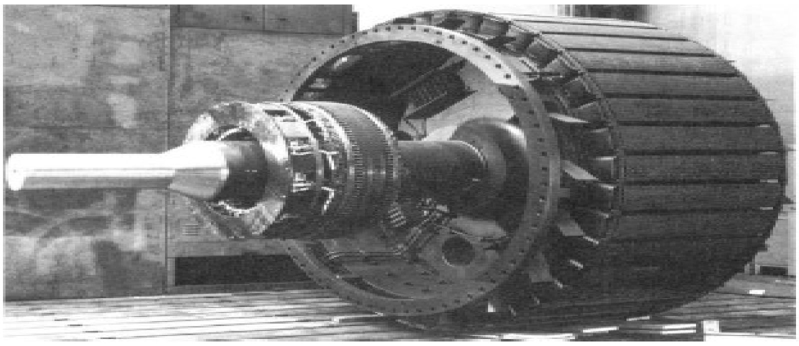


Fig 4. Rotor of a salient pole alternator

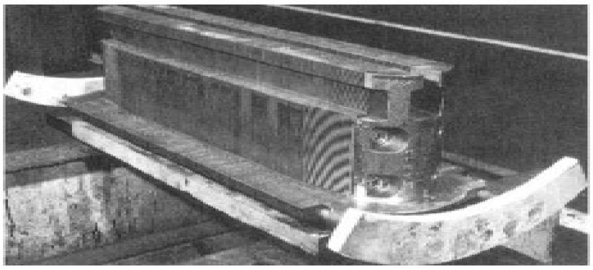


Fig 5. (a) Pole body (b) Pole with field coils of a salient pole alternator

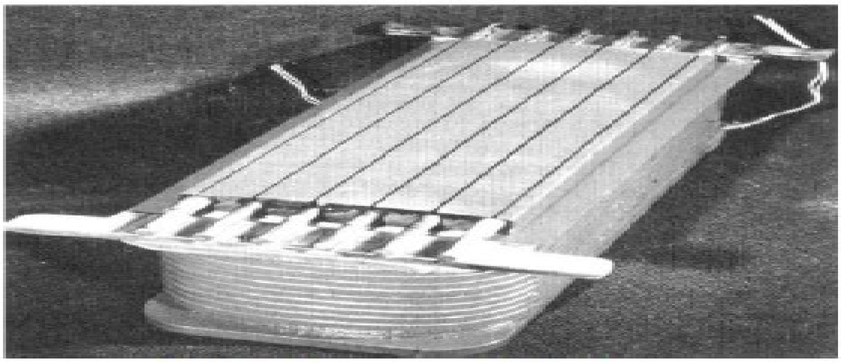


Fig 6. Slip ring and Brushes

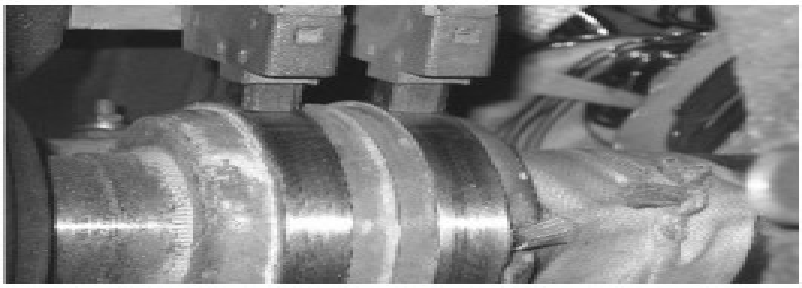


Fig 7. Rotor of a Non salient pole alternator

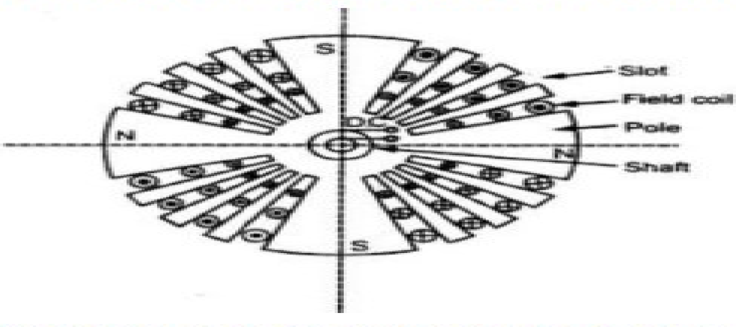


Fig 8. Rotor of a Non salient pole alternator

Rotor of water wheel generator consists of salient poles. Poles are built with thin silicon steel laminations of 0.5mm to 0.8 mm thickness to reduce eddy current laminations. The laminations are clamped by heavy end plates and secured by studs or rivets. For low, speed rotors poles have the bolted- on construction for the machines with little higher peripheral speed poles have dove tailed construction as shown in Figs. Generally rectangular or round pole constructions are used for such type of alternators. However, the round poles have the advantages over rectangular poles. Generators driven by water wheel turbines are of either horizontal or vertical shaft type. Generators with fairly higher speeds are built with horizontal shaft and the generators with higher power ratings and low speeds are built with vertical shaft design. Vertical shaft generators are of two types of designs (i) Umbrella type where in the bearing is mounted below the rotor. (ii) Suspended type where in the bearing is mounted above the rotor.

.Relative dimensions of Turbo and water wheel alternators:

Turbo alternators are normally designed with two poles with a speed of 3000 rpm for a 50 Hz frequency. Hence peripheral speed is very high. As the diameter is proportional to the peripheral speed, the diameter of the high speed machines has to be kept low. For a given volume of the machine when the diameter is kept low the axial length of the machine increases. Hence a turbo alternator will have small diameter and large axial length.
However in case of water wheel generators the speed will be low and hence number of poles required will be large. This will indirectly increase the diameter of the machine. Hence for a given volume of the machine the length of the machine reduces. Hence the water wheel generators will have large diameter and small axial length in contrast to turbo alternators.

Introduction to Design

Synchronous machines are designed to obtain the following information's.
(i) Main dimensions of the stator frame.
(ii) Complete details of the stator windings.
(iii) Design details of the rotor and rotor winding.
(iv) Performance details of the machine.
To proceed with the design and arrive at the design information the design engineer needs the following information.
(i) Specifications of the synchronous machine.
(ii) Information regarding the choice of design parameters.
(iii) Knowledge on the availability of the materials. (iv) Limiting values of performance parameters.
(v) Details of Design equations.

.Specifications of the synchronous machine:

Important specifications required to initiate the design procedure are as follows:
Rated output of the machine in kVA or MVA, Rated voltage of the machine in kV, Speed, frequency, type of the machine generator or motor, Type of rotor salient pole or non salient pole, connection of stator winding, limit of temperature, details of prime mover etc.

Main Dimensions:

Internal diameter and gross length of the stator forms the main dimensions of the machine. In order to obtain the main dimensions it is required to develop the relation between the output and the main dimensions of the machine. This relation is known as the output equation.

OUTPUT EQUATION OF SYNCHRONOUS MACHINE

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

KVA rating of AC machine,

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

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

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

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

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

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

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

From the above steps,

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

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

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

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

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

$Z = 6\ T_{ph}$

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

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

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

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

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

$$\therefore I_z Z = ac\pi D \quad \ldots (2)$$

From (1) and (2),

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

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

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

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

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

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

Where, Q = KVA output for alternator

D = Diameter of stator bore in m

L = Length of stator core in m

n_s = Synchronous speed in rps

B_{av} = Specific magnetic loading

ac = Specific electric loading in Amp. Cond. / m

K_{ws} = Stator winding factor

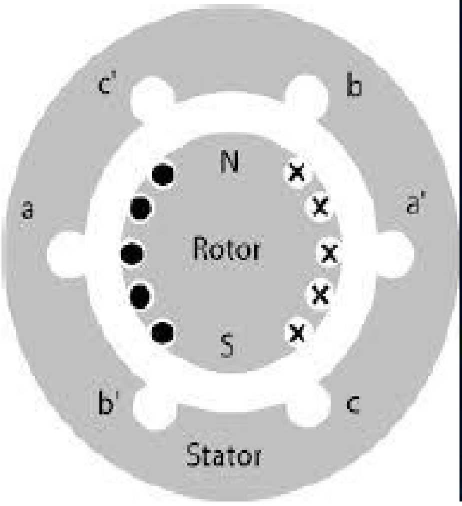
V_a = Peripheral speed in m/s

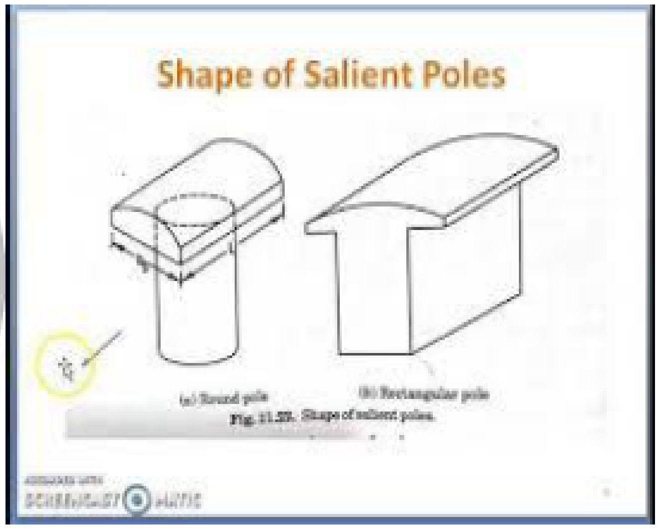
MAIN DIMENSIONS

The main dimensions of salient pole machines are D and L.
The choice of D and L depends on the type of pole and the permissible peripheral speed.
Two types of poles used are (i) Rectangular poles (ii) Round poles.
The figure 9 and 10 shows salient pole and cylindrical synchronous machine respectively.

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

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





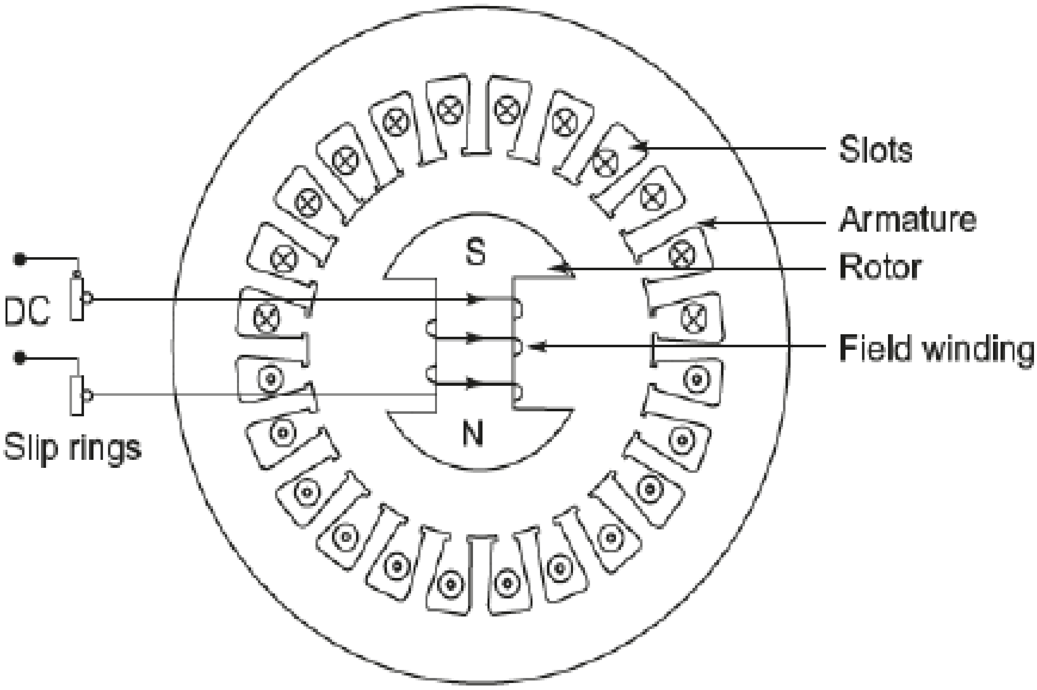


Figure 9. Salient pole synchronous machine

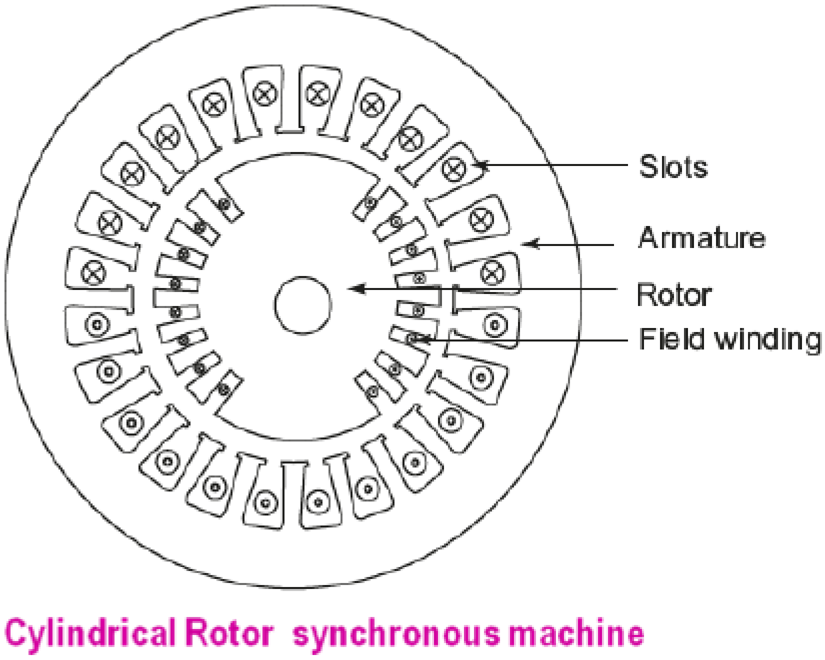


Figure 10. Cylindrical rotor synchronous machine

Run away speed

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

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

Peripheral speed

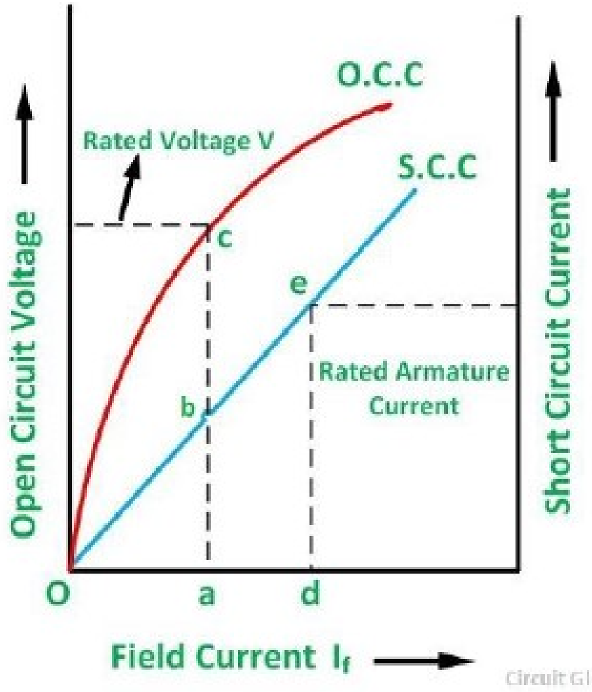
For bolted pole construction : 50 m / s

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

Short Circuit Ratio (SCR)

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

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



Effect of SCR on Machine Performance

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

Turns per phase

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

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

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

Where E_{ph} - induced emf per phase,

f - frequency of induced emf,

T_{ph} - Number of turns per phase

K_w - winding factor

Current per phase

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

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

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

Area or cross-section of stator conductor

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

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

Design of Damper winding

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

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

Where ac - specific electric loading,
τ - pole pitch
δ_d - current density in the bars (3 to 5 A/mm²)

Pole arc = Number of bars per pole x y_s x 0.8
= $N_d Y_s$ 0.8

Where y_s - slot pitch

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

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

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

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

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

Where d_d - diameter of damper bars

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

Design of Turbo Alternator

The values of specific loading for conventionally cooled generators

B_{av} = 0.54 to 0.65 wb/m²
ac = 50,000 to 75,000 Amp. Cond. / m

The values of specific loading for large water cooled generators

B_{av} = 0.54 to 0.62 wb/m²
ac = 1,80,000 to 2,00,000 Amp. Cond. / m

The maximum peripheral speed is 175 m/s

PROBLEMS

1. The field coils of a salient pole alternator are wound with a single layer winding of bare copper strip 30mm deep with separating insulation 0.15mm thick. Determine a suitable winding length, number of turns and thickness of conductor to develop an mmf of 12,000 A with potential difference of 5v per coil and with a loss of 1200 w/m^2 of total coil surface. The mean length of turn is 1.2m. The resistivity of copper is 0.021Ω/m and mm^2.

2. A 1250 kVA, 3 phase, 6600V, Salient pole alternator has the following data :
Air gap diameter = 1.6m Length of core = 0.45m Number of poles = 20 Armature ampere conductors per metre = 28,000 Ratio of pole are to pole pitch = 0.68 Stator slot pitch = 28mm Current density in damper bar = 3 A/mm$^{2.}$ Design suitable damper winding for the machine.

3. Determine the main dimensions for a 1000kVA, 50Hz,3 Phase, 375 rpm alternator. The average air gap flux density is 0.55 wb/m^2 and the ampere conductors per meter are 28,000. Use rectangular poles and assume a 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 50 m/s. The run away speed is 1.8 times the synchronous speed.

4. For a 250 kVA, 1100 V, 12 pole, 1500 rpm, three phase alternator. Determine air gap diameter, core length, number of stator slots and cross section of stator conductors. Assuring average gap density as 0.6 wb/m^2 and specific electric loading of 30000 amp.cond./m. assume $L / \zeta = 1.5$.

5.The field coils of a salient pole alternator are wound with a single layer winding of bare copper strip 30mm deep with separating insulation 0.15mm thick. Determine a suitable winding length, number of turns and thickness of conductor to develop an mmf of 12,000 A with potential difference of 5v per coil and with a loss of 1200 w/m^2 of total coil surface. The mean length of turn is 1.2m. The resistivity of copper is 0.021Ω/m and mm^2. **(5/11/2012)(13/4/2013)**

6.Determine the output coefficient for a 250 KVA, 1100 V, 3 phase, 12 pole, 50 Hz Alternator. Assuming Specific electric loading = 30000 amp. cond./m. and L/r = 1.5, find D and L. Assume average air gap density as 0.6 Wb/m^2. Find also the number of stator conductors, number of stator slots and cross-section of stator conductors.

7.A 1000 KVA, 3300.V, 50.HZ, 300 rpm, 3 phase alternator has 180 slots with 5 conductors per slot, single layer winding with full pitch coil is used. The winding is star connected with one circuit per phase. Determine the specific electric and magnetic loading if the stator bore is 2 m and the core length is 0.4 m. Using the same loading determine the corresponding data for 1250 KVA, 3300 V, 50 HZ, 250 rpm, 3 phase star connected alternator having 2 circuits per phase. The machines have 60° phase spread.

8.For a 250 KVA, 1100 V, 12 pole, 500 RPM, 3 phase alternator, determine the air gap diameter, core length, number of stator conductors. Assume average gap density as 0.6 Wb/m^2 and specific electric loading of 30000 Ampere Conductors per metre. $L/\tau = 1.5$.

9.A 1250 KVA, 3 phase, 6600V salient pole alternator has the following data Air gap length = 1.8 m, Core length =0.45m Number of poles =20 Armature ampere conductors per meter=33000, Ratio of pole arc to pole pitch =0.7,Stator slot pitch = 28mm and Current density in the damper bars = 3 $amps/mm^2$. Design a suitable damper winding for the machine.

10.Determine the main dimensions for a 10 kVA, 3 phase, 400/230V, star connected 1500 rpm,50Hz, alternator. Assume B_{av} = 0.045T, q= 22000 ac/m winding factor = 0.96. Ratio of core length to pole pitch = 1. Also determine the number of slots and conductors per slot.

11.Find the main dimension of a 2500 KVA, 187.5 rpm, 50 Hz, 3 phases, 3 KV salient pole synchronous generator. The generator is to be a vertical water wheel type. The specific magnetic loading is 0.6 Wb/m^2 and the specific electric loading 34000 ac/m. Use circular poles with ratio of core length to pole pitch = 0.65. Specify the type of pole construction used if the runaway speed is about 2 times the normal speed.

QUESTION BANK

UNIT-V

1.Name the two types of synchronous machines.
1. Salient pole machines
2. Cylindrical rotor machines.

2.What are the two type of poles used in salient pole machines?
The two types of poles used in salient pole machines are round pole and rectangular poles.

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

4.State three important features of turbo alternator rotors.
1. The rotors of turbo alternators have large axial length and small diameters.
2. Damping torque is provided by the rotor itself and so there is no necessity for additional damper winding.
3. They are suitable for high speed operations and so number of poles is usually 2 or 4.

5.What are the prime movers used for a) Salient pole alternator, b) Non salient pole alternator.
The prime movers used for salient pole alternators are water wheels like Kaplan turbine, Francis turbine, Pelton wheel etc., and diesel or petrol engines.
The prime movers used for non-salient pole alternators are steam turbines and gas turbines.

6.Distinguish between cylindrical pole and salient pole construction.
In cylindrical pole construction the rotor is made of solid cylinder and slots are cut on the outer periphery of the cylinder to accommodate field conductors In salient pole construction, the circular or rectangular poles are mounted on the outer surface of the cylinder. The field coils are fixed on the pole. The cylindrical pole construction is suitable for high speed operation , whereas the salient pole construction is suitable for slow speed operations.

7.Salient pole machines are not suitable for high speed operations, why?
The salient pole rotors cannot withstand the mechanical stresses developed at high speed. The projecting poles may be damaged due to mechanical stresses.

8.What is critical speed of alternator?
When the rotor of the alternator has an eccentricity, it may have a deflection while rotating. This deflection will be maximum at a speed called critical speed. When a rotor with eccentricity passes through critical speed, severe vibrations are developed.

9.Mention the uses of damper windings in a synchronous machine?

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

10.List the factors to be considered for separation of D and L for salient pole machines.
1. Peripheral speed
2. Number of poles
3. Short circuit ratio

11.Define pitch factor
The pitch factor is defined as the ratio of vector sum of emf induced in a coil to arithmetic sum of emf induced in the coil

12.Define distribution factor.
The distribution factor is defined as the ratio of vector sum to arithmetic sum of emf induced in the conductor of one phase spread.

13.Why alternators are rated in KVA?
The KVA rating of ac machine depends on the power factor of the load. The power factor in turn depends on the operating conditions. The operating conditions differ from place to place. Therefore the KVA rating is specified for all ac machines.

14 .What are the factors to be considered for the choice of specific magnetic loading?
1. Iron loss
2. Voltage rating
3. Transient short circuit current
4. Stability
5. Parallel operation.

15.Give typical values of flux density an ampere conductors per metre for large turbo alternators.
Bav = 0.54 to 0.65 wb/m2
ac = 50000 to 75000 amp.cond/m (For conventionally cooled machine)
ac = 180000 to 200000 amp.cond/m (for water cooled machine)

16.What are the factors to be considered for the choice of specific electric loading?
1. Copper loss
2. Temperature rise
3. Voltage rating
4. Synchronous reactance
5. Stray load losses

17.What is short circuit ratio?
The short circuit ratio is defined as the ratio of field current required to produce

rated voltage on open circuit to field current required to circulate the rated current on short circuit. It is also given as the reciprocal of synchronous reactance.

18.How the value of SCR affects the design of alternator?
For high stability and low regulation, the value of SCR should be high, which requires large air gap, when the length of air gap is large, the mmf requirement will be high so the field system will be large. Hence the machine will be costlier.

19.What are the advantages of large air gap in synchronous machines?
1. Reduction in armature reaction
2. Small value of regulation
3. Higher value of stability
4. A higher synchronous power which makes the machine less sensitive to load variation
5. Better cooling
6. Lower tooth pulsation loss
7. Less noise
8. Smaller unbalanced magnetic pull

20.Write the expression for length of air gap in salient pole synchronous machine
$lg = ATf_0/(B_gK_g \times 10^6)$ or $l_g = AT_a \times SCR \times K_f / B_{av} \times K_g \times 10^6$

21.List the influence of the air gap length on the performance of the synchronous machine.
1. Armature reaction
2. Noise
3. Unbalanced magnetic pull
4. Regulation
5. Tooth pulsation loss
6. Sensitivity to load variations

22.List the factors to be considered for the choice of slot in synchronous machines,
1. Balanced winding
2. Cost
3. Hot spot temperature in winding
4. Leakage reactance
5. Tooth losses
6. Tooth flux density

23.Determine the total number of slots in the stator of an alternator having 4 poles, 3 phase, 6 slots per pole per phase.
Total no. of slots = slots per pole per phase x no. of poles x no. of phase
= 6 x 4 x 3 = 72 slots
168.
24.What is the limiting factor for the diameter of synchronous machine?
The limiting factor of synchronous machine is the peripheral speed. The limiting value of peripheral speed is 175 m/s for cylindrical and 80 m/s for salient pole machines
25.Write the expression for air gap length in cylindrical rotor machines.

Length of air gap, $l_g = (0.5 SCR\ ac\ \tau\ K_f \times 10^{-6})/(K_g B_{av})$

26.What are the factors to be considered for selecting the number of poles in an alternator?
The number of poles depends on the speed of the prime mover and frequency of generated emf.
27.Discuss how the ventilation and cooling of large high speed alternator is carried out.
For high speed alternator two cooling methods are available and they are conventional cooling and direct cooling.
In conventional cooling methods, radial and axial ventilating ducts are provided in the core. Cooling is performed by forced circulation of air or hydrogen at a pressure higher than atmosphere.
In direct cooling methods, cooling ducts are provided in the stator and rotor slots or conductor itself will be in the form of tubes. Coolants like water or oil or hydrogen are circulated in the ducts to remove the heat directly from the conductors.
28.Mention the factors that govern the design of field system of the alternator.
1. Number of poles and voltage across each field winding
2. Amp-turn per pole
3. Copper loss in the field coil
4. Dissipating surface of field coil
5. Specific loss dissipation and allowable temperature rise.
29. Mention the advantages of fractional slot winding.
1. In low speed machines with large number of poles, fractional slot winding will reduce tooth harmonics
2. A range of machines with different speeds can be designed with a single lamination
3. The fractional slot winding reduces the harmonics in mmf and the leakage reactance of the winding.
30.What are the typical values of SCR for salient pole and turbo alternators?
For turbo alternators SCR is normally between 0.5 to 0.7 and that for salient pole alternator SCR varies from 1 to 1.5.
31.What type of prime movers is used in hydro electric stations depending on the head?
The type of water turbine used in hydroelectric station depends on water head. Pelton wheel is used for water heads of 400 m and above. Francis turbine is used for water heads upto 380 m. Kaplan turbine is used for water heads upto 50m.
32.List the types of synchronous machines operating on general power supply.
1. Hydro generators
2. Turbo generators
3. Engine driven generators
4. Motors
5. Compensators
33.Give the approximate values of runaway speed of the turbines with full gate opening.
Pelton wheel – 1.8 times the rated speed.
Francis turbine – 2 to 2.2 times the rated speed.

Kaplan turbine – 2.5 to 2.8 times the rated speed.
34.Write the output equation of a synchronous machine.
Q = C0D2Lns in KVA
C0 = 11KwsBav
ac x 10-3in KVA/m3-rps.