MUTHAYAMMAL ENGINEERING COLLEGE
(An Autonomous Institution)
(Approved by AICTE, New Delhi, Accredited by NAAC & Affiliated to Anna University)
Rasipuram - 637 408, Namakkal Dist., Tamil Nadu

L1

LECTURE HANDOUTS

EEE

III/V

Course Name with Code : 19EED05/ Design of Electrical Apparatus

Course Faculty : Mr. C. Ram Kumar

Unit : **I-**Introduction **Date of Lecture:**

Topic of Lecture:
Major considerations in Electrical Machine Design

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.

Prerequisite knowledge for Complete understanding and learning of Topic:
Generators
Motors and Transformers

Detailed content of the Lecture:
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,

1. **Magnetic circuit or the flux path**: Should establish required amount of flux using minimum mmf. The core losses should be less.
2. **Electric circuit or windings:** Should ensure required emf is induced with no complexity in winding arrangement. The copper losses should be less.
3. **Insulation:** Should ensure trouble free separation of machine parts operating at different potential and confine the current in the prescribed paths.
4. **Cooling system or ventilation:** Should ensure that the machine operates at the specified temperature.
5. **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.
h. Apart from the above factors Consumer, manufacturer or standard specifications may pose a limitation.

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=ju3qH37MfPk

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No2-4)

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L2

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code: 19EED05/ Design of Electrical Apparatus

Course Faculty : Mr. C. Ram Kumar

Unit : **I-**Introduction **Date of Lecture:**

Topic of Lecture:
Electrical Engineering Materials

Introduction :
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.

Prerequisite knowledge for Complete understanding and learning of Topic:
Conductor
Insulator
Magnet

1. Conducting materials

Commonly used conducting materials are copper and aluminum. 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 aluminum are shown in the table.

Sl. No	Particulars	Copper	Aluminum
1	Resistivity at 200C	0.0172 ohm / m/ mm2	0.0269 ohm / m/ mm2
2	Conductivity at 200C	58.14 x 106S/m	37.2 x 106S/m
3	Density at 200C	8933kg/m3	2689.9m3
4	Temperature coefficient (0-100oC)	0.393 % per 0C	0.4 % per 0C
5	Coefficient of linear expansion (0-100oC)	16.8x10-6 per oC	23.5 x10-6 per oC

- For the same resistance and length, cross-sectional area of aluminum is 61% larger than that of the copper conductor and almost 50% lighter than copper.
- Though the aluminum reduces the cost of small capacity transformers, it increases the size and cost of large capacity transformers.
- Aluminum is being much used now a days only because copper is expensive and not easily available. Aluminum is almost 50% cheaper than Copper and not much superior to copper.

2. 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 .
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.

Magnetic materials can broadly be classified as

1. Diamagnetic materials.
2. Paramagnetic materials.
3. Ferromagnetic materials.

Further the **Ferromagnetic materials can be classified** as

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

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=ju3qH37MfPk

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No.10-34)

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Course Name with Code : 19EED05/ Design of Electrical Apparatus

Course Faculty : Mr. C. Ram Kumar

Unit : **I-**Introduction **Date of Lecture:**

Topic of Lecture:
Electrical Engineering Materials

Introduction :
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.

Prerequisite knowledge for Complete understanding and learning of Topic:
Conductor
Insulator
Magnet

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.

The term insulting material is sometimes used in a broader sense to designate also insulating liquids, gas and vacuum.

Solid:

Used with field, armature, transformer windings etc.
The examples are:
1. Synthetic paper, wood, card board, cotton, jute, silk etc.,
2. Rubber : natural rubber, synthetic rubber-butadiene, silicone rubber, hypalon, etc.,
3. Mineral : mica, marble, slate, talc chloride 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.

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.

Insulation class		Maximum operating temperature in ℃	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.

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=ju3qH37MfPk

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No.10-34)

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LECTURE HANDOUTS

L4

EEE

III/VI

Course Name with Code : 19EED05/ Design of Electrical Apparatus

Course Faculty : Mr. C. Ram Kumar

Unit : **I-**Introduction **Date of Lecture:**

Topic of Lecture:
Choice of Specific Electrical loading

Introduction :

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

Flux density
Current

Detailed content of the Lecture:

Specific Electric Loading:

It is defined as the number of armature conductors per meter of armature periphery at the air gap.

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 D^2L 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 machines the diameter of the machine will be quite larger than the axial length.

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=Po3CWjo6wNo

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No. 457-460)

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LECTURE HANDOUTS

L5

EEE

III/VI

Course Name with Code : 19EED05/ Design of Electrical Apparatus

Course Faculty : Mr. C. Ram Kumar

Unit : **I-**Introduction **Date of Lecture:**

Topic of Lecture:
Choice of specific Magnetic loadings

Introduction :
The specific magnetic loading is defined as the total flux per unit area over the surface of the armature periphery and is denoted by B_{av} also known as average flux density.

Prerequisite knowledge for Complete understanding and learning of Topic:
Flux density
voltage

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 B_{av} also known as average flux density.

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.

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=Po3CWjo6wNo

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No. 457-460)

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LECTURE HANDOUTS

L6

EEE

III/VI

Course Name with Code: 19EED05/ Design of Electrical Apparatus

Course Faculty : Mr. C. Ram Kumar

Unit : **I-**Introduction **Date of Lecture:**

Topic of Lecture:
Thermal considerations

Introduction :
The heat is removed by convection, conduction and radiation. Usually, the convection through air, liquid or steam is the most significant method of heat transfer.

Prerequisite knowledge for Complete understanding and learning of Topic:

- Loose in electrical machines
- Transformer

Detailed content of the Lecture:

- The heat is removed by convection, conduction and radiation. Usually, the convection through air, liquid or steam is the most significant method of heat transfer.
- Forced convection is, inevitably, the most efficient cooling method if we do not take direct water cooling into account. The cooling design for forced convective cooling is also straightforward: the designer has to ensure that a large enough amount of coolant flows through the machine.
- This means that the cooling channels have to be large enough. If a machine with open-circuit cooling is of IP class higher than IP 20, using heat exchangers to cool the coolant may close the coolant flow.
- If the motor is flange mounted, a notable amount of heat can be transferred through the flange of the machine to the device operated by the motor.
- The proportion of heat transfer by radiation is usually moderate, yet not completely insignificant. A black surface of the machine in particular promotes heat transfer by radiation.

Conduction

- There are two mechanisms of heat transfer by conduction: first, heat can be transferred by molecular interaction, in which molecules at a higher energy level (at a higher temperature) release energy for adjacent molecules at a lower energy level via lattice vibration.
- Heat transfer of this kind is possible between solids, liquids and gases. The second means of conduction is heat transfer between free electrons.
- This is typical of liquids and pure metals in particular. The number of free electrons in alloys varies considerably, whereas in materials other than metals, the number of free electrons is small.

- The thermal conductivity of solids depends directly on the number of free electrons. Pure metals are the best heat conductors. Fourier's law gives the heat flow transferred by conduction.

$$\Phi_{\mathrm{th}} = -\lambda S \nabla T,$$

Temperature rise:

- The temperature rise of a machine depends on the power loss per cooling area S In electrical machines, the design of heat transfer is of equal importance as the electromagnetic design of the machine, because the temperature rise of the machine eventually determines the maximum output power with which the machine is allowed to be constantly loaded.
- As a matter of fact, accurate management of heat and fluid transfer in an electrical machine is a more difficult and complicated issue than the conventional electromagnetic design of an electrical machine.
- However, as shown previously in this material, problems related to heat transfer can to some degree be avoided by utilizing empirical knowledge of the machine constants available.
- When creating completely new constructions, empirical knowledge is not enough, and thorough modeling of the heat transfer is required. Finally, prototyping and measurements verify the successfulness of the design.
- The problem of temperature rise is twofold: first, in most motors, adequate heat removal is ensured by convection in air, conduction through the fastening surfaces of the machine and radiation to ambient.
- n machines with a high power density, direct cooling methods can also be applied. Sometimes even the winding of the machine is made of copper pipe, through which the coolant flows during operation of the machine.
- The heat transfer of electrical machines can be analyzed adequately with a fairly simple equation for heat and fluid transfer.
- The most important factor in thermal design is, however, the temperature of ambient fluid, as it determines the maximum temperature rise with the heat tolerance of the insulation. Second, in addition to the question of heat removal, the distribution of heat in different parts of the machine also has to be considered

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=MrOMsgBPOwE

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No. 35-45)

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L7

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05/ Design of Electrical Apparatus

Course Faculty : Mr. C. Ram Kumar

Unit : **I-**Introduction **Date of Lecture:**

Topic of Lecture:
Insulating Materials

Introduction :
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.

Prerequisite knowledge for Complete understanding and learning of Topic:
- Loose in electrical machines
- Transformer

Detailed content of the Lecture:
- Classification of insulating materials based on thermal consideration

Insulation class		Maximum operating temperature in ℃	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 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 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) = 130oC.
- 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 ^{o}C rise in temperature. The present day trend is to design the machine using class F insulation for class B temperature rise.

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=tM9QT1v0zq0

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No. 85-86)

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LECTURE HANDOUTS

L8

EEE **III/VI**

Course Name with Code : 19EED05/ Design of Electrical Apparatus

Course Faculty : Mr. C. Ram Kumar

Unit : **I-**Introduction **Date of Lecture:**

Topic of Lecture:
Rating of machines

Introduction :
Rating of a motor is the power output or the designated operating power limit based upon certain definite conditions assigned to it by the manufacturer.

Prerequisite knowledge for Complete understanding and learning of Topic:
- Electrical machines
- Transformer
- Power

Detailed content of the Lecture:
- The rating of machine refer to the whole of the numerical values of electrical and mechanical quantities with their duration and sequence assigned to the machines by the manufacturer and stated on the rating plate, the machine complying with the specified conditions.
- Rating of a single phase & three phase transformer in KVA is given as

$$Q = 2.22\ f\ B_m\ \delta\ K_w\ A_w\ A_i * 10^{-3}$$
$$Q = 3.33\ f\ B_m\ \delta\ K_w\ A_w\ A_i * 10^{-3}$$

Where f = frequency, Hz
B_m = maximum flux density, Wb/m^2
δ = current density, A/mm^2
K_w = Window space factor
A_w = Window area, m^2
A_i = Net core area, m^2

- Power rating for electrical machines indicates the required supply voltage for smooth running of that machine, it also shows the permissible maximum amount of current which can easily flows through the machine and there will be a chance of breakdown in the machine if those parameters goes beyond this limit.
- Similarly when we discuss about **motor power rating**, we are looking for the suitable conditions where maximum efficiency is obtained from the electric motor. When the motor have insufficient rating, there will be frequent damages and shut downs due to over loading, and this is not intended.
- On the other hand, if the power rating of a motor is decided liberally, the extra initial cost and then loss of energy due to operation below rated power makes this choice totally uneconomical.

- Another essential criteria of electrical motor power rating is that, during operation of motor, heat is produced and it is inevitable due to I2R loss in the circuit and friction within the motor.
- So, the ventilation system of the motor should be designed very carefully, to dissipate the generated heat as quickly as possible. The output power of the motor is directly related with the temperature rise, that's why it is also called thermal loading.
- The thermal dissipation will be ideal when the ventilation system is designed in such a way that the heat generated during the operation is equal to or less then heat dissipated by the motor to the surrounding.
- Now, due to the design of motors, temperature is not same everywhere inside the motor. There is a high amount of heat produced in the windings because, windings cause higher heat generation.
- The insulating materials used in the winding are also chosen depending on the amount of heat generated inside the motor during operation. So in the end it can be said that the main objectives of selecting and finding out **motor power rating** are-
    - To obtain the suitable thermal model of motor and design the machine properly.
    - Finding out motor duty class.
    - Calculating motor ratings for various classes of duty.

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=Wap0sv14sz8

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No. 887-890)

Course Faculty

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L9

LECTURE HANDOUTS

EEE

III/VI

Course Name with Code : 19EED05/ Design of Electrical Apparatus

Course Teacher : Mr. C.RAMKUMAR

Unit-1 : Introduction **Date of Lecture:**

Topic of Lecture:
Standard specifications

Introduction :
Rating of a motor is the power output or the designated operating power limit based upon certain definite conditions assigned to it by the manufacturer.

Prerequisite knowledge for Complete understanding and learning of Topic:

- Electrical machines
- Transformer
- Power

Detailed content of the Lecture:

- Standards that provide standard measurement, symbology or terminology are sometimes known as definition standards. These create a foundation on which many other standards can be created. The metric system is an example of a definition standard.
- IS 325-1966 : Specifications for 3ph induction motor
- IS 4029-1967 : Guide for testing 3ph induction motor
- IS12615-1986 : Specifications for energy efficient induction motor
- IS13555-1993 : Guide for selection & application of 3ph induction motor fordifferent types of driven equipment
- IS8789-1996 : Values of performance characteristics for 3ph inductionmotor
- IS 12066-1986: 3ph induction motors for machine tool

Standard specifications

1. Output : kW (for generators), kW or Hp (for motors)
2. Voltage : V volt
3. Speed : N rpm
4. Rating : Continuous or Short time
5. Temperature rise: θ0C for an ambient temperature of 400C
6. Cooling : Natural or forced cooling
7. Type: Generator or motor, separately excited or self-excited-shunt, series, or compound, if compound type of connection – long or short shunt, type of compounding – cumulative or differential, degree of compounding – over, under or level. With or without inter poles, with or without compensating windings,with or without equalizer rings in case of lap winding.
8. Voltage regulation (in case of generators) : Range and method

9. Speed control (in case of motors) : range and method of control
10. Efficiency: must be as for as possible high (As the efficiency increases, cost of the machine also increases).
11. Type of enclosure: based on the field of application – totally enclosed, screen protected, drip proof, flame proof, etc.,
12. Size of the machine etc.,

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=yBnlOWMhovE

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No. 890-893)

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L10

LECTURE HANDOUTS

EEE | **III/VI**

Course Name with Code : 19EED05/ Design of Electrical Apparatus

Course Faculty : Mr. C. Ram Kumar

Unit : **I-**Introduction **Date of Lecture:**

Topic of Lecture:
Choice of Specific Electrical loading(Tutorial I)

Introduction :
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.

Prerequisite knowledge for Complete understanding and learning of Topic:
Flux density
Current

Detailed content of the Lecture:

Problem1.1 *A 400 KW, 500 V, 450 rpm, 6 pole dc motor is built with an armature diameter of 0.87 m and core length of 0.32 m. The lap wound armature has 660 conductors. Calculate the specific electric and specific magnetic loadings.*

Given:

$$P = 400\ KW = 400 \times 1000\ watts$$

$V = 500$ V

$N = 450$ rpm

$p = 6$

$D = 0.87$ m

$L = 0.32$ m

$Z = 660$ conductors (Lap wound machine)

$a = p = 6$ (number of parallel path)

To find:

(*i*) Specific magnetic loading, (B_{av})

(*ii*) Specific electric loading, (ac)

☺***Solution:***

(*i*) Specific magnetic loading

$$B_{av} = \frac{p\phi}{\pi D L} \text{ Wb/m}^2 \text{ (or) tesla}$$

Unknown value ϕ - flux per pole, it can be obtained using back emf relation of dc machine

$$E_b = \frac{\phi Z N p}{60\, a}$$

$$E_b \approx V \text{ (}\because\text{ voltage drop in the armature is not given)}$$

a = number of parallel path

$a = p = 6$ [$\because$ lap wound dc machine]

$$\phi = \frac{E_b \times 60 \times a}{Z N p}$$

$$= \frac{500 \times 60 \times 6}{660 \times 450 \times 6}$$

$$\phi = 0.101 \text{ Wb}$$

$$B_{av} = \frac{6 \times 0.101}{\pi \times 0.87 \times 0.32}$$

$$\boxed{B_{av} = 0.6928 \approx 0.693 \text{ Wb/m}^2 \text{ or tesla}}$$ **Ans.**

(ii) Specific electric loading

$$ac = \frac{I_Z Z}{\pi D} \text{ ampere.conductors/metre}$$

I_Z - current through conductor in each parallel path

$$I_Z = \frac{I_a}{\text{parallel path}} = \frac{I_a}{a} = \frac{I_a}{p}$$

$$\text{Armature current, } (I_a) = \frac{P_a}{V} \qquad (\because P_a = P \text{ for motor})$$

$$I_a = \frac{400 \times 10^3}{500}$$

$$I_a = 800 \text{ Amps}$$

$$I_Z = \frac{800}{6} = 133.33 \text{ A}$$

$$ac = \frac{133.33 \times 660}{\pi \times 0.87}$$

$$\boxed{ac = 32196.8 \text{ ampere conductors per metre}}$$ **Ans.**

Result

Specific magnetic loading, B_{av} = 0.693 Wb/m² or tesla

Specific electric loading, ac = 32196.8 amp.cond/metre

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=Po3CWjo6wNo

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No. 457-460)

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LECTURE HANDOUTS

L11

EEE

III/VI

Course Name with Code : 19EED05/ Design of Electrical Apparatus

Course Faculty : Mr. C. Ram Kumar

Unit : **I-**Introduction **Date of Lecture:**

Topic of Lecture:
Choice of specific Magnetic loadings(Tutorial II)

Introduction :
The specific magnetic loading is defined as the total flux per unit area over the surface of the armature periphery and is denoted by B_{av} also known as average flux density.

Prerequisite knowledge for Complete understanding and learning of Topic:
Flux density
Voltage

Problem 1.2 *Calculate the specific electric and specific magnetic loading of 100 hp, 3000 V, 3 phase, 50 Hz, 8 pole, star connected flame proof induction motor having stator core length 0.5 m and stator bore 0.66 m. Turns/phase = 286. Assume full load efficiency = 0.938 and power factor = 0.86*

Given:

$$P = 100 \text{ hp} \Rightarrow P = 100 \times 0.746 \text{ KW} = 74.6 \text{ KW}$$
$$V = 3000 \text{ V}$$
$$m = 3$$
$$f = 50 \text{ Hz}$$
$$p = 8 \text{ (star connected induction motor)}$$
$$L = 0.5 \text{ m}; I_L = I_{ph}$$
$$D = 0.66 \text{ m}$$

$T_{ph} = 286$

$\eta = 0.938$

$p.f = \cos\phi = 0.86$

To find:

(*i*) Specific electric loading (ac)

(*ii*) Specific magnetic loading (B_{av})

Solution:

(*i*) Specific electric loading

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

Current through each conductor, $I_Z = I_{ph} = I_{LS}$ (star connected motor)

$$I_{LS} = \frac{P \times 10^3}{\sqrt{3} \times V_L \times \eta \times \cos\phi}$$

$$= \frac{74.6 \times 10^3}{\sqrt{3} \times 3000 \times 0.938 \times 0.86}$$

$$I_{LS} = 17.8 \text{ amps}$$

For star connected induction motor,

$$I_Z = I_L = I_{ph} = 17.8 \text{ amps}$$

Total number of stator conductor $Z = 6\,T_{ph}$

$$Z = 6 \times 286$$

$$Z = 1716 \text{ conductors}$$

∴ Specific electric loading, $ac = \dfrac{I_Z Z}{\pi D}$

$$ac = \frac{17.8 \times 1716}{\pi \times 0.66}$$

$$ac = 14731.4$$

$$ac \approx 14750 \text{ ampere conductors/metre}$$ **Ans.**

(*ii*) Specific magnetic loading

$$B_{av} = \frac{p\,\phi}{\pi D L}$$ (∴ In general)

Another formula are used to calculate B_{av} from output relation

$$Q = 11\, B_{av}\, ac\, K_{ws}\, D^2 L\, n_s \times 10^{-3} \text{ in KVA}$$

$$B_{av} = \frac{Q}{11\, ac\, K_{ws}\, D^2 L\, n_s \times 10^{-3}}$$

Take K_{ws} = stator winding factor $= 0.955$

$$\text{Synchronous speed, } N_s = \frac{120 f}{p} \text{ rpm}$$

$$n_s = \frac{N_s}{60} = \frac{2f}{p} \text{ in rps}$$

$$n_s = \frac{2 \times 50}{8} = 12.5 \text{ rps}$$

$$\therefore \quad B_{av} = \frac{92.477}{11 \times 14750 \times 0.955 \times (0.66)^2 \times 0.5 \times 10^{-3} \times 12.5}$$

$$\boxed{B_{av} = 0.219 \approx 0.22 \text{ Wb/m}^2 \text{ or tesla}}$$ **Ans.**

Result

Specific electric loading, ac = 14750 amp.conductor/metre

Specific magnetic loading, B_{av} = 0.22 Wb/m^2 or tesla

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=Po3CWjo6wNo

Important Books/Journals for further learning including the page nos.:

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Rasipuram - 637 408, Namakkal Dist., Tamil Nadu

L12

LECTURE HANDOUTS

EEE

III/VI

Course Name with Code : 19EED05/ Design of Electrical Apparatus

Course Faculty : Mr. C. Ram Kumar

Unit : **I-**Introduction **Date of Lecture:**

Topic of Lecture:
Thermal considerations(Tutorial III)

Introduction :
The heat is removed by convection, conduction and radiation. Usually, the convection through air, liquid or steam is the most significant method of heat transfer.

Prerequisite knowledge for Complete understanding and learning of Topic:

- Loose in electrical machines
- Transformer

Problem 1.10 *The heat dissipating surface of a 8 KW, totally enclosed induction motor can be approximated at a cylinder 700 mm in diameter and 1 m in length. The motor can be considered to be made up of a homogenous material weighing 400 kg and having specific heat of 725 J/kg/°C. The specific heat dissipation from its surface is 12 W/m²/°C. Find the temperature rise of the machine at full load, if the efficiency is 90%. Also find the thermal time constant.*

Given:

$$P_{out} = 8 \text{ KW} = 8000 \text{ watts}$$

$$D = 700 \text{ mm} = 0.7 \text{ m}$$

$$L = 1 \text{ m}$$

$$G = 400 \text{ kg}$$

$$h = 725 \text{ J/kg/°C (or) J/kg-°C}$$

$$\lambda = 12 \text{ W/m}^2\text{/°C}$$

$$\eta = 90\,\% = 0.9$$

To find:

(*i*) temperature rise of the machine at full load (θ_m)

(*ii*) thermal time constant (t_h)

☺***Solution:***

(*i*) Temperature rise of the machine at full load (or) final steady temperature rise when heating

$$\theta_m = \frac{Q}{S\lambda}$$

$$\text{Loss or heat generated, } Q = P_{out}\left(\frac{1-\eta}{\eta}\right)$$

$$Q = 8000\left(\frac{1-0.9}{0.9}\right)$$

$$Q = 888.88 \text{ watts}$$

$$\text{Heat dissipating surfaces, } S = \pi D L$$

$$= \pi \times 0.7 \times 1$$

$$S = 2.199 \text{ m}^2$$

∴ Temperature rise, $\theta_m = \frac{888.88}{12 \times 2.199}$

$$\boxed{\theta_m = 33.68\ °C}$$ **Ans.**

(*ii*) Heating time constant

$$t_h = \frac{G\,h}{S\,\lambda}$$

$$= \frac{400 \times 725}{2.199 \times 12} = 10990 \text{ sec}$$

$$\boxed{t_h = 3.052 \text{ hours}}$$ **Ans.**

Result:

(*i*) Temperature rise of the machine at full load $\theta_m = 33.68$ °C

(*ii*) Thermal time constant $t_h = 3.052$ hours

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=MrOMsgBPOwE

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No. 35-45)

Course Faculty

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L13

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code: 19EED05/ Design of Electrical Apparatus

Course Faculty : Mr. C. Ram Kumar

Unit : **I-**Introduction **Date of Lecture:**

Topic of Lecture:
Major considerations in Electrical Machine Design

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.

Prerequisite knowledge for Complete understanding and learning of Topic:
Generators
Motors and Transformers

Detailed content of the Lecture:

Problem1.1 *A 400 KW, 500 V, 450 rpm, 6 pole dc motor is built with an armature diameter of 0.87 m and core length of 0.32 m. The lap wound armature has 660 conductors. Calculate the specific electric and specific magnetic loadings.*

Given:

$$P = 400 \text{ KW} = 400 \times 1000 \text{ watts}$$

$$V = 500\ V$$
$$N = 450\ rpm$$
$$p = 6$$
$$D = 0.87\ m$$
$$L = 0.32\ m$$
$$Z = 660 \text{ conductors (Lap wound machine)}$$
$$a = p = 6 \text{ (number of parallel path)}$$

To find:

(*i*)Specific magnetic loading, (B_{av})

(*ii*) Specific electric loading, (ac)

☺***Solution:***

(*i*) Specific magnetic loading

$$B_{av} = \frac{p\phi}{\pi D L} \text{ Wb/m}^2 \text{ (or) tesla}$$

Unknown value ϕ - flux per pole, it can be obtained using back emf relation of dc machine

$$E_b = \frac{\phi Z N p}{60\, a}$$

$$E_b \approx V \text{ (} \Theta \text{ voltage drop in the armature is not given)}$$

$$a = \text{number of parallel path}$$

$$a = p = 6 \quad [\Theta \text{ lap wound dc machine}]$$

$$\phi = \frac{E_b \times 60 \times a}{Z N p}$$

$$= \frac{500 \times 60 \times 6}{660 \times 450 \times 6}$$

$$\phi = 0.101\ Wb$$

$$B_{av} = \frac{6 \times 0.101}{\pi \times 0.87 \times 0.32}$$

$$\boxed{B_{av} = 0.6928 \approx 0.693 \text{ Wb/m}^2 \text{ or tesla}}$$ **Ans.** ☜

(*ii*) Specific electric loading

$$ac = \frac{I_Z Z}{\pi D} \text{ ampere.conductors/metre}$$

I_Z - current through conductor in each parallel path

$$I_Z = \frac{I_a}{\text{parallel path}} = \frac{I_a}{a} = \frac{I_a}{p}$$

$$\text{Armature current, } (I_a) = \frac{P_a}{V} \qquad (\because P_a = P \text{ for motor})$$

$$I_a = \frac{400 \times 10^3}{500}$$

$$I_a = 800 \text{ Amps}$$

$$I_Z = \frac{800}{6} = 133.33 \text{ A}$$

$$ac = \frac{133.33 \times 660}{\pi \times 0.87}$$

$$\boxed{ac = 32196.8 \text{ ampere conductors per metre}}$$ **Ans.**

Result

Specific magnetic loading, B_{av} = 0.693 Wb/m² or tesla

Specific electric loading, ac = 32196.8 amp.cond/metre

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=ju3qH37MfPk

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No2-4)

Course Faculty

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LECTURE HANDOUTS

L14

EEE

III/VI

Course Name with Code : 19EED05/ Design of Electrical Apparatus

Course Faculty : Mr. C. Ram Kumar

Unit : **I-**Introduction **Date of Lecture:**

Topic of Lecture:
Choice of specific Magnetic loadings

Introduction :
The specific magnetic loading is defined as the total flux per unit area over the surface of the armature periphery and is denoted by B_{av} also known as average flux density.

Prerequisite knowledge for Complete understanding and learning of Topic:
Flux density
Voltage

Specific magnetic loading:

Problem 1.2 *Calculate the specific electric and specific magnetic loading of 100 hp, 3000 V, 3 phase, 50 Hz, 8 pole, star connected flame proof induction motor having stator core length 0.5 m and stator bore 0.66 m. Turns/phase = 286. Assume full load efficiency = 0.938 and power factor = 0.86*

Given:

$$P = 100\text{ hp} \Rightarrow P = 100 \times 0.746\text{ KW} = 74.6\text{ KW}$$
$$V = 3000\text{ V}$$
$$m = 3$$
$$f = 50\text{ Hz}$$
$$p = 8\text{ (star connected induction motor)}$$
$$L = 0.5\text{ m};\ I_L = I_{ph}$$
$$D = 0.66\text{ m}$$

$$T_{ph} = 286$$
$$\eta = 0.938$$
$$p.f = \cos\phi = 0.86$$

To find:

(*i*) Specific electric loading (ac)

(*ii*) Specific magnetic loading (B_{av})

Solution:

(*i*) Specific electric loading

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

Current through each conductor, $I_Z = I_{ph} = I_{LS}$ (star connected motor)

$$I_{LS} = \frac{P \times 10^3}{\sqrt{3} \times V_L \times \eta \times \cos\phi}$$

$$= \frac{74.6 \times 10^3}{\sqrt{3} \times 3000 \times 0.938 \times 0.86}$$

$$I_{LS} = 17.8 \text{ amps}$$

For star connected induction motor,

$$I_Z = I_L = I_{ph} = 17.8 \text{ amps}$$

Total number of stator conductor $Z = 6\, T_{ph}$

$$Z = 6 \times 286$$

$$Z = 1716 \text{ conductors}$$

∴ Specific electric loading, $ac = \dfrac{I_Z Z}{\pi D}$

$$ac = \frac{17.8 \times 1716}{\pi \times 0.66}$$

$$ac = 14731.4$$

$$\boxed{ac \approx 14750 \text{ ampere conductors/metre}}$$ **Ans.**

(*ii*) Specific magnetic loading

$$B_{av} = \frac{p\,\phi}{\pi D L}$$ (∴ In general)

Another formula are used to calculate B_{av} from output relation

$$Q = 11 B_{av}\, ac\, K_{ws}\, D^2 L\, n_s \times 10^{-3} \text{ in KVA}$$

$$B_{av} = \frac{Q}{11\, ac\, K_{ws}\, D^2 L\, n_s \times 10^{-3}}$$

Take K_{ws} = stator winding factor = 0.955

$$\text{Synchronous speed, } N_s = \frac{120 f}{p} \text{ rpm}$$

$$n_s = \frac{N_s}{60} = \frac{2f}{p} \text{ in rps}$$

$$n_s = \frac{2 \times 50}{8} = 12.5 \text{ rps}$$

$$\therefore \quad B_{av} = \frac{92.477}{11 \times 14750 \times 0.955 \times (0.66)^2 \times 0.5 \times 10^{-3} \times 12.5}$$

$$\boxed{B_{av} = 0.219 \approx 0.22 \text{ Wb/m}^2 \text{ or tesla}} \quad \textbf{Ans.}$$

Result

Specific electric loading, ac = 14750 amp.conductor/metre

Specific magnetic loading, B_{av} = 0.22 Wb/m^2 or tesla

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=Po3CWjo6wNo

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No. 457-460)

Course Faculty

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LECTURE HANDOUTS

L15

EEE

III/VI

Course Name with Code : 19EED05/ Design of Electrical Apparatus

Course Faculty : Mr. C. Ram Kumar

Unit : **I-**Introduction **Date of Lecture:**

Topic of Lecture:
Rating of machines

Introduction :
Rating of a motor is the power output or the designated operating power limit based upon certain definite conditions assigned to it by the manufacturer.

Prerequisite knowledge for Complete understanding and learning of Topic:

- Electrical machines
- Transformer
- Power

Detailed content of the Lecture:

Problem 1.11 *An induction motor has to perform the following duty cycle:*

100 KW for 10 minutes

No load for 6 minutes

55 KW for 7 minutes

No load for 4 minutes

which is repeated indefinitely. Determine a suitable capacity of a continuously rated motor to perform the aforesaid duty. Motors standard (continuous) ratings of 45, 55, 100 KW are available. The ratio of maximum torque to nominal torque to nominal torque should be less than 1.8.

Given:

$P_1 = 100$ KW; $t_1 = 10$ min

$P_2 = 0$; $t_2 = 6$ min

$P_3 = 55$ Kw; $t_3 = 7$ min

$P_4 = 0$; $t_4 = 4$ min

To find:

Determination of motor rating

Solution:

Suitable capacity of a continuously rated motor to perform the specified duty can be found by using equivalent power method.

$$P_{eq} = \sqrt{\frac{P_1^2\, t_1 + P_2^2\, t_2 + P_3^2\, t_3 + P_4^2\, t_4}{t_1 + t_2 + t_3 + t_4}}$$

$$P_{eq} = \sqrt{\frac{100^2 \times 10 + 0 + 55^2 \times 7 + 0}{10 + 6 + 7 + 4}}$$

$$P_{eq} = 66.99 \text{ KW}$$

Given as, A motor of standard ratings (45, 55, 100 KW).

∴ A motor having standard rating 100 KW is selected.

We know that,

$$\text{Power} \propto \text{Torque} \quad \text{(If speed is constant)}$$

$$\frac{P_{max}}{P_{nom}} = \frac{T_{max}}{T_{nom}} = \frac{100}{100} = 1$$

The ratio of maximum torque to its nominal torque is satisfied for the given condition as $\frac{T_{max}}{T_{nom}}$ should be less than 1.8.

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=Wap0sv14sz8

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No. 887-890)

Course Faculty

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L16

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code: Design of Electrical Apparatus/19EED05

Course Faculty : Mr. C. Ram Kumar

Unit : II- D.C Machines **Date of Lecture:**

Topic of Lecture:
Output Equations

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

- Construction of dc motor
- Types o motor

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

Ia : 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

= (φ Z N P/60 A)× Ia× 10-3

= (Pφ) × (I a Z/A) × N x 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 = Pφ /π DL Wb/m2 or tesla denoted by T

Therefore Pφ = Bav π DL ....(2)

The term (Ia 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 q. That is,

Therefore Ia Z/A = q π D ....(3)

Substitution of equations 2 and 3 in 1, leads to

$kW = Bav\ \pi\ DL \times q\ \pi\ D \times (N \times 10^{-3} / 60)$

$= 1.64 \times 10\text{-}4\ B\ q\ D2\ L\ N$

$= C0\ D^2\ L\ N$

Where C0 is called the output coefficient of the DC machine and is equal to 1.64 x 10-4 Bq.

Therefore D2 L = (Kw/1.64 × 10-4 B q N) m3

The above equation is called the output equation. The D2L product represents the size of the machine or volume of iron used. In order that the maximum output is obtained /kg of iron used, D2L product must be as less as possible. For this, the values of q and Bav must be high.

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=PZppwqNMAws

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No6.2-6.4)

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L17

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code: Design of Electrical Apparatus/19EED05

Course Faculty : Mr. C. Ram Kumar

Unit : II- D.C Machines **Date of Lecture:**

Topic of Lecture:

Main Dimensions

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.

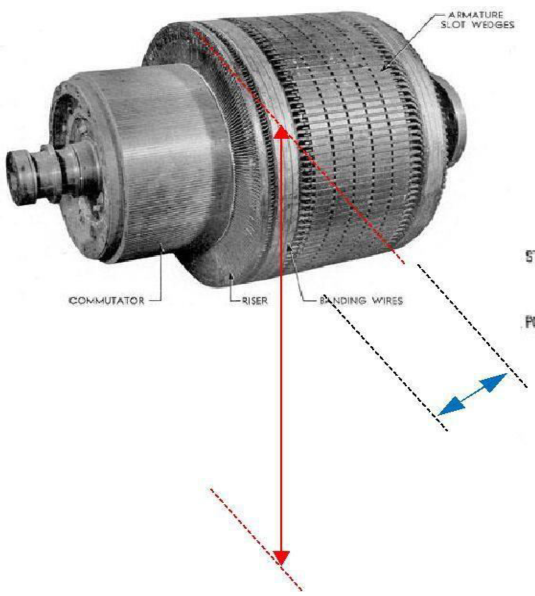
Prerequisite knowledge for Complete understanding and learning of Topic:

- Construction of dc motor
- Types o motor

Detailed content of the Lecture:

Main Dimensions

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.



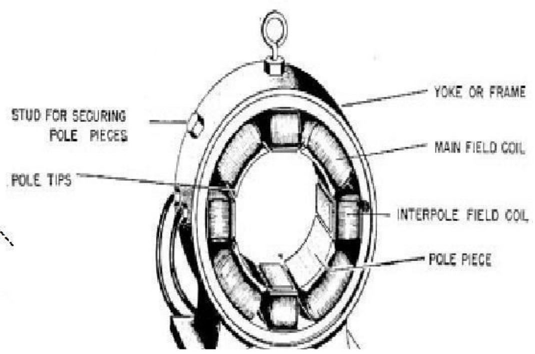
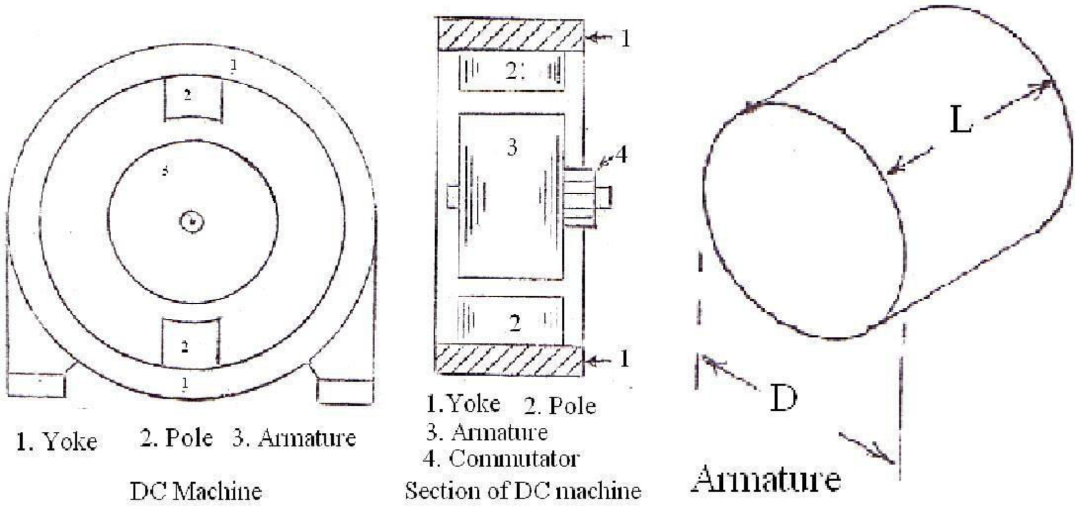


Fig Armature of a dc machine Fig. Yoke and pole arrangement of a dc machine



Video Content / Details of website for further learning (if any): https://www.youtube.com/watch?v=020AeaYRb24
Important Books/Journals for further learning including the page nos.: Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No6.1-6.2)

Course Faculty

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L18

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : Design of Electrical Apparatus/19EED05

Course Faculty : Mr. C. Ram Kumar

Unit : II- D.C Machines **Date of Lecture:**

Topic of Lecture:
Choice of Specific Electrical loading

Introduction :
Specific electrical loading 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.

Prerequisite knowledge for Complete understanding and learning of Topic:
- Construction of dc motor
- Types o motor

Detailed content of the Lecture:

Specific Electric Loading:

Specific electrical loading 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.

(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 machines the diameter of the machine will be quite larger than the axial length.

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=020AeaYRb24

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No6.5-6.8)

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LECTURE HANDOUTS

L19

EEE **III/VI**

Course Name with Code : Design of Electrical Apparatus/19EED05

Course Faculty : Mr. C. Ram Kumar

Unit : II- D.C Machines **Date of Lecture:**

Topic of Lecture:
Choice of Magnetic Loading

Introduction :
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.

Prerequisite knowledge for Complete understanding and learning of Topic:
- Construction of dc motor
- Types of motor

Detailed content of the Lecture:

Choice of 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.

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.

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=020AeaYRb24

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No6.5-6.8)

Course Faculty

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Course Name with Code : Design of Electrical Apparatus/19EED05

Course Faculty : Mr. C. Ram Kumar

Unit : II- D.C Machines **Date of Lecture:**

Topic of Lecture:
Selection of number of poles

Introduction :

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

- Construction of dc motor
- Poles
- Armature winding

Detailed content of the Lecture:

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

i) Frequency

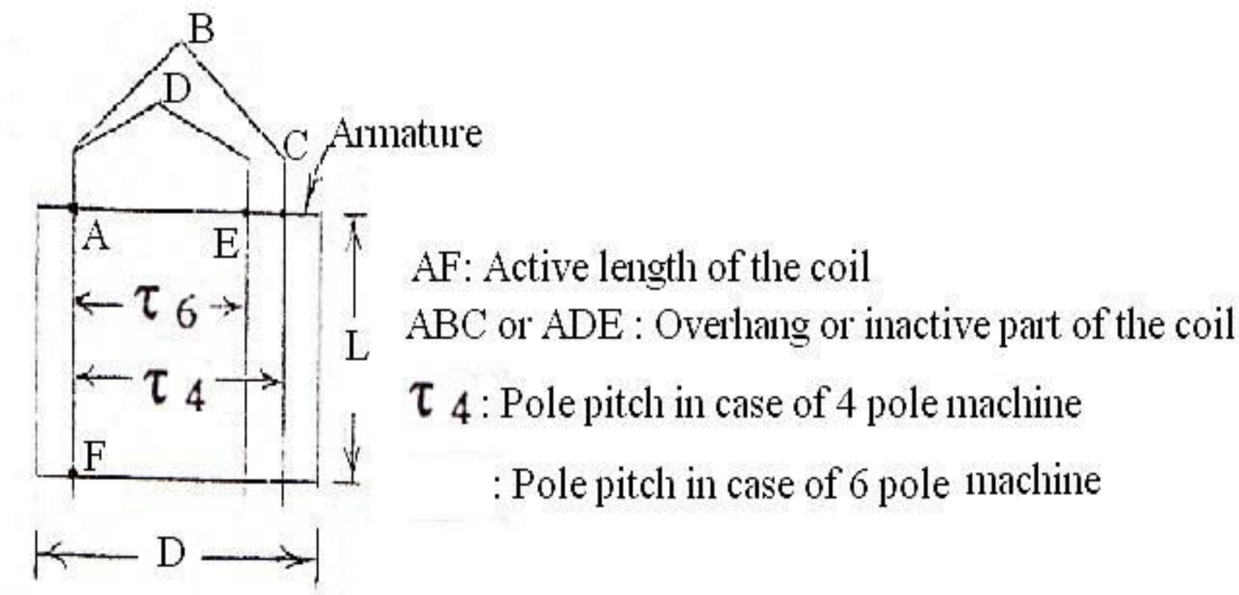
- As the number of poles increases, frequency of the induced EMF increases core loss in the armature increases and therefore efficiency of the machine decreases.

ii) Weight of the iron used for the yoke

- Since the flux carried by the yoke is approximately φ/2 and the total flux φT = pφ is a constant for a given machine, flux density in the yoke.

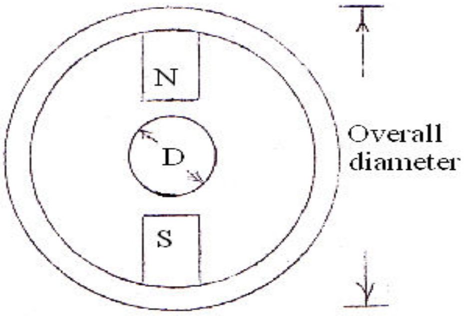
iii) Weight of overhang copper:

- For a given active length of the coil, overhang ∝ pole pitch goes on reducing as the number of poles increases. As the overhang length reduces, the weightof the inactive copper used at the overhang also reduces.

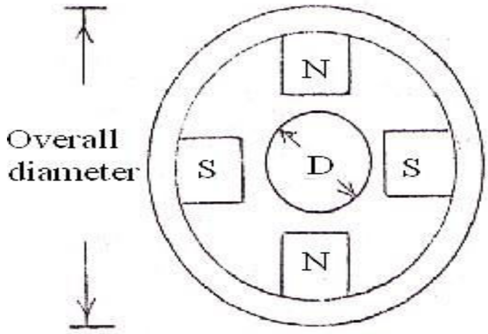


iv) Overall diameter:

- 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.



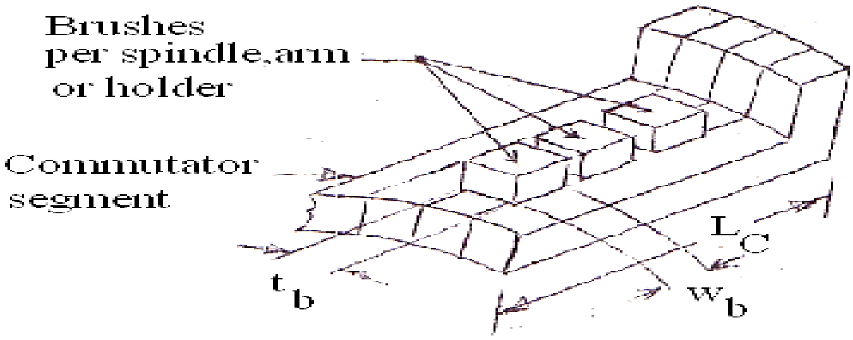
Diameter in case of 2 pole machine



Diameter in case of 4 pole machine

v) Length of the commutator:

Since each brush arm collects the current from every two parallel paths



A portion of the commutator

Video Content / Details of website for further learning (if any):

https://www.youtube.com/results?search_query=selection+o+poles

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No 9.18-9.20)

Course Faculty

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L21

LECTURE HANDOUTS

EEE

III/VI

Course Name with Code : Design of Electrical Apparatus/19EED05

Course Faculty : Mr. C. Ram Kumar

Unit : II- D.C Machines **Date of Lecture:**

Topic of Lecture:
Selection of number of poles (Derivation and simple problem)

Introduction :
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.

Prerequisite knowledge for Complete understanding and learning of Topic:

- Construction of dc motor
- Poles
- Armature winding

Detailed content of the Lecture:

Selection of number of poles

- Selection of number of poles in DC machines 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.
- (a) Frequency of the armature induced emf f = PN/120 should as for as possible between 25 and 50 Hz.
- (b) Armature ampere turns / pole = I Z / 2AP

Example:

Select a suitable number of poles for a 100kW, 500V DC machine.

Armature current (approximately) = I = (100 x10)/500 = 200A

For a current of 200A a lap or wave winding can be used. Since the minimum number of paths and poles is two, 2 poles are sufficient for the machine.

However to gain more advantages of more number of poles, let the number of poles be 4.

- **Video Content /** Details **of website for further learning (if any):**

  https://www.youtube.com/results?search_query=selection+o+poles

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No 9.18-9.20)

Course Faculty

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L22

LECTURE HANDOUTS

EEE

III/VI

Course Name with Code : Design of Electrical Apparatus/19EED05

Course Faculty : Mr. C. Ram Kumar

Unit : II- D.C Machines **Date of Lecture:**

Topic of Lecture:
Problem on Armature Design

Introduction :
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.

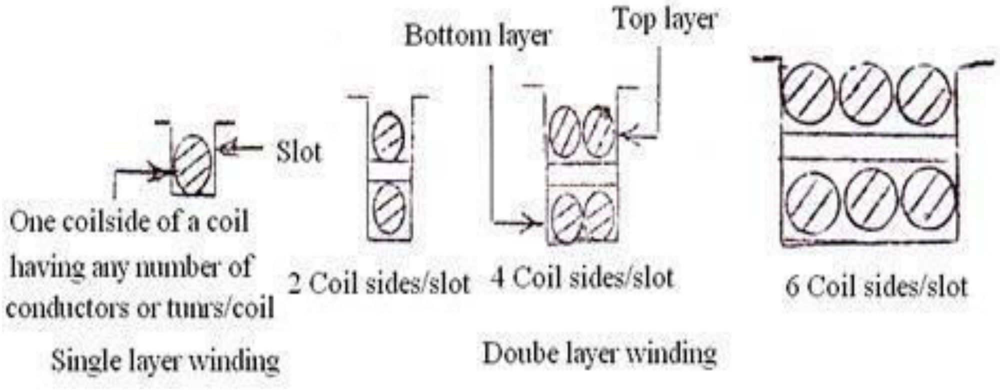
Prerequisite knowledge for Complete understanding and learning of Topic:

- Construction of dc motor
- Poles
- Armature winding

Detailed content of the Lecture:

Armature Design

- 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 design calculations become complicated (because of the complicated expression of non- sinusoidal wave).
- Core loss increases (because of the fundamental and harmonic components of the non-sinusoidal wave) and efficiency reduces.
- 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.



- 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 number 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.
- As the number of slots increases, cost of punching the slot increases, number of coils increases and hence the cost of the machine increases.
- As the number of slots increases, slot pitch λs = (slot width bs + tooth width bt) = πD/ number of slots 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. Therefore efficiency of the machine decreases.

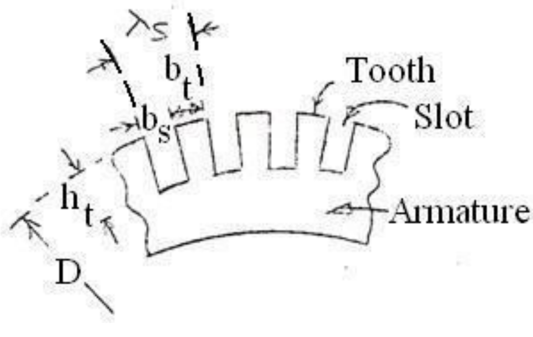


Fig. Armature Dimension view

- 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 assumed 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 an integer.

- **Video Content /** Details **of website for further learning (if any):**

https://www.youtube.com/watch?v=Ao3B4wcZkg8

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No 9.40-9.43)

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LECTURE HANDOUTS | **L23**

EEE | **III/VI**

Course Name with Code : Design of Electrical Apparatus/19EED05

Course Faculty : Mr. C. Ram Kumar

Unit : II- D.C Machines **Date of Lecture:**

Topic of Lecture:
Derivation on commutators design.

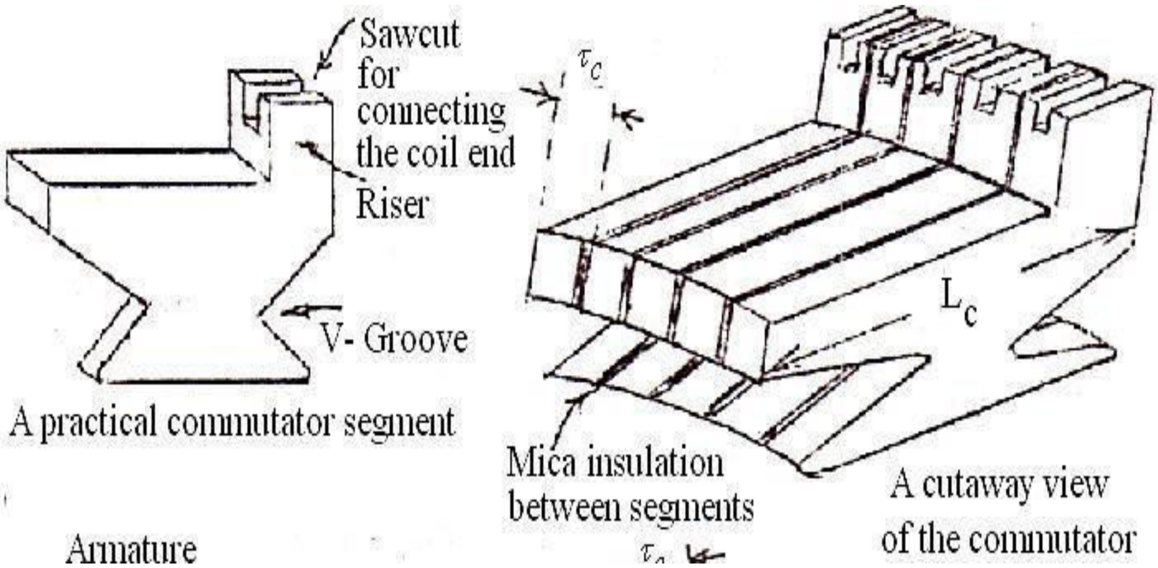
Introduction :
The Commutator is an assembly of Commutator segments or bars tapered in section. The segments made of hard drawn copper are insulated from each other by mica or micanite, the usual thickness of which is about 0.8 mm. The number of commutator segments is equal to the number of active armature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

Prerequisite knowledge for Complete understanding and learning of Topic:
- Construction of dc motor
- Commutator
- Armature winding

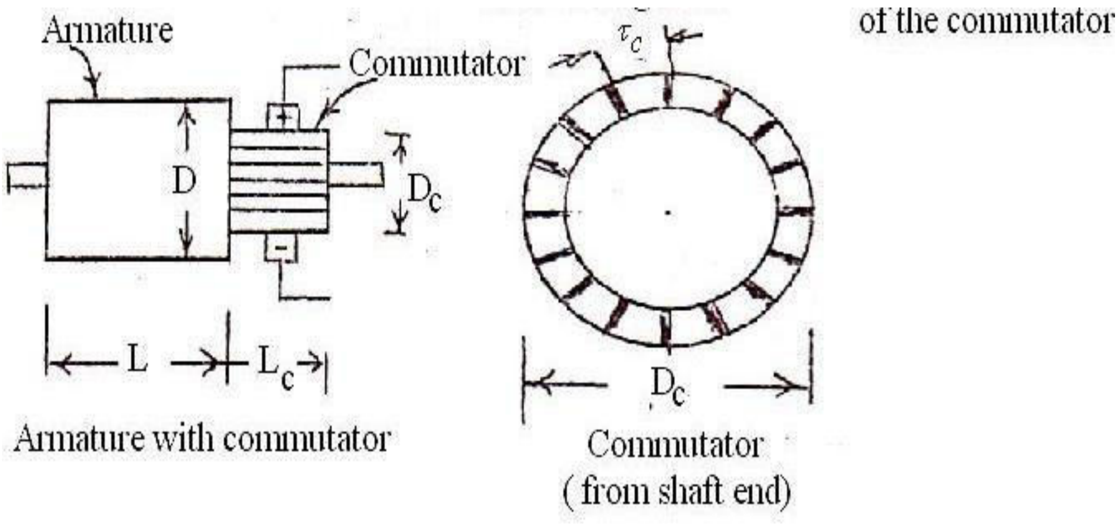
Detailed content of the Lecture:

Derivation on commutators design:

- 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 $v_c = \pi D_C N / 60$ 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 τ_C = (outside width of one segment + mica insulation between segments) = πD_C / 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

- **Video Content /** Details **of website for further learning (if any):**
  https://www.youtube.com/watch?v=q3q8z4tnVkc

Important Books/Journals for further learning including the page nos.:
Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No 9.7-9.9)

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LECTURE HANDOUTS

EEE

III/VI

Course Name with Code : Design of Electrical Apparatus/19EED05

Course Faculty : Mr. C. Ram Kumar

Unit : II- D.C Machines **Date of Lecture:**

Topic of Lecture:
Derivation on brushes design.

Introduction :
Since the brushes of each brush arm collets the current from two parallel paths, current collected by each brush arm is 2 I/2 Ia and the cross-sectional area of the brush or brush arm or holder or spindle A_b =Ib/ δcm^2. The current density δ_p depends on the brush material and can be assumed between and 6.5 A / cm2 for carbon.

Prerequisite knowledge for Complete understanding and learning of Topic:
- Construction of dc motor
- Brushes

Detailed content of the Lecture:

Derivation on brushes design

- Since the brushes of each brush arm collets the current from two parallel paths, current collected by each brush arm is 2 I/2 Ia and the cross-sectional area of the brush or brush arm or holder or spindle
- A_b = cm^2. The current density δ_p depends on the brush material and can be assumed between and 6.5 A / cm2 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
  - tb is the thickness of the brush ii) wb is the width of the brush and
- nbis the number of sub divided brushes thenAb = tbwbnb
- 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

- **Video Content /** Details **of website for further learning (if any):**
  https://www.youtube.com/watch?v=KyPmb0REUu4

Important Books/Journals for further learning including the page nos.:
Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No 9.10-9.12)

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L25

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code: Design of Electrical Apparatus/19EED05

Course Faculty : Mr. C. Ram Kumar

Unit : II- D.C Machines **Date of Lecture:**

Topic of Lecture:
Main Dimensions (Tutorial - I)

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.

Prerequisite knowledge for Complete understanding and learning of Topic:
- Construction of dc motor
- Types o motor

Detailed content of the Lecture:

Main Dimensions

A 5 KW, 250V, 4 pole, 1500 rpm DC shunt Generator is designed to have a square pole face. The specific magnetic loading and specific electric loading are 0.42 wb/m² and 15000 ac/m respectively. Find the main dimensions of the machine. Assume full load efficiency = 0.87 and pole arc to pole pitch ratio is 0.66.

[A.U MAY 2011, 2015]

Given data:

P = 5 KW	$B_{av} = 0.42\ wb/m^2$
V = 250 V	$ac = 15000\ ac/m$
$p = 4$	$\eta = 87\%$
N= 1500 rpm	$\psi = 0.66$

To find

Main Dimensions D & L

☺ ***Solution:***

Output equation of DC machine

$$P_a = C_o D^2 L n_s \Rightarrow D^2 L = \frac{P_a}{C_o n}$$

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

Speed in r.p.s $\quad n = \frac{1500}{60} = 25\, rps$

Output Coefficient, $C_o = \pi^2 B_{av}\, ac \times 10^{-3} = \pi^2 \times 0.42 \times 15000 \times 10^{-3} = 62.1$

$$D^2L = \frac{5.75}{62.1 \times 25} = 3.7 \times 10^{-3}\, m^3 \qquad \dots 1$$

For a square pole Face, L = b

$$b = \psi\tau, \tau = \frac{\pi D}{P}$$

$$\therefore L = \psi\frac{\pi D}{p} = 0.66 \times \frac{\pi D}{4}$$

$$L = 0.518\, D \qquad \dots 2$$

Substitute equation (2) in (1)

$$0.518\, D^3 = 3.7 \times 10^{-3}$$

$$D^3 = 7.1428 \times 10^{-3}$$

$$D = 0.193\, m$$

Substitute $D = 0.193$ in equation (2)

$$L = 0.1\, m$$

Video Content / Details of website for further learning (if any):

https://www.youtube.com/watch?v=020AeaYRb24

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No6.1-6.2)

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LECTURE HANDOUTS

L26

EEE

III/VI

Course Name with Code : Design of Electrical Apparatus/19EED05

Course Faculty : Mr. C. Ram Kumar

Unit : II- D.C Machines **Date of Lecture:**

Topic of Lecture:
Selection of number of poles (Tutorial - II)

Introduction :
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.

Prerequisite knowledge for Complete understanding and learning of Topic:
- Construction of dc motor
- Poles
- Armature winding

Detailed content of the Lecture:

Selection of number of poles

Determine the main dimensions, number of poles and the length of air gap of a 600 KW, 500 V, 900 rpm generator. Assume average gap density as 0.6 Wb/m² and ampere conductors per meter as 35000. The ratio of pole arc to pole pitch is 0.75 and efficiency of the machine is 91%. The design constrains are : peripheral speed should not exceed 40m/s, frequency of flux reversal should not exceed 50Hz, current per brush arm should not exceed 400 A and armature mmf per pole should not exceed 7500 AT. The mmf required for air gap is 50 per cent of armature mmf and gap contraction factor is 1.15.

Given data:

$V = 500$ V	$ac = 35{,}000$ Ac/m	
$P = 600$ KW	$\psi = 0.75$	
$N = 900$ rpm	$\eta = 0.91$	
Generator	$K_g = 1.15$	
$B_{av} = 0.6$ wb/m^2	$AT_g = 0.5 \times AT_a$	

To find

Main Dimension } $D = ?$, $L = ?$

No.of poles, $p = ?$

length of Air-gap, $l_g = ?$

(i) **Number of poles,**

Step1:

Frequency = 25 to 50 Hz

$$f = 25\text{Hz} \Rightarrow p = \frac{120f}{N} = \frac{120\times25}{900} \simeq 3$$

$$f = 30\text{Hz} \Rightarrow p = \frac{120\times30}{900} \simeq 4$$

$$f = 35\text{Hz} \Rightarrow p = \frac{120\times35}{900} \simeq 5$$

$$f = 40\text{Hz} = p \simeq 5$$

$$f = 45\text{Hz} = p = 6$$

$$f = 50\,Hz = p \simeq 7$$

p = 4 (or) 6 lies within the limits

Step 2:

$$\text{Full load current, } I_L = \frac{P\times10^3}{V} = \frac{600\times10^3}{500} = 1200\,\text{A}$$

$$I_L = I_a = 1200\,\text{A}$$

Assume lap winding, $a = p$

Current per brush arm

$$I_b = 2\times\frac{I_a}{p} \not> 400\text{A}$$

$$p = 4,\; I_b = \frac{2\times1200}{4} = 600\text{ A}$$

$$p = 6,\; I_b = \frac{2\times1200}{6} = 400\text{ A}$$

$\therefore p = 6$ is Selected

(ii) Main Dimensions:

$$D^2L = \frac{P_a}{C_o n} \qquad \left[\begin{array}{l}\because \text{output equation} \\ P_a = C_o D^2 L n\end{array}\right]$$

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

$$C_o = \pi^2 \times 0.6 \times 35000 \times 10^{-3} = 207.26$$

Armature power, $P_a = \frac{P}{\eta} = \frac{600}{0.91} = 659\,KW$

$$D^2L = \frac{659}{207.26 \times 15} = 0.212\,m^3$$

Assuming square pole face, $L = b$

$$L = \psi\tau \Rightarrow L = \frac{\psi\pi D}{p} = \frac{0.75 \times \pi D}{6}$$

$$L = 0.393\ D$$

Substitute (2) in (1)

$$D^2[0.393D] = 0.212$$

$$D^3 = \frac{0.212}{0.393}$$

$$D = 0.815\,m$$

Substitute 'D' in (2),

$$L = 0.393 \times 0.815$$

$$L = 0.33\ m$$

$$D = 0.815\,m \ \ \&\ \ L = 0.33\,m$$

Peripheral speed,

$$V_a = \pi D n \ngtr 40\ m/sec$$

$$V_a = \pi \times 0.815 \times 15 = 38.4\ m/s$$

$\boxed{\therefore D = 0.815\,m \ \&\ L = 0.33\,m}$ is selected

Video Content / Details of website for further learning (if any):

https://www.youtube.com/results?search_query=selection+o+poles

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No 9.18-9.20)

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L27

LECTURE HANDOUTS

EEE

III/VI

Course Name with Code : Design of Electrical Apparatus/19EED05

Course Faculty : Mr. C. Ram Kumar

Unit : II- D.C Machines **Date of Lecture:**

Topic of Lecture:
Problem on Armature Design(Tutorial - III)

Introduction :
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.

Prerequisite knowledge for Complete understanding and learning of Topic:

- Construction of dc motor
- Poles
- Armature winding

Detailed content of the Lecture:

Determine the diameter and length of armature core for a 55KW, 110 V, 1000 rpm, 4 pole shunt generator, assuming specific electric and magnetic loading of 26000 amps.cond./m and 0.5 Wb/m² respectively. The pole arc is should be about 70% of pole pitch and length of core about 1.1 times the pole arc. Allow 10 ampere for the field current and assume a voltage drop of 4 volts for the armature circuit. Specify the winding used and also determine suitable values for the number of armature conductors and number of slots.

[A.U MAY 2012, NOV 2013, NOV 2014]

Given data:

$P = 55KW$, $V = 110\ V$, $p = 4$

$B_{av} = 0.5\ wb/m^2$, $ac = 26000\ ac/m$, $b = 0.7\tau$, $L = 1.1\ b$

$N = 1000\ rpm$, $I_F = 10\ A$, $I_a R_a = 4$ volts

To find: (i) D,L (ii) Winding used (iii) Z (iv) S_a (v) C

Solution :

(i) $D^2 L = \frac{P_a}{C_o n}$ $\Rightarrow \left[\because \text{Output equation } P_a = C_o D^2 L n\right]$

Armature power $P_a = EI_a \times 10^{-3}$ $n = \frac{1000}{60} = 16.67$ r.p.s

$E = V + I_a R_a = 110 + 4 = 114$ volts

Armature current, $I_a = I_L + I_F$

$$I_L = \frac{P}{V \times 10^{-3}} = \frac{55}{110 \times 10^{-3}} = 500\ A$$

$$\therefore I_a = 500 + 10 = 510\ A$$

$$P_a = 114 \times 510 \times 10^{-3} = 58.14\ KW$$

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

$$C_o = \pi^2 \times 0.5 \times 26000 \times 10^{-3} = 128.3$$

$$D^2 L = \frac{58.14}{128.3 \times 16.67} = 0.0272\, m^3 \quad \text{... 1}$$

Given that $L = 1.1\,b \;\&\; b = 0.7\tau$

$$L = 1.1 \times (0.7\tau) = 1.1 \times 0.7 \times \frac{\pi D}{p} \qquad \left[\because \tau = \frac{\pi D}{p}\right]$$

$$L = 0.6048D \quad \text{... 2}$$

Substitute (2) in (1)

$$D^2[0.6048D] = 0.0272$$

$$D^3 = \frac{0.0272}{0.6048}$$

$$D = 0.356\text{m}$$

Substitute 'D' in (2)

$$L = 0.6048 \times 0.356$$

$$L = 0.215\, m$$

$$D = 0.356\text{ m}, \quad L = 0.215\, m$$

(ii) Specify the winding used,

for wave winding, current per parallel path $= \frac{I_a}{2} = \frac{510}{2} = 255\text{A}$

For lap winding, current per parallel path, $= \frac{I_a}{p} = \frac{I_a}{4} = \frac{510}{4} = 127.5\text{A}$

In wave winding the limit exceeded 200A

∴ lap winding is preferred.

(iii) Number of Armature Conductors :

Emf induced, $E = \frac{\phi Z N p}{60\, a} \Rightarrow Z = \frac{60\, E a}{\phi N p}$

Average flux density, $B_{av} = \frac{\phi p}{\pi D L} \Rightarrow \phi = \frac{B_{av}\, \pi D L}{p} = \frac{0.5\pi \times 0.356 \times 0.215}{4} = 0.03\, wb$

$$Z = \frac{60 \times 114 \times 4}{0.03 \times 1000 \times 4} = 228$$

$$Z = 228$$

(iv) Number of Slots:

Number of Armature slots $\Big\} S_a = \frac{\pi D}{Y_{sa}}$; $Y_{sa} = 25\, mm$ to $35\, mm$

Y_{sa} – Armature slot pitch

When $Y_{sa} = 25\ mm$, $S_a = \frac{\pi \times 0.356}{25 \times 10^{-3}} = 45$

When , $Y_{sa} = 35\ mm$, $S_a = \frac{\pi \times 0.356}{35 \times 10^{-3}} = 32$

✓ For lap winding, number of slots should be a multiple of pole pair

∴ The allowable choice of slots are; 32, 34, 36, 38, 40, 42, 44

✓ To reduce flux pulsations, the slot per pole should be an integer $\pm$ 1/2

Let slots per pole = 9 $\pm$ 1/2 = 8.5 or 9.5 Y_{sa} – Armature slot pitch

Let us choose 9.5 slots per pole.

Number of slots = slots per pole × Number of poles = 9.5 × 4 = 38

$$\boxed{S_a = 38}$$

Conductor per slot $= \frac{Z}{S_a} = \frac{228}{38} = 6$

- **Video Content /** Details **of website for further learning (if any):**
  https://www.youtube.com/watch?v=Ao3B4wcZkg8

Important Books/Journals for further learning including the page nos.:

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No 9.40-9.43)

Course Faculty

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Rasipuram - 637 408, Namakkal Dist., Tamil Nadu

L28

LECTURE HANDOUTS

EEE

III/VI

Course Name with Code: Design of Electrical Apparatus/19EED05

Course Faculty : Mr. C. Ram Kumar

Unit : II- D.C Machines **Date of Lecture:**

Topic of Lecture:
Problem on Armature Design(Tutorial - IV)

Introduction :
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.

Prerequisite knowledge for Complete understanding and learning of Topic:

- Construction of dc motor
- Poles
- Armature winding

Detailed content of the Lecture:

Determine the main dimensions, number of poles and the length of air gap of a 1000 kW, 500 V, 300 rpm DC generator. Assume average gap density as 0.7 Wb/m² and ampere conductors per meter as 40000. The pole arc to pole pitch ratio is 0.7 and efficiency is 92%. The mmf required for air gap is 55 % of armature mmf and gap contraction factor is 1.15. The following are the design constrains: peripheral speed should not exceed 30 m/s, frequency of flux reversals should not exceed 50 Hz, current per brush arm should not exceed 400 A and armature mmf per pole should not exceed 10000 A.[A.U NOV 2012]

Given data:

$P = 1000$ KW ac = 40000 ac/m $V_a \ngtr 30$ m/s

$V = 500$ V $b/\tau = \psi = 0.7$ $f \ngtr 50$ Hz

$N = 300$ rpm $\eta = 92\%$ current per brush arm $\ngtr 400$ A

DC Generator $AT_g = 55\%$ of AT_a

$B_{av} = 0.7$ wb/m²

$K_g = 1.15$

Armature mmf per pole $\ngtr 10000$ AT

To find:

(i) Number of poles,p

(ii) Main dimensions (D & L)

(iii) Length of Air gap (l_g)

☺ ***Solution:***

(i) Number of poles

☞ **Step 1:**

* Frequency ranges from 25 to 50 Hz

$$f = 25 Hz \Rightarrow p = \frac{120f}{N} = \frac{120 \times 25}{300} = 10$$

$$f = 30\,Hz \Rightarrow \quad p = \frac{120f}{N} = \frac{120\times30}{300} = 12$$

$$f = 35\text{Hz} \Rightarrow \quad p = \frac{120f}{N} = \frac{120\times35}{300} = 14$$

$$f = 40\text{Hz} \Rightarrow \quad p = \frac{120f}{N} = \frac{120\times40}{300} = 16$$

$$f = 45\text{Hz} \Rightarrow \quad p = \frac{120f}{N} = \frac{120\times45}{300} = 18$$

$$f = 50\text{Hz} \Rightarrow \quad p = \frac{120f}{N} = \frac{120\times50}{300} = 20$$

All the number of poles value are even integer.

$\therefore$ Number of poles = 10 (or) 12 (or) 14 (or) 16 (or) 18 (or) 20

Step 2:

Full load current, $I_L = \frac{P\times10^3}{V} = \frac{1000\times10^3}{500} = 2000\,A$

$$I_L = I_a = 2000\,A$$

Assume lap winding, $a = p$

Current per brush arm $(I_b) \ngtr 400\,A$

$$I_b = \frac{2I_a}{p}$$

(i) for p = 10, $I_b = \frac{2\times2000}{10} = 400\,A$

(ii) for p = 12, $I_b = \frac{2\times2000}{12} = 333.3\,A$

(iii) for p = 14, $I_b = 285.7\,A$

(iv) for p = 16, $I_b = 250\,A$

(v) for p = 18, $I_b = 222\,A$

(vi) for p = 20, $I_b = 200\,A$

The following number of poles satisfies the condition,

$$p = 12, 14, 16, 18, 20$$

Let us choose $\boxed{p = 20}$

(ii) **Main dimensions :**

The output equation of DC machine

$$P_a = C_o D^2 L n \Rightarrow D^2 L = \frac{P_a}{C_o n} \quad \text{... 1}$$

Armature power $P_a = \frac{P}{\eta} = \frac{1000}{0.92} = 1086.9 \text{KW}$

$$C_o = \pi^2 B_{av} ac \times 10^{-3} = \pi^2 \times 0.7 \times 40000 \times 10^{-3} = 276.3$$

Speed in r.p.s, $n = \frac{N}{60} = \frac{300}{60} = 5 \; r.p.s$

From (1),

$$D^2 L = \frac{1086.9}{276.3 \times 5} = 0.7867 \, m^3 \quad \text{... 2}$$

Assuming square pole face, $L = b$

Given that, $\frac{b}{\tau} = 0.7 \quad \Rightarrow \frac{L}{\tau} = 0.7$

$$L = 0.7\tau \quad \Rightarrow L = \frac{0.7 \, \pi D}{p}$$

$$L = \frac{0.7 \pi D}{20} \Rightarrow L = 0.1099 D \quad \text{... 3}$$

Substitute (3) in (2)

$$D^2 [0.1099 D] = 0.7867$$

$$D^3 = \frac{0.7867}{0.1099} \Rightarrow D^3 = 7.158 \Rightarrow D = \sqrt[3]{7.158}$$

$$\boxed{D = 1.9 \, m}$$

Substitute 'D' in equation (3),

$$L = 0.1099 \times 1.9$$

$$\boxed{L = 0.208\ m}$$

Also given that, peripheral speed, $V_a = \pi D n \not> 30\ m/s$

$$V_a = \pi \times 1.9 \times 5 = 29.8\ m/s$$

$\therefore$ The design with $\boxed{D = 1.9\ m}$ & $\boxed{L = 0.208\ m}$ is acceptable

(iii) Length of Air gap,

length of Air gap, $\ell_g = \dfrac{AT_g}{800000 B_g K_g}$

Given, $AT_g = 0.55\ AT_a$

$$AT_a = \frac{I_z . Z}{2p} = \frac{ac\ \pi D}{2p} \qquad \left[\because ac = \frac{I_z . Z}{\pi D}\right]$$

$$AT_a \not> 10{,}000\ AT \qquad AT_a = \frac{40000 \times \pi \times 1.9}{2 \times 20} = 5969\ AT$$

$$AT_g = 0.55 \times 5969 = 3282\ AT$$

$$B_g = \frac{B_{av}}{\psi} = \frac{0.7}{0.7} = 1\ wb/m^2$$

length of Air gap

$$\ell_g = \frac{AT_g}{800000 \times B_g \times K_g}$$

$$\ell_g = \frac{3282}{800000 \times 1 \times 1.5}$$

$$\ell_g = 3.56\ mm$$

- **Video Content /** Details **of website for further learning (if any):** https://www.youtube.com/watch?v=Ao3B4wcZkg8

Important Books/Journals for further learning including the page nos.:
Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No 9.40-9.43)

Course Faculty

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Course Name with Code : Design of Electrical Apparatus/19EED05

Course Faculty : Mr. C. Ram Kumar

Unit : II- D.C Machines **Date of Lecture:**

Topic of Lecture:
Derivation on brushes design. (Tutorial - V)

Introduction :
Since the brushes of each brush arm collets the current from two parallel paths, current collected by each brush arm is 2 I/2 Ia and the cross-sectional area of the brush or brush arm or holder or spindle A_b =Ib/ δcm². The current density δ_p depends on the brush material and can be assumed between and 6.5 A / cm2 for carbon.

Prerequisite knowledge for Complete understanding and learning of Topic:
- Construction of dc motor
- Brushes

Detailed content of the Lecture:

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

Given data:

P = 800KW D_c = 100cm

V = 400V $\delta_b = 0.075\, A/mm^2$

N = 300 $r.p.m$ $P_b = 14.7\, KN/m^2$

p = 10 $\mu = 0.23$

Brush contact drop = 2.2 V

To find

Total commutator Losses=?

Solution:

Total commutator Losses = Brush friction loss + Brush contact loss

$$\text{Brush friction losses} = W_{ef} = \mu P_b A_B \times V_c$$

$$A_B = pA_b; \quad A_b = \frac{I_a/\text{brush arm}}{\text{current density}}$$

$$I_a = \frac{P\times10^3}{V} = \frac{800\times1000}{400} = 2000\,A$$

Current per brush arm, $= \frac{2I_a}{p} = \frac{2\times2000}{10} = 400\,A$

Brush area per brush arm $A_b = \frac{400}{0.075} = 5333mm^2$

Total brush area on the commutator $A_B = pA_b = 10\times5333 = 53.3\times10^3 m^2$

peripheral speed $V_c = \pi D_c n = \pi\times100\times10^{-2}\times\left(\frac{300}{60}\right) = 15.7m/s$

$$W_{ef} = 0.23\times14.7\times10^3\times53.3\times10^3\times15.7 = 2830\,W$$

Brush contact loss $= I_a \times$ brush contact drop $= 2000\times2.2 = 4400\,W$

$\therefore$ Total commutator loss $= 2830 + 4400 = 7230\,W$

- **Video Content /** Details **of website for further learning (if any):** https://www.youtube.com/watch?v=KyPmb0REUu4

Important Books/Journals for further learning including the page nos.:
Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No 9.10-9.12)

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LECTURE HANDOUTS

L30

EEE

III/VI

Course Name with Code : Design of Electrical Apparatus/19EED05

Course Faculty : Mr. C. Ram Kumar

Unit : II- D.C Machines

Date of Lecture:

Topic of Lecture:

Derivation on commutators design. (Tutorial - VI)

Introduction :

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

- Construction of dc motor
- Commutator
- Armature winding

Detailed content of the Lecture:

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.

Given data :

$P = 350kW$

$V = 440V$

$D = 0.75m$

$C = 288$

$p = 6$

$N = 600rpm$

To find

$D_c = ?$ $n_b = ?$ $w_b = ?$

$N_{cs} = ?$ $t_b = ?$

$W_{cs} = ?$ $L_c = ?$

☺ ***Solution:***

Let the diameter of the commutator $(D_c) = 0.68\,D$

$D_c = 0.68 \times 0.75 = 0.51m$

peripheral speed of commutator, $V_c = \pi D_c n$ $\left[\begin{array}{l} D_c = 62\%D \rightarrow 350/700V \\ D_c = 68\%D \rightarrow 200/250V \\ D_c = 75\%D \rightarrow 100\backslash125V \end{array}\right]$

$$V_c = \pi \times 0.51 \times \frac{600}{60} = 16.09\, m/sec$$

$V_c > 15 m/s$, Hence reduce D_c

Let, $D_c = 0.66\,D$, $D_c = 0.66 \times 0.75 = 0.495\, m$

$V_c = \pi \times 0.495 \times 10 = 15.55\, m/sec$

$V_c > 15 m/s$, Hence reduce D_c

Let

$D_c = 0.64D$, $D_c = 0.64 \times 0.75 = 0.48\, m$

$V_c = \pi \times 0.48 \times 10 = 15.0\, m/s$

$\therefore D_c = 0.48\, m$ is acceptable

Number of commutator segments = Number of coils = 288

The actual commutator pitch, $\beta_c = \frac{\pi D_c}{C} = \frac{\pi \times 0.48}{288} = 5.2 \times 10^{-3}\, m$

$= 5.2\, mm$

The commutator pitch is above the minimum value of 4mm

$$\text{Number of brushes, } n_b = \frac{\text{current per brush area}}{\text{Current per brush}}$$

$$\text{Current per brush area} = \frac{2I_a}{p}$$

$$I_a = \frac{P \times 10^{-3}}{V} = \frac{350 \times 10^3}{440} = 795.5\, amps$$

Current per brush area $= \frac{2\times 795.5}{6} = 265.2$ A

$$n_b = \frac{265.2}{70} \simeq 4$$

Assume lap winding, $\therefore n_b = p = 6$

current carried by each brush } $I_b = \frac{265.2}{6} = 44.2$

Let current density in each brush } $\delta_b = 75\times 10^{-3}$ A/mm^2

Area of each brush, $a_b = \frac{44.2}{75\times 10^{-3}} = 589.3 mm^2$

Let thickness of brush = 3 × width of commutator segment

BC

$$t_b = 3\times 5.2 = 15.6 mm$$

width of brush, $w_b = \frac{a_b}{t_b} = \frac{589.3}{15.6} \approx 38. mm$

Let

$C_b = 5 mm$

$C_1 = 20 mm$

$C_2 = 20$mm

Length of the commutator,

$$L_c = n_b(w_b + C_b) + C_1 + C_2$$

$$L_c = 6(38+5)+20+20$$

$$L_c \simeq 0.3 m$$

- **Video Content /** Details **of website for further learning (if any):**
  https://www.youtube.com/watch?v=q3q8z4tnVkc

Important Books/Journals for further learning including the page nos.:
Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010 (Page No 9.7-9.9)

Course Faculty

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L31

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : III - TRANSFORMERS **Date of Lecture:**

Topic of Lecture: Main Dimensions

Introduction :

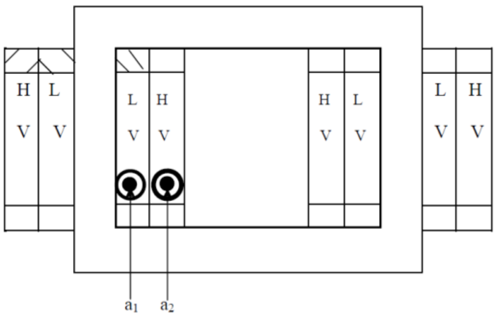
1. Load on the transformer will be at or near the full load throughout the period of operation. When the load is less, the transformer, which is in parallel with other transformers, may be put out of service.
2. Generally designed to achieve maximum efficiency at or near the full load. Therefore iron loss is made equal to full load copper loss by using a higher value of flux density. In other words, power transformers are generally designed for a higher value of flux density.
3. Necessity of voltage regulation does not arise .The voltage variation is obtained by the help of tap changers provided generally on the high voltage side. Generally Power transformers are deliberately designed for a higher value of leakage reactance, so that the short-circuit current, effect of mechanical force and hence the damage is less.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Transformer
2. Construction of Transformer
3. Torque and emf equations

Detailed Content:

Rating of the transformer in kVA = $V_1 I_1 \times 10^{-3} = E_1 I_1 \times 10^{-3} = 4.44\ \varphi m\ f\ T_1 \times I_1 \times 10^{-3}$----(1)



Note: Each leg carries half of the LV and HV turns

Area of copper in the window

$$A_{cu} = a_1T_1 + a_2T_2 = \frac{I_1T_1}{\delta} + \frac{I_2T_2}{\delta} + \frac{2I_1T_1}{\delta} = A_WK_W$$

Therefore $I_1T_1 = \frac{A_WK_W\delta}{2}$---- (2)

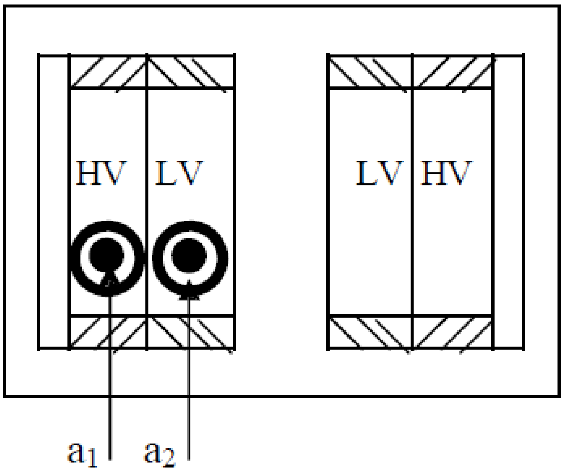
After substituting (2) in (1),

$$KVA = 4.44A_iB_mf \times \frac{A_WK_W\delta}{2} \times 10^{-3}$$

Single phase shell type transformer

Rating of the transformer in kVA = $V_1I_1 \times 10^{-3} = E_1I_1 \times 10^{-3}$

= 4.44 φm f $T_1 \times I_1$ x 10-3 …(1)



Note : Since there are two windows, it is sufficient to design one of the two windows as both the windows are symmetrical. Since the LV and HV windings are placed on the central leg, each window accommodates T1 and T2 turns of both primary and secondary windings.

Area of copper in the window

$$A_W = a_1T_1 + a_2T_2 = \frac{I_1T_1}{\delta} + \frac{I_2T_2}{\delta} + \frac{2I_1T_1}{\delta} = A_WK_W$$

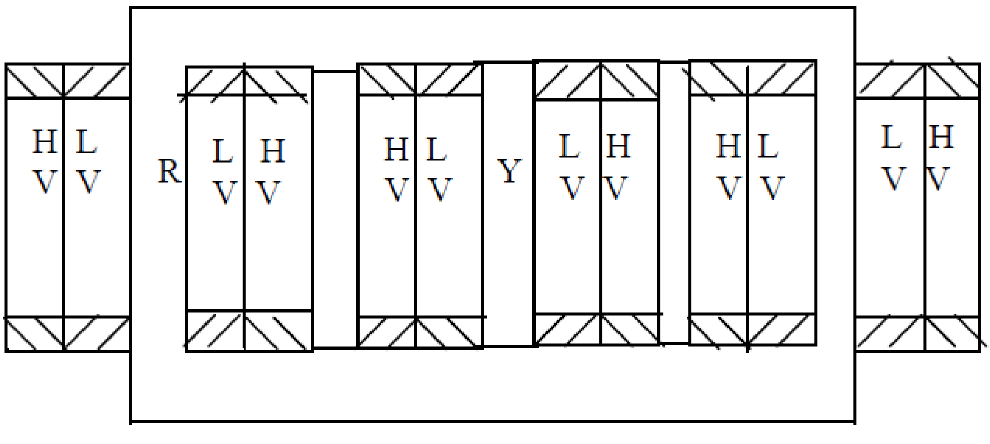
Therefore $I_1T_1 = \frac{A_WK_W\delta}{2}$-------(2)

After substituting (2) in (1),

$$KVA = 4.44A_iB_mf \times \frac{A_WK_W\delta}{2} \times 10^{-3}$$

Three phase core type transformer

Rating of the transformer in kVA = $V_1I_1 \times 10^{-3} = E_1I_1 \times 10^{-3} = 3 \times 4.44\ \varphi_m\ f\ T_1 \times I_1 \times 10^{-3}$…(1)



Note: Since there are two windows, it is sufficient to design one of the two windows, as both the windows are symmetrical. Since each leg carries the LV &HV windings of one phase, each window carry the LV & HV windings of two phases

Since each window carries the windings of two phases, area of copper in the window, say due to R & Y phases

$$A_{cu} = (a_1T_1 + a_2T_2) + (a_1T_1 + a_2T_2)$$

$$= 2(a_1T_1 + a_2T_2) = 2\left(\frac{I_1T_1}{\delta} + \frac{I_2T_2}{\delta}\right)$$

$$= 2 \times \frac{2I_1T_1}{\delta} = A_W K_W$$

Therefore $I_1T_1 = \frac{A_W K_W \delta}{4}$ -------(2)

After substituting (2) in (1)

$$KVA = 3 \times 4.44 A_i B_m f \times \frac{A_W K_W \delta}{4} \times 10^{-3}$$

Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
https://www.youtube.com/watch?v=vz4a65ALLs0
https://swayam.gov.in/nd1_noc19_ee65/preview

Important Books/Journals for further learning including the page nos.: 376-378
Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010

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L32

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : III - TRANSFORMERS **Date of Lecture:**

Topic of Lecture: kVA output equation on three phase transformers

Introduction :

1. Load on the transformer will be at or near the full load throughout the period of operation. When the load is less, the transformer, which is in parallel with other transformers, may be put out of service.
2. Generally designed to achieve maximum efficiency at or near the full load. Therefore iron loss is made equal to full load copper loss by using a higher value of flux density. In other words, power transformers are generally designed for a higher value of flux density.
3. Necessity of voltage regulation does not arise .The voltage variation is obtained by the help of tap changers provided generally on the high voltage side. Generally Power transformers are deliberately designed for a higher value of leakage reactance, so that the short-circuit current, effect of mechanical force and hence the damage is less.

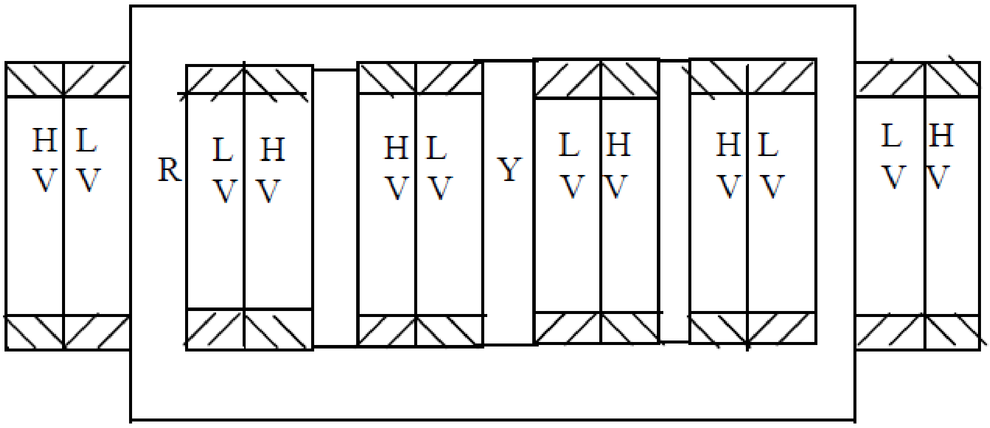
Prerequisite knowledge for Complete understanding and learning of Topic:

1. Transformer
2. Construction of Transformer
3. Torque and emf equations

Detailed Content:

Three phase core type transformer

Rating of the transformer in kVA = $V_1 I_1 \times 10^{-3} = E_1 I_1 \times 10^{-3} = 3 \times 4.44\ \varphi_m\ f\ T_1 \times I_1 \times 10^{-3}$…(1)



Note: Since there are two windows, it is sufficient to design one of the two windows, as both the windows are symmetrical. Since each leg carries the LV &HV windings of one phase, each window carry the LV & HV windings of two phases

Since each window carries the windings of two phases, area of copper in the window, say due to R & Y phases

$$A_{cu} = (a_1T_1 + a_2T_2) + (a_1T_1 + a_2T_2)$$

$$= 2(a_1T_1 + a_2T_2) = 2\left(\frac{I_1T_1}{\delta} + \frac{I_2T_2}{\delta}\right)$$

$$= 2 \times \frac{2I_1T_1}{\delta} = A_WK_W$$

Therefore $I_1T_1 = \frac{A_WK_W\delta}{4}$ ------- (2)

After substituting (2) in (1)

$$KVA = 3 \times 4.44A_iB_mf \times \frac{A_WK_W\delta}{4} \times 10^{-3}$$

Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
https://www.youtube.com/watch?v=vz4a65ALLs0
https://swayam.gov.in/nd1_noc19_ee65/preview

Important Books/Journals for further learning including the page nos.: 376-378
Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010

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L33

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : III - TRANSFORMERS **Date of Lecture:**

Topic of Lecture: kVA output equation on single phase transformers

Introduction :

1. Load on the transformer will be at or near the full load throughout the period of operation. When the load is less, the transformer, which is in parallel with other transformers, may be put out of service.
2. Generally designed to achieve maximum efficiency at or near the full load. Therefore iron loss is made equal to full load copper loss by using a higher value of flux density. In other words, power transformers are generally designed for a higher value of flux density.
3. Necessity of voltage regulation does not arise .The voltage variation is obtained by the help of tap changers provided generally on the high voltage side. Generally Power transformers are deliberately designed for a higher value of leakage reactance, so that the short-circuit current, effect of mechanical force and hence the damage is less.

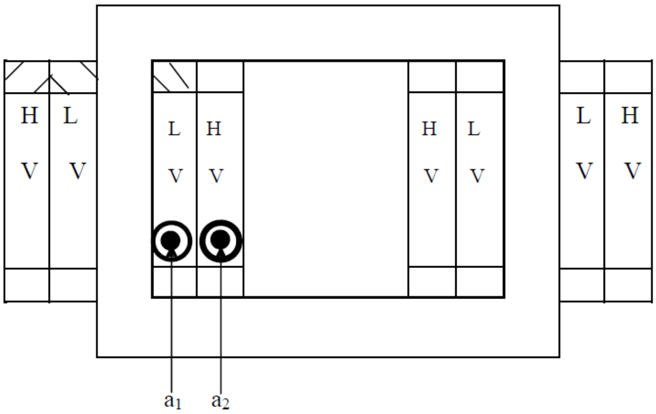
Prerequisite knowledge for Complete understanding and learning of Topic:

1. Transformer
2. Construction of Transformer
3. Torque and emf equations

Detailed Content:

Single phase core type transformer

Rating of the transformer in kVA = $V_1 I_1 \times 10^{-3} = E_1 I_1 \times 10^{-3} = 4.44\ \varphi_m f T_1 \times I_1 \times 10^{-3}$----(1)



Note: Each leg carries half of the LV and HV turns

Area of copper in the window

$$A_{cu} = a_1T_1 + a_2T_2 = \frac{I_1T_1}{\delta} + \frac{I_2T_2}{\delta} + \frac{2I_1T_1}{\delta} = A_WK_W$$

Therefore $I_1T_1 = \frac{A_WK_W\delta}{2}$----(2)

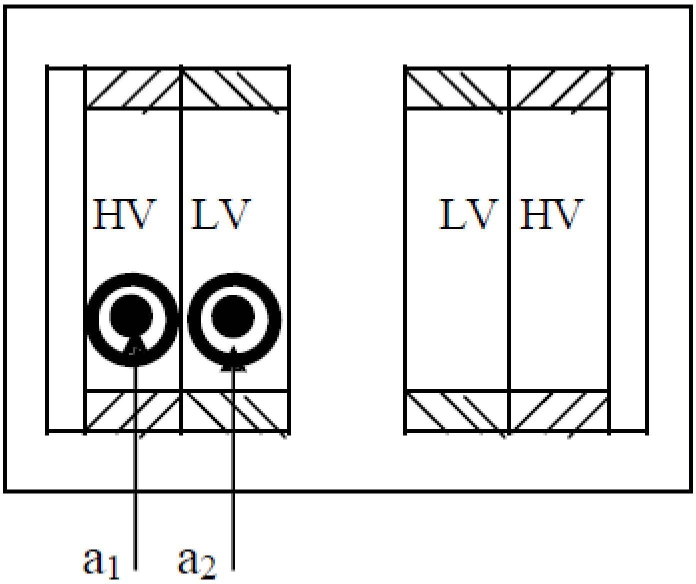
After substituting (2) in (1),

$$KVA = 4.44A_iB_mf \times \frac{A_WK_W\delta}{2} \times 10^{-3}$$

Single phase shell type transformer

Rating of the transformer in kVA = V_1I_1 x 10^{-3} = E_1I_1 x 10^{-3}

= 4.44 φm f T_1 x I_1 x 10-3 …(1)



Note : Since there are two windows, it is sufficient to design one of the two windows as both the windows are symmetrical. Since the LV and HV windings are placed on the central leg, each window accommodates T1 and T2 turns of both primary and secondary windings.

Area of copper in the window

$$A_W = a_1T_1 + a_2T_2 = \frac{I_1T_1}{\delta} + \frac{I_2T_2}{\delta} + \frac{2I_1T_1}{\delta} = A_WK_W$$

Therefore $I_1T_1 = \frac{A_WK_W\delta}{2}$-------(2)

After substituting (2) in (1),

$$KVA = 4.44 A_i B_m f \times \frac{A_W K_W \delta}{2} \times 10^{-3}$$

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L34

LECTURE HANDOUTS

EEE

III/VI

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : III - TRANSFORMERS **Date of Lecture:**

Topic of Lecture:
Window space factor

Introduction :
Window space factor is defined as the ratio of copper area in the window to the area of the window. For a given window area, as the voltage rating of the transformer increases, quantity of insulation in the window increases, area of copper reduces. Thus the window space factor reduces as the voltage increases.

Prerequisite knowledge for Complete understanding and learning of Topic:
1. Transformer
2. Construction of Transformer
3. Torque and emf equations

Detailed Content:
- Window space factor is defined as the ratio of copper area in the window to the area of the window.
- For a given window area, as the voltage rating of the transformer increases, quantity of insulation in the window increases, area of copper reduces. Thus the window space factor reduces as the voltage increases.
- It depends upon the relative amounts of insulation and copper provided, which in turn depends upon the voltage rating and output o transformers. The following empirical formulae may be used for estimating the value of window space factor

$$K_w = 10/(30+kV)$$

- Where kV is the voltage of h.v. winding in kilo-volt. The above formula is for transformers of rating between 50 to 200 kVA.
- Space factor is larger for large outputs and smaller outputs. For a transformer of about 1000 kVA rating Kw = 12/(30+kV) and for transformers of about 20 kVA rating Kw = 8/(30 + kV). The values of space actor for intermediate rating can be interpolated.

$$K_w = \frac{\text{Area of copper in the window } A_{cu}}{\text{Area of the window } A_w} < 1.0$$

- For a given window area, as the voltage rating of the transformer increases, quantity of insulation in the window increases, area of copper reduces. Thus the window space factor reduces as the voltage increases. A value for Kw can be calculated by the following empirical formula.

$$K_w = \frac{10}{30 + kV_{hv}}$$

where kVhv is the voltage of the high voltage winding expressed in kV.

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L35

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : III - TRANSFORMERS **Date of Lecture:**

Topic of Lecture:
Design of core and winding

Introduction :

1. Load on the transformer will be at or near the full load throughout the period of operation. When the load is less, the transformer, which is in parallel with other transformers, may be put out of service.
2. Generally designed to achieve maximum efficiency at or near the full load. Therefore iron loss is made equal to full load copper loss by using a higher value of flux density. In other words, power transformers are generally designed for a higher value of flux density.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Transformer
2. Construction of Transformer
3. Torque and emf equations

Detailed Content:

In an electrical power transformer, there are primary, secondary and sometimes also tertiary windings. The performance of a transformer mainly depends upon the flux linkages between these windings. For efficient flux linking between these windings, one low reluctance magnetic path common to all windings should be provided in the transformer. This low reluctance magnetic path in the transformer is known as the **core of a transformer**. The three main types of transformer cores are:

1. Core Type Transformers
2. Shell Type Transformers
3. Air Core Transformers

Influence of Diameter of Transformer Core

Let us consider, the diameter of the **transformer core** be 'D'.
Then, the cross-sectional area of the core,

$$A = \frac{\pi D^2}{4}$$

Now, voltage per turn,

$$E = 4.44\phi_m f = 4.44AB_m f$$

Where, B_m is the maximum flux density of the core.

$$= \frac{4.44\pi D^2 B_m f}{4}$$

E is proportional to D^2.
Therefore voltage per turn is increased with increase in diameter of transformer core.
Again if voltage across the winding of transformer is V.
Then V = eN, where N is the number of turns in winding.
If V is constant, e is inversely proportional to N. And hence, D^2 is inversely proportional to N. So, diameter of the core is increased, the number of turns in the transformer winding reduced. Reduction of number of turns, reduction in height of the core legs in-spite of reduction of core legs height increased in core diameter, results increase in overall diameter of magnetic **core of transformer**. This increased steel weight ultimately leads to increased core losses in transformer. Increased diameter of the core leads to increase in the main diameter on the winding. In – spite of increased diameter of the winding turns, reduced number of turns in the windings, leads to less copper loss in transformer.
So, we go on increasing diameter of the transformer core, losses in the transformer core will be increased but at the same time, load loss or copper loss in transformer is reduced. On the other hand, if diameter of the core is decreased, the weight of the steel in the core is reduced; which leads to less core loss of transformer, but in the same time, this leads to increase in number of turns in the winding, means increase in copper weight, which leads to extra copper loss in transformer. So, diameter of the core must be optimized during **designing of transformer core**, considering both the aspects.

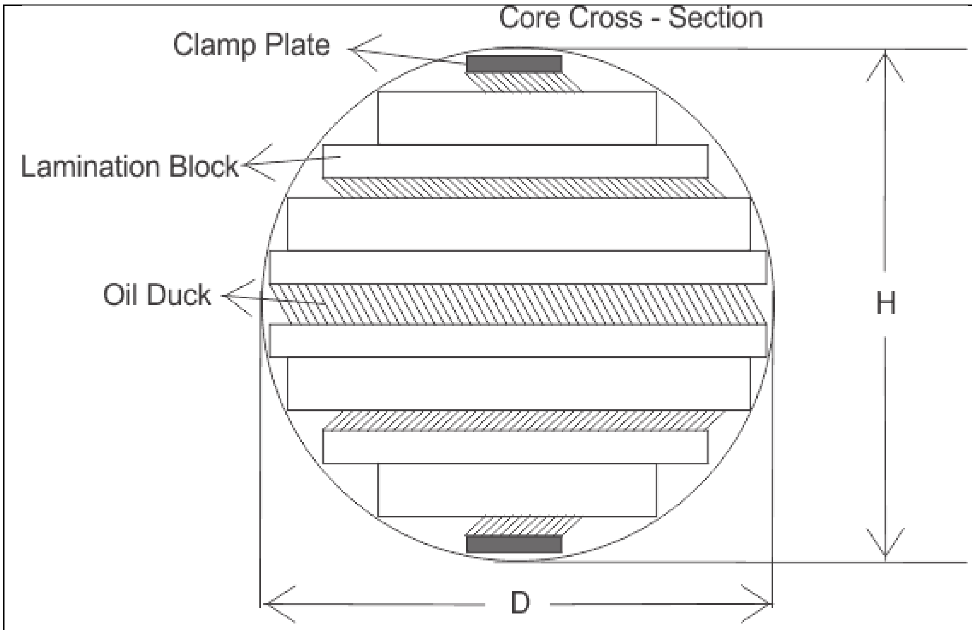
Material for Transformer Core

The main problem with the **transformer core** is its hysteresis and eddy current losses. Hysteresis loss in transformer mainly depends upon its core materials. It is found that, a small quantity of silicon alloyed with low carbon content steel produces material for transformer core, which has low hysteresis loss and high permeability. Because of increasing demand of power, it is required to further reduce the core losses and for that, another technique is employed on steel, which is known as cold rolling. This technique arranges the orientation of grain in ferromagnetic steel in the direction of rolling.
The core steel which has undergone through both the silicon alloying and cold rolling treatments is commonly known as CRGOS or Cold Rolled Grain Oriented Silicon Steel. This material is now universally used for manufacturing transformer core.

Although this material has low specific iron loss but still; it has some disadvantages, like, it is susceptible to increase loss due to flux flow in direction other than grain orientation and it also susceptible to impaired performance due to impact of bending and blanking the cutting CRGOS sheet. Both the surfaces of the sheet are provided with an insulating of oxide coating.

Optimum Design of Cross-Section of Transformer Core

The maximum flux density of CRGO steel is about 1.9 Tesla. Means the steel becomes saturated at the flux density 1.9 Tesla. One important criteria for the **design of transformer core**, is that, it must not be saturated during the transformer's normal operation mode. Voltages of transformer depend upon its total magnetizing flux. Total magnetizing flux through core is nothing but the product of flux density and cross – sectional area of the core. Hence, flux density of a core can be controlled by adjusting the cross sectional area of the core during its design.



The ideal shape of cross-section of a transformer core is circular. For making perfect circular cross section, each and every successive lamination steel sheet should be cut in different dimension and size. This is absolutely uneconomical for practical manufacturing. In reality, manufacturers use different groups or packets of predefined number of same dimension lamination sheets. The group or packet is a block of laminated sheets with a predefined optimum height (thickness). The core is an assembly of these blocks in such a successive manner as per their size from core central line, that it gives an optimum circular shape of the cross-section. Such typical cross-section is shown in the figure below.

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L36

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : III - TRANSFORMERS **Date of Lecture:**

Topic of Lecture:
Overall dimensions

Introduction :

1. Load on the transformer will be at or near the full load throughout the period of operation. When the load is less, the transformer, which is in parallel with other transformers, may be put out of service.
2. Generally designed to achieve maximum efficiency at or near the full load. Therefore iron loss is made equal to full load copper loss by using a higher value of flux density. In other words, power transformers are generally designed for a higher value of flux density.
3. Necessity of voltage regulation does not arise .The voltage variation is obtained by the help of tap changers provided generally on the high voltage side. Generally Power transformers are deliberately designed for a higher value of leakage reactance, so that the short-circuit current, effect of mechanical force and hence the damage is less.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Transformer
2. Construction of Transformer
3. Torque and emf equations

Detailed Content:

Overall dimensions

The main dimensions of the transformer are

(i) Height of window(Hw)

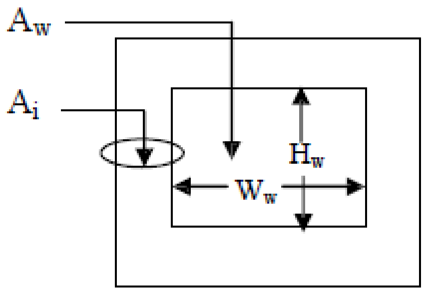
(ii) Width of the window(Ww)

The other important dimensions of the transformer are

(i) width of largest stamping(a)

(ii) diameter of circumscribing circle

As the iron area of the leg Ai and the window area Aw = (height of the window Hw x Width of the window Ww) increases the size of the transformer also increases. The size of the transformer increases as the output of the transformer increases.



1. Output-kVA
2. Voltage-V1/V2 with or without tap changers and tapings
3. Frequency-f Hz
4. Number of phases – One or three
5. Rating – Continuous or short time
6. Cooling – Natural or forced
7. Type – Core or shell, power or distribution
8. Type of winding connection in case of 3 phase transformers – star-star, star-delta, delta-delta, delta-star with or without grounded neutral
9. Efficiency, per unit impedance, location (i.e., indoor, pole or platform mounting etc.), temperature rise etc.,

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LECTURE HANDOUTS

EEE | **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : III - TRANSFORMERS **Date of Lecture:**

Topic of Lecture: Temperature rise in Transformers

Introduction :

1. Load on the transformer will be at or near the full load throughout the period of operation. When the load is less, the transformer, which is in parallel with other transformers, may be put out of service.
2. Generally designed to achieve maximum efficiency at or near the full load. Therefore iron loss is made equal to full load copper loss by using a higher value of flux density. In other words, power transformers are generally designed for a higher value of flux density.
3. Necessity of voltage regulation does not arise .The voltage variation is obtained by the help of tap changers provided generally on the high voltage side. Generally Power transformers are deliberately designed for a higher value of leakage reactance, so that the short-circuit current, effect of mechanical force and hence the damage is less.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Transformer
2. Construction of Transformer
3. Torque and emf equations

Detailed Content:

Losses dissipated in transformers in the core and windings get converted into thermal energy and cause heating of the corresponding transformer parts. The heat dissipation occurs as follows: i) from the internal heated parts to the outer surface in contact with oil by conduction ii) from oil to the tank walls by convection and iii) from the walls of the tank to the atmosphere by radiation and convection.

Q = Power loss(heat produced), J/s or W

G = weight of the active material of the Machine, kg

h = specific heat, J/kg-°C

S = cooling surface area, m2

λ = specific heat dissipation, W/ m2 -◦C

c = 1/ λ = cooling coefficient, m2 -◦C / W

θm = final steady temperature rise,◦C

The temperature of the machine rises when it is supplying load. As the temperature rises, the heat is dissipated partly by conduction, partly by radiation and in most cases largely by air cooling. The temperature rise curve is exponential in nature. Assuming the theory of heating of homogeneous bodies ,

Heat developed = heat stored + heat dissipated

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LECTURE HANDOUTS

L38

EEE

III/VI

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : III - TRANSFORMERS **Date of Lecture:**

Topic of Lecture: Tank Design

Introduction :

1. Load on the transformer will be at or near the full load throughout the period of operation. When the load is less, the transformer, which is in parallel with other transformers, may be put out of service.
2. Generally designed to achieve maximum efficiency at or near the full load. Therefore iron loss is made equal to full load copper loss by using a higher value of flux density. In other words, power transformers are generally designed for a higher value of flux density.
3. Necessity of voltage regulation does not arise .The voltage variation is obtained by the help of tap changers provided generally on the high voltage side. Generally Power transformers are deliberately designed for a higher value of leakage reactance, so that the short-circuit current, effect of mechanical force and hence the damage is less.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Transformer
2. Construction of Transformer
3. Torque and emf equations

Detailed Content:

3.1. Design of Tank

Because of the losses in the transformer core and coil, the temperature of the core and coil increases. In small capacity transformers the surrounding air will be in a position to cool the transformer effectively and keeps the temperature rise well with in the permissible limits. As the capacity of the transformer increases, the losses and the temperature rise increases. In order to keep the temperature rise with in limits, air may have to be blown over the transformer. This is not advisable as the atmospheric air containing moisture, oil particles etc., may affect the insulation. To overcome the problem of atmospheric hazards, the transformer is placed in a steel tank filled with oil. The oil conducts the heat from core and coil to the tank walls. From the tank walls the heat goes dissipated to surrounding atmosphere due to radiation and convection. Further as the capacity of the transformer increases, the increased loss demands a higher dissipating area of the tank or a bigger sized tank. These calls for more space, more volume of oil and increases the cost and transportation problems. To overcome these difficulties, the dissipating area is to be increased by artificial means without increasing the size of the tank. The dissipating area can be increased by

1. fitting fins to the tank walls
2. fitting tubes to the tank and
3. using corrugated tank
4. using auxiliary radiator tanks

Since the fins are not effective in dissipating heat and corrugated tank involves constructional difficulties, they are not much used now a days. The tanks with tubes are much used in practice. Tubes in more number of rows are to be avoided as the screening of the tank and tube surfaces decreases the dissipation. Hence, when more number of tubes are to be provided, a radiator attached with the tank is considered. For much larger sizes forced cooling is adopted.

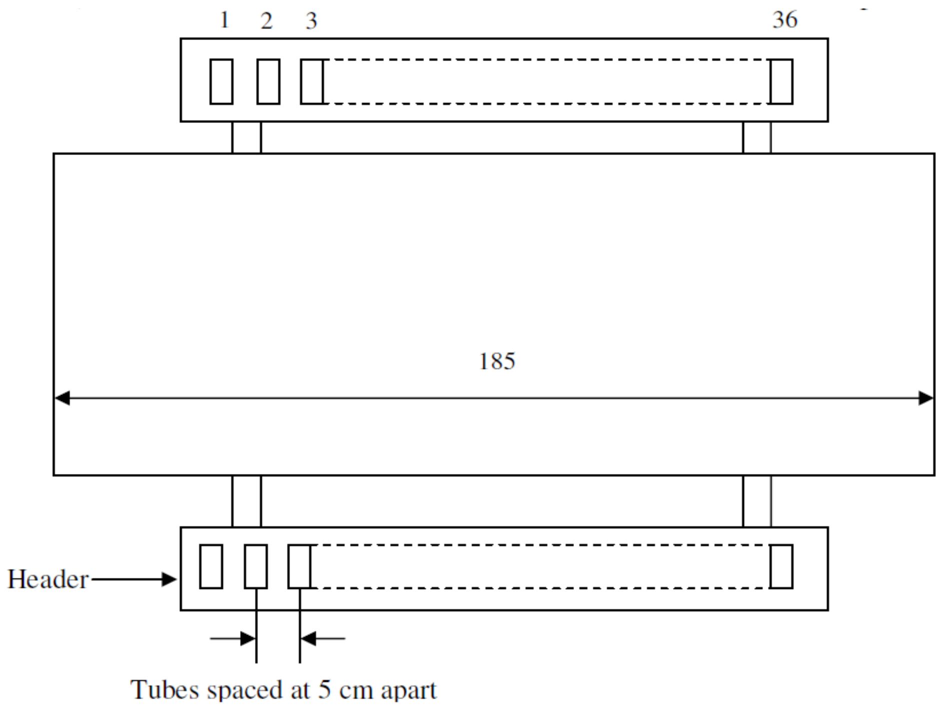
Dimensions of the Tank

The dimensions of tank depends on the type and capacity of transformer, voltage rating and electrical clearance to be provided between the transformer and tank, clearance to accommodate the connections and taps, clearance for base and oil above the transformer etc.,. These clearances can assumed to be between

(30 and 60) cm in respect of tank height

(10 and 20) cm in respect of tank length and

(10 and 20) cm in respect of tank width or breadth.



Tank height Ht = [Hw + 2Hy or 2a + clearance (30 to 60) cm] for single and three phase core, and single phase shell type transformers.

= [3(Hw + 2Hy or 2a) + clearance (30 to 60) cm] for a three phase shell type transformer.

Tank length Lt = [D + Dext + clearance (10 to 20) cm] for single phase core type transformer = [2D + Dext + clearance (10 to 20) cm] for three phase core type transformer = [4a + 2Ww + clearance (10 to 20) cm] for single and three phase shell type transformer.

Width or breadth of tank Wt = [Dext + clearance (10 to 20) cm] for all types of transformers with a circular coil.

= [b + Ww + clearance (10 to 20) cm] for single and three phase core type transformers having rectangular coils.

= [b + 2Ww + clearance (10 to 20) cm] for single and three phase shell type transformers.

When the tank is placed on the ground, there will not be any heat dissipation from the bottom surface of the tank. Since the oil is not filled up to the brim of the tank, heat transfer from the oil to the top of the tank is less and heat dissipation from the top surface of the tank is almost negligible. Hence the effective surface area of the tank St from which heat is getting dissipated can assumed to be 2Ht (Lt + Wt) m^2.

Heat goes dissipated to the atmosphere from tank by radiation and convection. It has been found by experiment that 6.0W goes radiated per m^2 of plain surface per degree centigrade difference between tank and ambient air temperature and 6.5W goes dissipated by convection / m^2 of plain surface / degree centigrade difference in temperature between tank wall and ambient air. Thus a total of 12.5W/m^2/^{0}C goes dissipated to the surrounding. If θ is the temperature rise, then at final steady temperature condition, losses responsible for temperature rise is losses dissipated or transformer losses = 12.5 $S_t \theta$.

Number and dimensions of tubes

If the temperature rise of the tank wall is beyond a permissible value of about 500C, then cooling tubes are to be added to reduce the temperature rise. Tubes can be arranged on all the sides in one or more number of rows. As number of rows increases, the dissipation will not proportionally increase. Hence the number of rows of tubes are to be limited. Generally the number of rows in practice will be less than four.

With the tubes connected to the tank, dissipation due to radiation from a part of the tank surface screened by the tubes is zero. However if the radiating surface of the tube, dissipating the heat is assumed to be equal to the screened surface of the tank, then tubes can assumed to be radiating no heat. Thus the full tank surface can assumed to be dissipating the heat due to both radiation and convection & can be taken as 12.5 $S_t\theta$watts.

Because the oil when get heated up moves up and cold oil down, circulation of oil in the tubes will be more. Obviously, this circulation of oil increases the heat dissipation. Because of this siphoning action, it has been found that the convection from the tubes increase by about 35 to 40%. Thus if the improvement is by 35%, then the dissipation in watts from all the tubes of area $A_t = 1.35 \times 6.5 A_t\theta = 8.78\ A_t\theta$.

Thus in case of a tank with tubes, at final steady temperature rise condition,

Losses = $12.5\ S_t\theta + 8.78\ A_t\theta$

Round, rectangular or elliptical shaped tubes can be used. The mean length or height of the tubes is generally taken as about 90% of tank height.

In case of round tubes, 5 cm diameter tubes spaced at about 7.5cm (from centre to centre) are used. If dt is the diameter of the tube, then dissipating area of each tube at = pdt x $0.9H_t$. if n_t is the number of tubes, then $A_t = a_t n_t$.

Now a days rectangular tubes of different size spaced at convenient distances are being much used, as it provides a greater cooling surface for a smaller volume of oil. This is true in case of elliptical tubes also. The tubes can be arranged in any convenient way ensuring mechanical strength and aesthetic view.

Video Content / Details of website for further learning (if any):

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Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : III - TRANSFORMERS **Date of Lecture:**

Topic of Lecture:
Methods of cooling of Transformers

Introduction :

1. Load on the transformer will be at or near the full load throughout the period of operation. When the load is less, the transformer, which is in parallel with other transformers, may be put out of service.
2. Generally designed to achieve maximum efficiency at or near the full load. Therefore iron loss is made equal to full load copper loss by using a higher value of flux density. In other words, power transformers are generally designed for a higher value of flux density.
3. Necessity of voltage regulation does not arise .The voltage variation is obtained by the help of tap changers provided generally on the high voltage side. Generally Power transformers are deliberately designed for a higher value of leakage reactance, so that the short-circuit current, effect of mechanical force and hence the damage is less.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Transformer
2. Construction of Transformer
3. Torque and emf equations

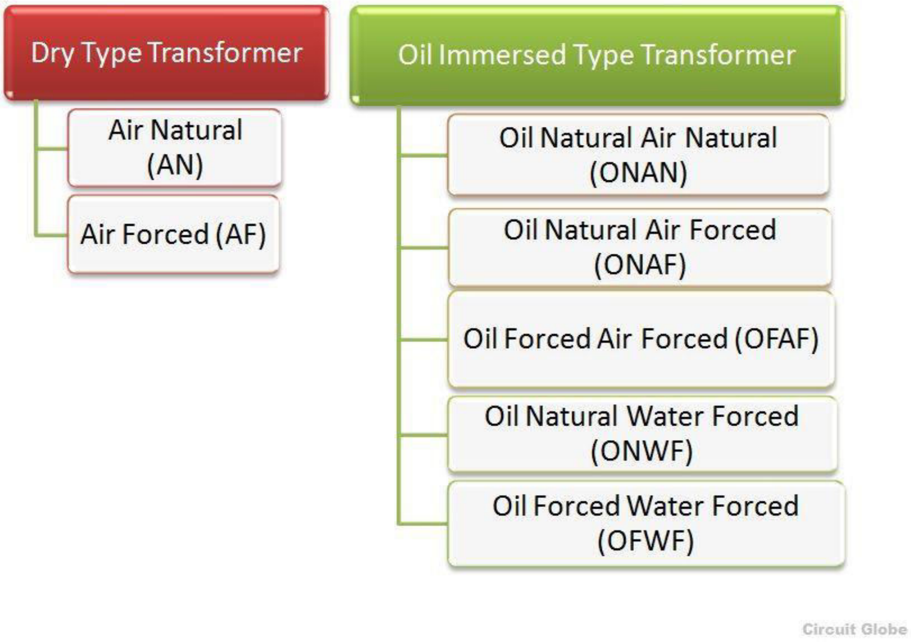
Detailed Content:

Methods of cooling of Transformers.

Cooling of Transformer is the process by which heat generated in the transformer is dissipated or treated to the safe value. This is achieved by various cooling methods of transformer available. The major factor for the generation of heat in the transformer is the various losses like hysteresis, eddy current, iron, and copper loss. Among all the various losses the major contributor of the heat generation is the copper loss or I2R loss.

1. Air natural
2. Air blast
3. Oil natural
4. Oil natural – air forced
5. Oil natural water forced

6. Forced circulation of oil
7. Oil forced – air natural
8. Oil forced – air forced
9. Oil forced – water forced



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LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : III - TRANSFORMERS **Date of Lecture:**

Topic of Lecture:
Main Dimensions (Tutorial -I)

Introduction :

1. Load on the transformer will be at or near the full load throughout the period of operation. When the load is less, the transformer, which is in parallel with other transformers, may be put out of service.
2. Generally designed to achieve maximum efficiency at or near the full load. Therefore iron loss is made equal to full load copper loss by using a higher value of flux density. In other words, power transformers are generally designed for a higher value of flux density.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Transformer
2. Construction of Transformer
3. Torque and emf equations

Detailed Content:

Calculate the core & window areas required for a 1000 KVA, 6600/400 V, 50 Hz, 1ϕ core type transformer. Assume a maximum flux density of 1.25 Wb/m² and current density of 2.5 A/mm², voltage per turn = 30V. Window space factor = 0.32.

Given data :

$Q = 1000$ KVA $E_t = 30V$

$V_p = 6600$ V $K_w = 0.32$

$V_s = 400$ V $B_m = 1.25\ wb/m^2$

$f = 50$ Hz $\delta = 2.5\ A/mm^2$

1ϕ core type

To find

(i) Core Area (A_i)

(ii) Window Area (A_w)

(i) Core Area, $A_i = \frac{\phi_m}{B_m}$

EMF per turn,

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

$$\therefore A_i = \frac{\phi_m}{B_m} = \frac{0.1351}{1.25} = 0.108\, m^2 ;$$

$$\boxed{A_i = 0.108\, m^2}$$

(ii) Window area can be calculated from the KVA rating,

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

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

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

$$A_w = 0.0834\, m^2$$

$$A_w = 0.0834 \times 10^6\, mm^2$$

Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
https://www.youtube.com/watch?v=vz4a65ALLs0
https://swayam.gov.in/nd1_noc19_ee65/preview

Important Books/Journals for further learning including the page nos.: 376-378
Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010

Course Faculty

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Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : III - TRANSFORMERS **Date of Lecture:**

Topic of Lecture:

KVA output equation on three phase transformers (Tutorial - II)

Introduction :

1. Load on the transformer will be at or near the full load throughout the period of operation. When the load is less, the transformer, which is in parallel with other transformers, may be put out of service.
2. Generally designed to achieve maximum efficiency at or near the full load. Therefore iron loss is made equal to full load copper loss by using a higher value of flux density. In other words, power transformers are generally designed for a higher value of flux density.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Transformer
2. Construction of Transformer
3. Torque and emf equations

Detailed Content:

A 3 phase, 50 Hz, oil cooled core type transformer has the following dimensions: distance between core centers = 0.2 m ; height of window = 0.24m; diameter of circumscribing circle = 0.14 m. The flux density in the core is 1.25 Wb/m² and the current density in the conductors is 2.5 A/mm². Estimate the KVA rating. Assume a window space factor of 0.2 and a core area factor = 0.56. The core is 2 stepped. *[A.U May 2015]*

Given data :

3ϕ

$f = 50$ Hz

Core type transformer

$D = 0.2\ m$

$H_w = 0.24\ m$

$d = 0.14\ m$

$B_m = 1.25\ Wb/m^2$

$\delta = 2.5\ A/mm^2$

$K_w = 0.2$

$K_c = 0.56$

To Find

KVA rating of Transformer, (Q)

The KVA rating of 3 ϕ transformer in given by,

$$Q = 3.33\, f\, B_m\, A_i\, A_w\, K_w\, \delta \times 10^{-3} \quad \ldots (1)$$

The known quantities of the above equation are :

Frequency (f). flux density (B_m), current density (δ),

window space factor (K_w)

We need to calculate A_i & A_w,

Area of window, $A_w = H_w \times W_w$

width of window, $W_w = D - d = 0.2 - 0.14 = 0.06\, m$

$\therefore\ A_w = 0.24 \times 0.06 = 0.0144\, m^2$; $\boxed{A_w = 0.0144\ m^2}$ ... (2)

Given that core area factor, $K_c = 0.56$,

$$\text{Also, } K_c = \frac{Ai}{d^2}$$

From the above expression of K_c,

The net core area, $A_i = K_c\, d^2$

$\therefore\ A_i = 0.56 \times (0.14)^2 = 0.01097 \simeq 0.0111 m^2$ ... (3)

$\boxed{A_i = 0.011\ m^2}$

Substitute Equations (2) & (3) in (1),

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

$$Q = 3.33 \times 50 \times 1.25 \times 0.011 \times 0.2 \times 0.0144 \times 2.5 \times 10^6 \times 10^{-3}$$

$$Q = 16.4835\ \text{KVA} \cong 16.5\ \text{KVA}$$

$\boxed{Q = 16.5\ \text{KVA}}$

Video Content / Details of website for further learning (if any): https://nptel.ac.in/courses/108104140/ https://www.youtube.com/watch?v=vz4a65ALLs0 https://swayam.gov.in/nd1_noc19_ee65/preview
Important Books/Journals for further learning including the page nos.: 376-378 Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010

Course Faculty

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L42

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : III - TRANSFORMERS **Date of Lecture:**

Topic of Lecture:
Design of core and winding (Tutorial - III)

Introduction :

1. Load on the transformer will be at or near the full load throughout the period of operation. When the load is less, the transformer, which is in parallel with other transformers, may be put out of service.
2. Generally designed to achieve maximum efficiency at or near the full load. Therefore iron loss is made equal to full load copper loss by using a higher value of flux density. In other words, power transformers are generally designed for a higher value of flux density.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Transformer
2. Construction of Transformer
3. Torque and emf equations

Detailed Content:

Determine the dimensions for core & window for a 5 KVA, 50 Hz, 1 phase, core type transformer. A rectangular core is used with long side twice as long as short side. The window height is 3 times the width. Voltage per turn = 1.8V, space factor = 0.2, current density = 1.8A/mm², Flux density = 1 Wb/m². (A.U NOV 2013)

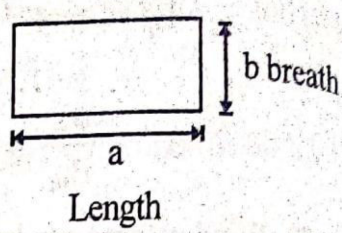
Given data :

$Q = 5$ KVA	$E_t = 1.8$ V	Long side = 2 × short side	*To find*
$f = 50$ Hz	$K_w = 0.2$	rectangular core	A_i, A_w
1ϕ core type	$\delta = 1.8\ A/mm^2$		H_w, W_w
$H_w = 3\ W_w$	$B_m = 1\ wb/m^2$		axb

Net core area, $A_i = \frac{\phi_m}{B_m}$; $\phi_m = \frac{E_t}{4.44 f} = \frac{1.8}{4.44 \times 50} = 0.0081\, wb$

$$A_i = \frac{0.0081}{1} = 0.0081\, m^2, \qquad \boxed{A_i = 0.0081\, m^2}$$

Since it is a rectangular core,



$$a = 2b$$

$$\left.\begin{array}{l}\text{Gross}\\ \text{core}\\ \text{Area}\end{array}\right\} A_{gi} = \text{Length} \times \text{breadth} = a \times b$$

$$A_{gi} = \frac{A_i}{S_f} = \frac{0.0081}{0.9} = 0.009\, m^2 \qquad \begin{bmatrix} S_f - \text{stacking factor} \\ \text{Typical value} = 0.9 \end{bmatrix}$$

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

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

$$b = \sqrt{\frac{A_{gi}}{2}} = \sqrt{\frac{0.09}{2}} = 0.067\, m \qquad \boxed{b = 0.067m}$$

$$a = 2b = 2 \times 0.067 = 0.134\, m \qquad \boxed{a = 0.134m}$$

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

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

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

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

Also, $A_w = H_w W_w$

Given, $H_w = 3W_w$

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

$$W_w = \sqrt{\frac{A_w}{3}} = \sqrt{\frac{0.0154}{3}} = 0.0716\,m$$

$$W_w = 0.0716\,m$$

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

$$H_w = 0.2148\,m$$

Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
https://www.youtube.com/watch?v=vz4a65ALLs0
https://swayam.gov.in/nd1_noc19_ee65/preview

Important Books/Journals for further learning including the page nos.: 376-378
Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010

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L43

EEE

III/VI

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : III - TRANSFORMERS **Date of Lecture:**

Topic of Lecture:
Overall dimensions (Tutorial - IV)

Introduction :

1. Load on the transformer will be at or near the full load throughout the period of operation. When the load is less, the transformer, which is in parallel with other transformers, may be put out of service.
2. Generally designed to achieve maximum efficiency at or near the full load. Therefore iron loss is made equal to full load copper loss by using a higher value of flux density. In other words, power transformers are generally designed for a higher value of flux density.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Transformer
2. Construction of Transformer
3. Torque and emf equations

Detailed Content:

Determine the main dimensions of core and yoke for a 200 KVA, 50 Hz, 1 phase core type transformer. A cruciform core is used with distance between adjacent limbs equal to 1.6 times the width of core laminations. Assume voltage per turn 14V, maximum flux density = 1.1 Wb/m², Window space factor = 0.32, Current density = 3 A/mm² and Stacking factor = 0.9. The net iron area is 0.56d² in a cruciform core where d is the diameter of circumscribing circle. Also the width of largest stamping is 0.85d. (A.U May 2012) (NOV 2014)

Given data :

$Q = 200$ KVA	$E_t = 14$ V	$S_f = 0.9$	**To find**
$f = 50$ Hz	$B_m = 1.1\ wb/m^2$	$A_i = 0.56\ d^2$	A_i, A_w, H_w
1ϕ core type	$K_w = 0.32$	$W = 0.85\ d$	W_w, D_y, H_y
$D = 1.6$ W	$\delta = 3\ A/mm^2$		D,W,H,L

☺ ***Solution :***

EMF per turn, $E_t = 4.44\, f\, \phi_m \Rightarrow E_t = 4.44\, f\, B_m\, A_i$;

Net core area, $$A_i = \frac{E_t}{4.44\, f\, B_m} = \frac{14}{4.44 \times 50 \times 1.1} = 0.0573\, m^2$$

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

Given that, $$A_i = 0.56\, d^2 \Rightarrow d = \sqrt{\frac{A_i}{0.56}} = \sqrt{\frac{0.0573}{0.56}} = 0.32 m$$

$$\boxed{d = 0.32\, m}$$

Width of largest stamping $W = 0.85\, d = 0.85 \times 0.32 = 0.272\, m$;

$$\boxed{W = 0.272\, m}$$

$$D = 1.6\, W = 1.6 \times 0.272 = 0.435\, m; \quad \boxed{D = 0.435 m}$$

Width of window, $W_w = D - d = 0.435 - 0.32 = 0.115\, m$

$$\boxed{W_w = 0.115 m}$$

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

$$A_w = \frac{200}{2.22 \times 50 \times 1.1 \times 0.32 \times 3 \times 10^6 \times 0.0573 \times 10^{-3}} = 0.0298\, m^2$$

$$\boxed{A_w = 0.0298\, m^2}$$

$$H_w = \frac{A_w}{W_w} = \frac{0.0298}{0.115} = 0.2591\, m; \quad \boxed{H_w = 0.2591\, m}$$

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

Height of yoke, $H_y = D_y\ 0.272\, m$

Overall height of frame, $H = H_w + 2\, H_y = 0.2591 + (2 \times 0.272)$

$$\boxed{H = 0.8031\, m}$$

Overall length of frame, $L = D + W = 0.435 + 0.272 = 0.707 m$

$$\boxed{L = 0.707\, m}$$

Video Content / Details of website for further learning (if any): https://nptel.ac.in/courses/108104140/ https://www.youtube.com/watch?v=vz4a65ALLs0 https://swayam.gov.in/nd1_noc19_ee65/preview
Important Books/Journals for further learning including the page nos.: 376-378 Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010

Course Faculty

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LECTURE HANDOUTS **L44**

EEE **III/V**

Course Name with Code : 16EED09 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar & Mr. R. Vinoth

Unit : III - TRANSFORMERS **Date of Lecture:**

Topic of Lecture:
Overall dimensions (Tutorial - V)

Introduction :

1. Load on the transformer will be at or near the full load throughout the period of operation. When the load is less, the transformer, which is in parallel with other transformers, may be put out of service.
2. Generally designed to achieve maximum efficiency at or near the full load. Therefore iron loss is made equal to full load copper loss by using a higher value of flux density. In other words, power transformers are generally designed for a higher value of flux density.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Transformer
2. Construction of Transformer
3. Torque and emf equations

Detailed Content:

Determine the dimensions of the core, the number of turns and the cross-sectional area of conductors in the primary and secondary windings of a 100 kVA, 2200/480 V single phase core type transformer to operate at a frequency of 50 Hz, assuming the following data : approximate voltage per turn = 7.5 V, Maximum flux density = 1.2 wb/m², ratio of effective cross-sectional area of core to square of diameter of circumscribing circle = 0.6, ratio of height to width of window = 2, window space factor = 0.28, current density = 2.5 A/mm².

Given data :

$Q = 100$ KVA	1ϕ core type	*To find*
$V_p = 2200$ V	$E_t = 7.5$ V	A_i, d, A_w, H_w,
$V_s = 480$ V	$A_i/d^2 = 0.6$	W_w, T_p, T_s, a_p, a_s
$f = 50$ Hz	$B_m = 1.2\ wb/m^2$	
$K_{ws} = 0.28$	$H_w/W_w = 2$	
	$\delta = 2.5\ A/mm^2$	

Iron Area, $A_i = \frac{E_t}{4.44\, f\, B_m} = \frac{7.5}{4.44 \times 50 \times 1.2} = 0.0282\, m^2$

$$\boxed{A_i = 0.0282\, m^2}$$

Given, $A_i/d^2 = 0.6 \Rightarrow d = \sqrt{\frac{A_i}{0.6}} = \sqrt{\frac{0.0282}{0.6}} = 0.2168\, m$

$$\boxed{d = 0.2168\, m}$$

Window area,

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

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

$$\boxed{A_w = 0.038\, m^2}$$

Given, $\frac{H_w}{W_w} = 2 \Rightarrow H_w = 2\, W_w$ ... (1)

We know that, Area of window, $A_w = H_w \times W_w$ ... (2)

Sub (1) in (2), $A_w = 2\, W_w \times W_w \Rightarrow W_w = \sqrt{\frac{A_w}{2}} = \sqrt{\frac{0.0382}{2}}$

$$\boxed{W_w = 0.1378\, m}$$

$H_w = 2\, W_w = 2 \times 0.1378,$ $\boxed{H_w = 0.2756\, m}$

No. of Primary turns, $T_p = \frac{V_p}{E_t} = \frac{2200}{7.5} = 293$

No. of Secondary turns, $T_s = \frac{V_s}{E_t} = \frac{480}{7.5} = 64$

Area of primary conductor, $a_p = \frac{I_p}{\delta}$

$$I_p = \frac{Q}{V_p \times 10^{-3}} = \frac{100}{2200 \times 10^{-3}} = 45.45 \text{ A}$$

$$a_p = \frac{45.45}{2.5} = 18.18\ mm^2$$

$$\boxed{a_p = 18.18\ mm^2}$$

Area of secondary conductors, $a_s = \frac{I_s}{\delta}$

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

$$a_s = \frac{208.33}{2.5} = 83.33\ mm^2$$

$$\boxed{a_s = 83.33\ mm^2}$$

Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
https://www.youtube.com/watch?v=vz4a65ALLs0
https://swayam.gov.in/nd1_noc19_ee65/preview

Important Books/Journals for further learning including the page nos.: 376-378

Sawhney, A.K   A Course in Electrical Machine Design   Dhanpat Rai & Sons   2010

Course Faculty

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L45

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : III - TRANSFORMERS **Date of Lecture:**

Topic of Lecture:
Tank Design (Tutorial - VI)

Introduction :

1. Load on the transformer will be at or near the full load throughout the period of operation. When the load is less, the transformer, which is in parallel with other transformers, may be put out of service.
2. Generally designed to achieve maximum efficiency at or near the full load. Therefore iron loss is made equal to full load copper loss by using a higher value of flux density. In other words, power transformers are generally designed for a higher value of flux density.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Transformer
2. Construction of Transformer
3. Torque and emf equations

Detailed Content:

A 1000 kVA 6600/440 V, 50 Hz, 3 phase, delta/star, core type oil immersed natural cooled (ON) transformer. The design data of the transformer is : distance between centers of adjacent limbs = 0.47m, outer diameter of high voltage winding = 0.44 m, height of frame = 1.24m. Core loss = 3.7 kW and I^2R loss = 10.5 kW. Design a suitable tank for the transformer. The average temperature rise of oil should not exceed 35° C. The specific heat dissipation from the tank walls is 6 W/m² – °C and 6.5 W/m² – °C due to radiation and convection respectively. Assume that the convection is improved by 35% due to provision of tubes.

Given data:

$Q = 1000$ KVA	$D = 0.47\ m$	$\theta = 35°$ C	*To find*
$V_p = 6600$ V	$D_{oc} = 0.44\ m$	35 % improved	Design of tank
$V_s = 440$ V	$H = 1.24\ m$		with cooling tubes
$f = 50$ Hz	core loss = 3.7 KW		
3ϕ core type	I^2R loss = 10.5 KW		

Number of tubes, $n_t = \frac{\text{Total area of tubes}}{\text{Area of each tube}} = \frac{X\,S_t}{\pi\, d_t\, l_t}$

Dissipating surface of tank $S_t = 2\,H_T\,(L_T + W_T)$

Width of the tank, $W_T = 2D + D_{oc} + 2C_1$

$$W_T = (2 \times 0.47) + 0.44 + (2 \times 70 \times 10^{-3}) \quad (\because C_1 = 70\,mm)$$

$$\boxed{W_T = 1.52}$$

Length of tank, $L_T = D_{oc} + 2\,C_2$ $(\because C_2 = 90\,mm)$

$$L_T = 0.44 + (2 \times 90 \times 10^{-3})$$

$$\boxed{L_T = 0.62\,m}$$

Height of tank, $H_T = H + C_3 + C_4$ $\left(\because \begin{array}{l} C_3 = 100\,mm \\ C_4 = 400\,mm \end{array}\right)$

$$H_T = 1.24 + (100 \times 10^{-3}) + (400 \times 10^{-3})$$

$$\boxed{H_T = 1.74\,m}$$

$$\therefore\; S_t = 2 \times 1.74\,(0.62 + 1.52) = 7.447\,m^2$$

$$\boxed{S_t = 7.447\,m^2}$$

$$\left.\begin{array}{l}\text{Loss dissipated by tank} \\ \text{walls by radiation \& convection}\end{array}\right\} = (6 + 6.5)\,S_t = 12.5\,S_t$$

$$\left.\begin{array}{l}\text{Loss dissipated by cooling} \\ \text{tubes due to convection}\end{array}\right\} = 6.5 \times \frac{135}{100} \times X\,S_t = 8.775\;XS_t$$

$$\left.\begin{array}{l}\text{Total loss dissipated by} \\ \text{tank \& tubes}\end{array}\right\} = 12.5\,S_t + 8.775\;X\,S_t$$

$$= S_t\,[12.5 + 8.775\,X]$$

Temperature rise in transformer with cooling tubes, $\theta = \frac{\text{Total loss}}{\text{Total loss dissipated}}$

$$\theta = \frac{\text{Core loss} + I^2R\text{ loss}}{\text{Total loss dissipated}} = \frac{[3.7 + 10.5] \times 10^3}{S_t\,[12.5 + 8.775\,X]}$$

$$X = \frac{1}{8.775}\left[\frac{14.2 \times 10^3}{\theta\,S_t} - 12.5\right]$$

$$X = \frac{1}{8.775} = \left[\frac{14.2\times10^{3}}{35\times7.447} - 12.5\right] = 4.784$$

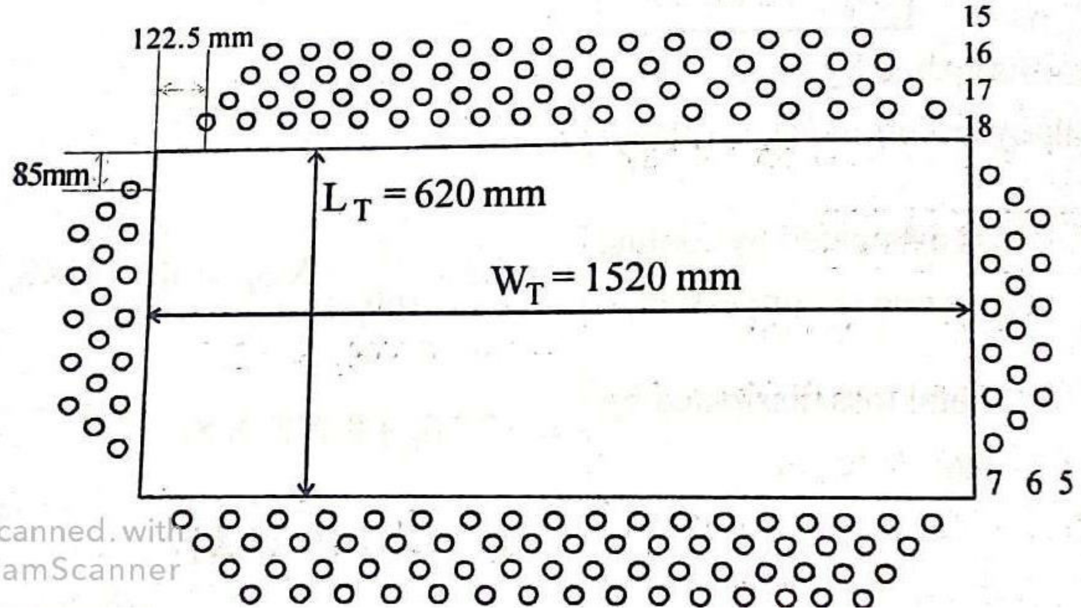
$$\text{Total area of tubes} = X\,S_t = 4.784\times7.447 = 35.62\ m^2$$

$$\text{Area of each tube} = \pi\, d_t\, l_t$$

$$= \pi\times50\times10^{-3}\times1.4 = 0.22\ m^2$$

$$n_t = \frac{35.62}{0.22} = 162 \text{ tubes}$$

$$\boxed{n_t = 162 \text{ tubes}}$$



Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
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Important Books/Journals for further learning including the page nos.: 376-378
Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010

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Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : IV-INDUCTION MOTORS **Date of Lecture:**

Topic of Lecture: Output equation of Induction motor

Introduction :

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Induction motors
2. Construction of induction machines
3. Torque and emf equations

Detailed Content:

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

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

Consider an 'm' phase machine, with usual notations

Output 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

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

$= 2.22\, f\, \Phi Z_{ph} K_w$

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

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

Output = $1.11 \times P\Phi \times 3I_{ph}\, Z_{ph} \times n_s\, K_w\, \eta \cos\Phi \times 10^{-3}$ 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

Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
https://www.youtube.com/watch?v=vz4a65ALLs0
https://swayam.gov.in/nd1_noc19_ee65/preview

Important Books/Journals for further learning including the page nos.: 344-360

Sawhney, A.K   A Course in Electrical Machine Design   Dhanpat Rai & Sons   2010

Course Faculty

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LECTURE HANDOUTS

L47

EEE

III/VI

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : IV-INDUCTION MOTORS **Date of Lecture:**

Topic of Lecture: Main dimensions & Length of air gap

Introduction :

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Induction motors
2. Construction of induction machines
3. Torque and emf equations

Detailed Content:

Main dimensions

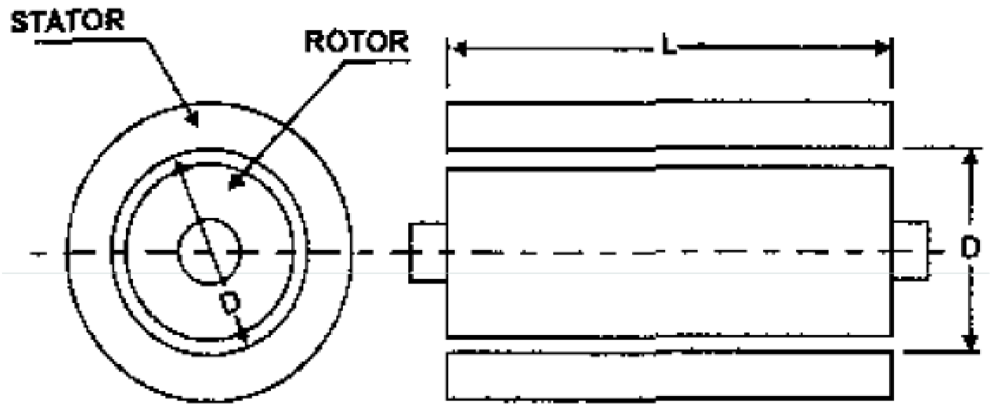

Fig.9 shows the details of main dimensions of the of an induction motor.

Length of air gap

Magnetizing current and power factor being very important parameters in deciding the performance of induction motors, the induction motors are designed for optimum value of air gap or minimum air gap possible. Hence in designing the length of the air gap following empirical formula is employed.

Air gap length $lg = 0.2 + 2\sqrt{DL}$ mm

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

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

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

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

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

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

$$D^2L = \frac{Q}{C_0 n_s}$$

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LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : IV-INDUCTION MOTORS **Date of Lecture:**

Topic of Lecture:

Rules for selecting rotor slots of squirrel cage machines

Introduction :

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Induction motors
2. Construction of induction machines
3. Torque and emf equations

Detailed Content:

Rules for selecting rotor slots of squirrel cage machines

- Number of stator slots should not be equal to rotor slots satisfactory results are obtained when S_r is 15 to 30% larger or smaller than S_s.
- The difference (S_s - S_r) should not be equal to + or - p, + or – 2p or + or – 5 p to avoid synchronous cusps.
- The difference (S_s - S_r) should not be equal to + or - 1, + or – 2 , + or – (p+1) or + or – (p+2) to avoid noise and vibrations.

Number of slots: Proper numbers of rotor slots are to be selected in relation to number of stator slots otherwise undesirable effects will be found at the starting of the motor. Cogging and Crawling are the two phenomena which are observed due to wrong combination of number of rotor and stator slots. In addition, induction motor may develop unpredictable hooks and cusps in torque speed characteristics or the motor may run with lot of noise. Let us discuss Cogging and Crawling phenomena in induction motors.

Crawling: The rotating magnetic field produced in the air gap of the will be usually nonsinusoidal and generally contains odd harmonics of the order 3rd, 5th and 7th. The third harmonic flux will produce the three times the magnetic poles compared to that of the fundamental. Similarly the 5th and 7th harmonics will produce the poles five and seven times the fundamental respectively. The presence of harmonics in the flux wave affects the torque speed characteristics. The Fig. below shows the effect of 7th harmonics on the torque speed characteristics of three phase induction motor. The motor with presence of 7th harmonics is to have a tendency to run the motor at one seventh of its normal speed. The 7th harmonics will produce a dip in torque speed characteristics at one seventh of its normal speed as shown in torque speed characteristics.

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LECTURE HANDOUTS

EEE | **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : IV-INDUCTION MOTORS **Date of Lecture:**

Topic of Lecture: Design of rotor bars & slot

Introduction :

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Induction motors
2. Construction of induction machines
3. Torque and emf equations

Detailed Content:

Design of rotor bars & slots

There are two types of rotor construction. One is the squirrel cage rotor and the other is the slip ring rotor. Most of the induction motor are squirrel cage type. These are having the advantage of rugged and simple in construction and comparatively cheaper. However they have the disadvantage of lower starting torque. In this type, the rotor consists of bars of copper or aluminum accommodated in rotor slots. In case slip ring induction motors the rotor complex in construction and costlier with the advantage that they have the better starting torque. This type of rotor consists of star connected distributed three phase windings. Between stator and rotor is the air gap which is a very critical part. The performance parameters of the motor like magnetizing current, power factor, over load capacity, cooling and noise are affected by length of the air gap. Hence length of the air gap is selected considering the advantages and disadvantages of larger air gap length.

Advantages:

(i) Increased overload capacity

(ii) Increased cooling

(iii) Reduced unbalanced magnetic pull

(iv) Reduced in tooth pulsation

(v) Reduced noise

Disadvantages

(i) Increased Magnetising current

(ii) Reduced power factor

Slip ring rotor

Squrrel cage rotor

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L50

EEE

III/VI

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : IV-INDUCTION MOTORS **Date of Lecture:**

Topic of Lecture:
Design of end rings

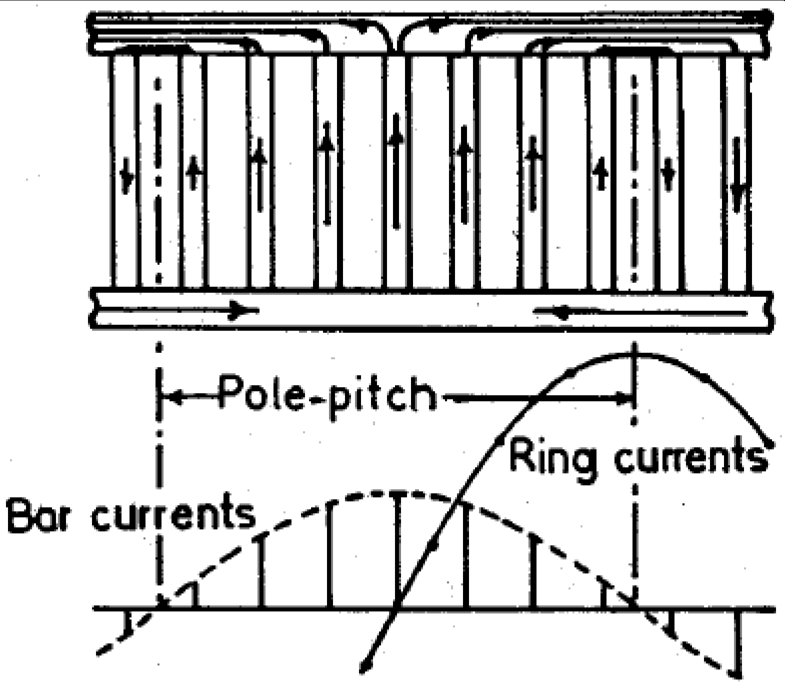
Introduction :
The main purpose of designing an induction motor is to obtain the complete physical dimensions of all the parts of the machine as mentioned below to satisfy the customer specifications. The following design details are required.

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

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Induction motors
2. Construction of induction machines
3. Torque and emf equations

Detailed Content:
All the rotor bars are short circuited by connecting them to the end rings at both the end rings. The rotating magnetic field produced will induce an emf in the rotor bars which will be sinusoidal over one pole pitch. As the rotor is a short circuited body, there will be current flow because of this EMF induced. The distribution of current and end rings are as shown in Fig. below. Referring to the figure considering the bars under one pole pitch, half of the number of bars and the end ring carry the current in one direction and the other half in the opposite direction. Thus the maximum end ring current may be taken as the sum of the average current in half of the number of bars under one pole.



Maximum end ring current Ie(max) = ½ (Number rotor bars / pole) Ib(av)

= ½ x Sr/P x Ib/1.11

Hence rms value of Ie = $1/2\sqrt{2}$ x Sr/P x Ib/1.11

= $1/\pi$ x Sr/P x Ib/1.11

Area of end ring:

Knowing the end ring current and assuming suitable value for the current density in the end rings cross section for the end ring can be calculated as

Area of each end ring Ae = Ie / δ_e mm^2, current density in the end ring may be assume as 4.5 to 7.5 amp/mm^2.

Copper loss in End Rings:

Mean diameter of the end ring (Dme) is assumed as 4 to 6 cms less than that of the rotor. Mean length of the current path in end ring can be calculated as $l_{me} = \pi D_{me}$. The resistance of the end ring can be calculated as re = 0.021 x l_{me} / Ae

Total copper loss in end rings = 2 x Ie^2 x re

Equivalent Rotor Resistance:

Knowing the total copper losses in the rotor circuit and the

equivalent rotor current equivalent rotor resistance can be calculated as follows.

Equivalent rotor resistance r'

r = Total rotor copper loss / 3 x $(Ir')^2$

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EEE | **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : IV-INDUCTION MOTORS **Date of Lecture:**

Topic of Lecture:

Design of wound rotor

Introduction :

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Induction motors
2. Construction of induction machines
3. Torque and emf equations

Detailed Content:

Design of wound Rotor:

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

Number of rotor slots:

As mentioned earlier the number of rotor slots should never be equal to number of stator slots. Generally for wound rotor motors a suitable value is assumed for number of rotor slots per pole per phase, and then total number of rotor slots are calculated. So selected number of slots should be such that tooth width must satisfy the flux density limitation. Semiclosed slots are used for rotor slots.

Number of rotor Turns: Number of rotor turns are decided based on the safety consideration of the personal working with the induction motors. The volatge between the slip rings on open circuit must be limited to safety values. In general the voltage between the slip rings for low and medium voltage machines must be limited to 400 volts. For motors with higher voltage ratings and large size motors this voltage must be limited to 1000 volts. Based on the assumed voltage between the slip rings comparing the induced voltage ratio in stator and rotor the number of turns on rotor winding can be calculated.

Voltage ratio Er/ Es = (Kwr x Tr) / (Kws x Ts)

Hence rotor turns per phase Tr = (Er/Es) (Kws/Kwr) Ts

Er = open circuit rotor voltage/phase

Es = stator voltage /phase

Kws = winding factor for stator

Kwr = winding factor for rotor

Ts = Number of stator turns/phase

Rotor Current

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

Ir = (Kws x Ss x Z's) x I'r / (Kwr x Sr x Z'r) ;

Kws – winding factor for the stator,

Ss – number of stator slots,

Z's – number of conductors / stator slots,

Kwr – winding factor for the rotor,

Sr – number of rotor slots,

Z'r – number of conductors / rotor slots and

I'r – equivalent rotor current in terms of stator current

I'r = 0.85 Is where Is is stator current per phase.

Area of Rotor Conductor: Area of rotor conductor can be calculated based on the assumed value for the current density in rotor conductor and calculated rotor current. Current density rotor conductor can be assumed between 4 to 6 Amp/mm^2

Ar = Ir / δ_r mm2

Ar < 5mm^2 use circular conductor, else rectangular conductor, for rectangular conductor width to thickness ratio = 2.5 to 4. Then the standard conductor size can be selected similar to that of stator conductor.

Size of Rotor slot:

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

Length of the mean Turn can be calculated from the empirical formula lmt = 2L + 2.3 τ_p + 0.08m Resistance of rotor winding is given by Rr = (0.021 x lmt x Tr) / Ar

Total copper loss = 3 I_r^2 Rr Watts

Flux density in rotor tooth: It is required that the dimension of the slot is alright from the flux density consideration. Flux density has to be calculated at 1/3rd height from the root of the teeth. This flux density has to be limited to 1.8 Tesla. If not the width of the tooth has to be increased and width of the slot has to be reduced such that the above flux density limitation is satisfied. The flux density in rotor can be calculated by as shown below.

Diameter at 1/3rd height Dr' = D - 2/3 x htr x 2

Slot pitch at 1/3rd height = τ'r = τ x Dr' /Sr

Tooth width at this section = b'tr = τ'sr – bsr

Area of one rotor tooth = a'tr = b'tr x li

Iron length of the rotor li = (L- wd x nd)ki, ki = iron space factor

Area of all the rotor tooth / pole A'tr = b't x li x Sr /P

Mean flux density in rotor teeth B'tr = φ / A'tr

Maximum flux density in the rotor teeth < 1.5 times B'tr

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LECTURE HANDOUTS

EEE | **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : IV-INDUCTION MOTORS **Date of Lecture:**

Topic of Lecture:

Magnetizing current, Short circuit current

Introduction :

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.

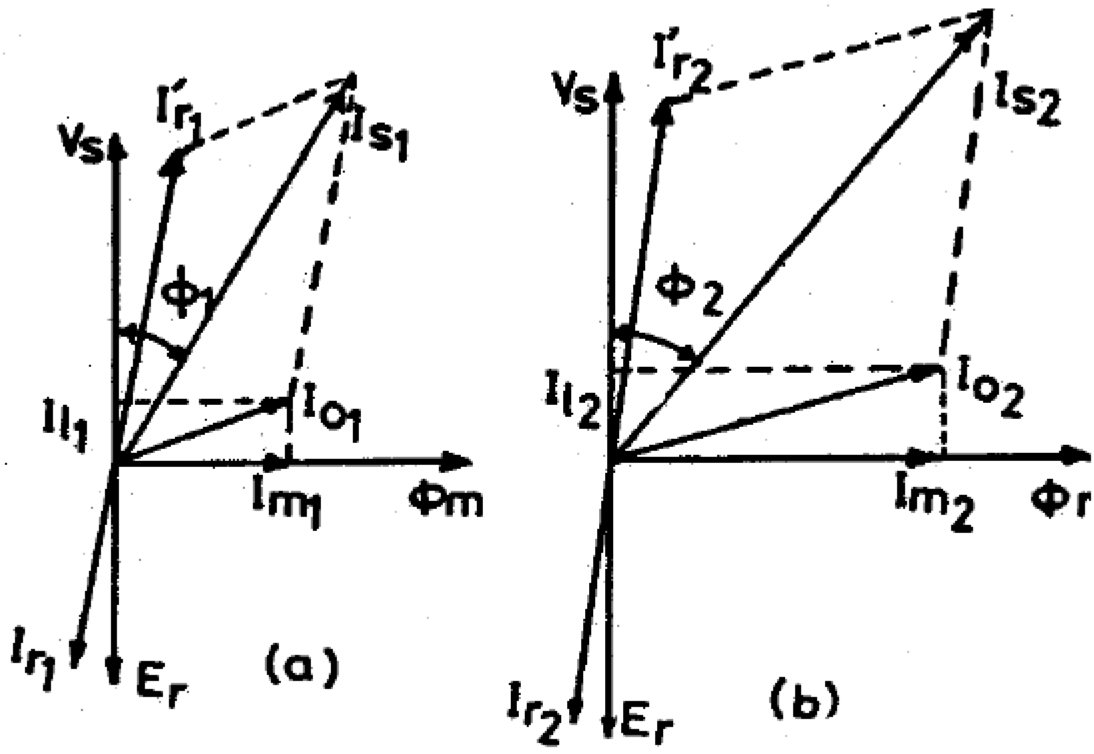
Prerequisite knowledge for Complete understanding and learning of Topic:

1. Induction motors
2. Construction of induction machines
3. Torque and emf equations

Detailed Content:

Magnetizing current

Effect of magnetizing current and its effect on the power factor can be understood from the phasor diagram of the induction motor shown in Fig.



Phasor diagram of induction motor

Magnetizing current and power factor being very important parameters in deciding the performance of induction motors, the induction motors are designed for optimum value of air gap or minimum air gap possible. Hence in designing the length of the air gap following empirical formula is employed.

Air gap length lg = $0.2 + 2\sqrt{DL}$ mm

Short circuit current

Short circuit current

$$SCR\downarrow = \frac{1}{X_s\uparrow}, X_s\uparrow \Rightarrow Z_s\uparrow, Z_s\uparrow, I_{sc}\downarrow = \frac{E_s}{Z_s\downarrow}$$

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LECTURE HANDOUTS

EEE

III/VI

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : IV-INDUCTION MOTORS **Date of Lecture:**

Topic of Lecture:

Operating characteristics

Introduction :

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.

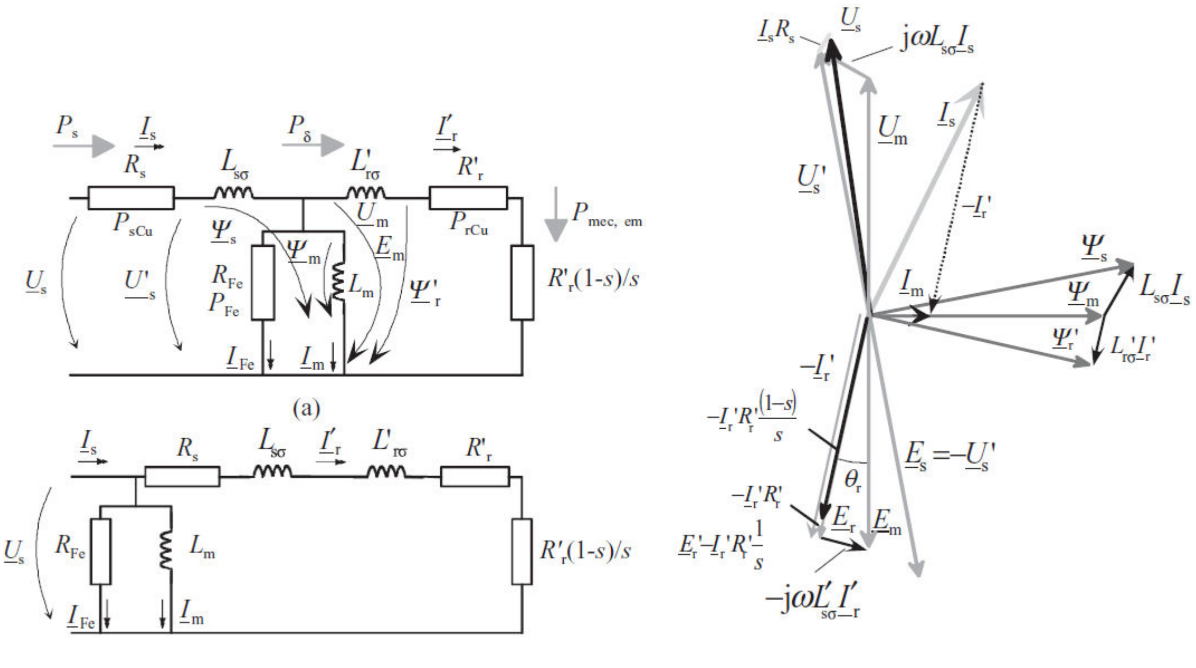
Prerequisite knowledge for Complete understanding and learning of Topic:

1. Induction motors
2. Construction of induction machines
3. Torque and emf equations

Detailed Content:

Operating characteristics.

Now, the equivalent circuit of an asynchronous motor per phase, the quantities of which are calculated in the machine design, is worth recollecting. Figure 7.12 illustrates a single-phase equivalent circuit of an ordinary induction motor per phase, a simplified equivalent circuit anda phasor diagram.



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LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : IV-INDUCTION MOTORS **Date of Lecture:**

Topic of Lecture:
Losses and Efficiency

Introduction :
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.

Prerequisite knowledge for Complete understanding and learning of Topic:
1. Induction motors
2. Construction of induction machines
3. Torque and emf equations

Detailed Content:
Copper loss in End Rings:

Mean diameter of the end ring (Dme) is assumed as 4 to 6 cms less than that of the rotor. Mean length of the current path in end ring can be calculated as $l_{me} = \pi D_{me}$. The resistance of the end ring can be calculated as re = 0.021 x l_{me} / Ae

Total copper loss in end rings = 2 x Ie^2 x re

Squirrel cage rotor consists of a set of copper or aluminum 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’. Aluminum rotor bars are usually die-cast into the rotor slots, which results in a very rugged construction. Even though the aluminum rotor bars are in direct contact with the steel laminations, practically all the rotor current flows through the aluminum bars and not in the lamination

Copper loss in rotor bars:

Knowing the length of the rotor bars and resistance of the rotor bars cu losses in the rotor bars can be calculated. Length of rotor bar lb = L + allowance for skewing

Rotor bar resistance = 0.021 x lb / Ab

Copper loss in rotor bars = Ib x rb x number of rotor bars.

Video Content / Details of website for further learning (if any):

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Rasipuram - 637 408, Namakkal Dist., Tamil Nadu

L55

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : IV-INDUCTION MOTORS **Date of Lecture:**

Topic of Lecture: Output equation of Induction motor(Tutorial I)

Introduction :

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Induction motors
2. Construction of induction machines
3. Torque and emf equations

Detailed Content:

Problem 4.1 *Find the main dimensions of a 15 KW, three phase 400 volts, 50 Hz, 2810 rpm squirrel cage induction motor having an efficiency of 88 percent and full load power factor of 0.9. Specific magnetic loading is 0.5 Wb/m² and specific electric loading = 25000 A/m. Take rotor peripheral speed as approximately 20 m/sec at synchronous speed.*

(Anna Univ, May/June 2009, Nov/Dec 2007, Nov/Dec 2006)

Given:

$$P = 15 \text{ KW}$$
$$m = 3$$
$$V_L = 400 \text{ volts}$$
$$f = 50 \text{ Hz}$$
$$\text{Rotor speed, } N_r = 2810 \text{ rpm}$$
$$\eta = 88\% = 0.88$$
$$\text{Power factor, } \cos\phi = 0.9$$
$$B_{av} = 0.5 \text{ Wb/m}^2 \text{ (or) Tesla}$$
$$ac = 25000 \text{ A/m (or) ampere conductors/metre}$$
$$\text{Peripheral speed, } V_r = 20 \text{ m/s}$$

To find:

Main dimensions,

(*i*) Stator diameter (or) Stator bore (D)

(*ii*) Stator core length (L)

☺***Solution:***

The output equation (or) KVA input of 3ϕ induction motor

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

$$\text{KVA input, } Q = \frac{KW}{\eta \cos\phi} = \frac{P}{\eta\cos\phi}$$

$$= \frac{15}{0.88 \times 0.9}$$

$$Q = 18.94 \text{ KVA}$$

Output coefficient, $C_O = 1.11\,\pi^2 B_{av}\, ac\, K_{ws} \times 10^{-3}$

$= 1.11\,\pi^2 \times 0.5 \times 25000 \times 0.955 \times 10^{-3}$

$C_O = 131.3$ (∵ Take $K_{ws} = 0.955$)

The nearest synchronous speed for corresponding 50 Hz frequency is 3000 rpm because rotor speed given as 2810 rpm.

Synchronous speed in rps, $n_s = \dfrac{N_s}{60}$

$n_s = \dfrac{3000}{60} = 50$ rps

∴ $Q = C_O D^2 L n_s$

$18.94 = 131.3 \times D^2 L \times 50$

$D^2 L = 2.8849 \times 10^{-3}$

The rotor diameter is almost equal to stator bore,

Peripheral speed, $V_r = \pi D n_s$

$20 = \pi D \times 50$

$\boxed{D = 0.127 \text{ m}}$ **Ans.**

Substitute D = 0.127 m in $D^2 L = 2.8849 \times 10^{-3}$

$(0.127)^2 L = 2.8849 \times 10^{-3}$

$L = \dfrac{2.8849 \times 10^{-3}}{(0.127)^2}$

$\boxed{L = 0.178 \text{ m}}$ **Ans.**

Result

Main dimensions,

(*i*) Stator diameter (or) Stator bore, D = 0.127 m

(*ii*) Stator core length, L = 0.178 m

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EEE | **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : IV-INDUCTION MOTORS **Date of Lecture:**

Topic of Lecture: Design of rotor bars & slot(Tutorial II)

Introduction :

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Induction motors
2. Construction of induction machines
3. Torque and emf equations

Detailed Content:

Problem 4.10 *A 11 KW, three phase 6 pole, 50 Hz, 220 volts star connected induction motor has 54 stator slots, each containing 9 conductors. Calculate the value of bar and end ring currents. The number of rotor bars is 64. The machine has an efficiency of 86 percent and a power factor of 0.85. The rotor mmf may be assumed to be 85% of stator MMF. Also find the bar and end ring sections if the current density is 5 A/mm².* *(Anna Univ, May/June 2009, Nov/Dec 2012)*

Given:

$$P = 11 \text{ KW}$$
$$m = 3$$
$$p = 6$$
$$f = 50 \text{ Hz}$$
$$V_L = 220 \text{ volts}$$
$$S_s = 54$$
$$\text{Conductors/slot, } Z_{ss} = 9$$
$$\text{Number of rotor bars} = \text{number of rotor slots, } S_r = 64$$
$$\eta = 86\% = 0.86$$
$$\text{Power factor, } \cos\phi = 0.85$$
$$\text{Rotor mmf} = 85\% \text{ of stator mmf}$$
$$\delta_b = \delta_e = 5 \text{ A/mm}^2$$

To find:

(*i*) Rotor bar current (I_b)

(*ii*) End ring current (I_e)

(*iii*) Cross section area of each rotor bars (a_b)

(*iv*) Cross section area of each end rings (I_e)

☺***Solution:***

(*i*) Rotor bar current (I_b)

$$\text{Rotor bar current, } I_b = 0.85 \frac{6\, T_s\, I_s}{S_r}$$

For 3 ϕ induction motor,

$$\text{Total number of stator conductors, } Z_s = 6\, T_{ph} = 6\, T_s$$

$$\text{Conductors/slot} \times \text{number of stator slots} = 6\, T_s$$

$$Z_{ss} \times S_s = 6\, T_s$$

$$T_s = \frac{Z_{ss} \times S_s}{6}$$

Number of stator turns per phase, $T_s = \frac{9 \times 54}{6}$

$$T_s = 81$$

Stator current per phase, $I_s = I_{LS}$ ($\because$ star connected induction motor)

$$I_s = I_{LS} = \frac{P \times 10^3}{\sqrt{3}\ V_L\ \eta \cos\phi}$$

$$= \frac{11 \times 10^3}{\sqrt{3} \times 220 \times 0.86 \times 0.85}$$

$$I_s = 39.49\ A$$

$$I_b = \frac{6\ T_s\ I_s}{S_r} \times 0.85$$

$\therefore$

$$I_b = 0.85 \times \frac{6 \times 81 \times 39.49}{64} = 254.89$$

$\therefore$ Rotor bar current, $\boxed{I_b \approx 255\ A}$ **Ans.**

(ii) End ring current (I_e).

End ring current, $I_e = \frac{S_r I_b}{\pi p}$

$$= \frac{64 \times 255}{\pi \times 6} = 866$$

$$\boxed{I_e = 866\ A}$$ **Ans.**

(iii) Cross-section area of each rotor bars (a_b)

Area of each rotor bar, $a_b = \frac{I_b}{\delta_b}$

$$= \frac{255}{5} = 55$$

$$\boxed{a_b = 51\ mm^2}$$ **Ans.**

(iv) Cross section area of each end rings (a_e)

Area of each end rings, $a_e = \frac{I_e}{\delta_e}$

$$= \frac{866}{5} = 173.2$$

$a_e = 173.2 \text{ mm}^2$ **Ans.**

Result

(*i*) Rotor bar current, $I_b = 255$ A

(*ii*) End ring current, $I_e = 866$ A

(*iii*) Cross section of rotor bars, $a_b = 51 \text{ mm}^2$

(*iv*) Cross section of end rings, $a_e = 173.2 \text{ mm}^2$

Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
https://www.youtube.com/watch?v=vz4a65ALLs0
https://swayam.gov.in/nd1_noc19_ee65/preview

Important Books/Journals for further learning including the page nos.: 622-623
Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010

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L57

LECTURE HANDOUTS

EEE

III/VI

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : IV-INDUCTION MOTORS **Date of Lecture:**

Topic of Lecture:

Design of end rings(Tutorial III)

Introduction :

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Induction motors
2. Construction of induction machines
3. Torque and emf equations

Detailed Content:

(ii) Cross section ...

Problem 4.11 *Find the current in the bars and end rings of a cage rotor of a 6 pole, 3 ph, induction motor having 72 stator slots with 15 conductors in each slot if the stator current per phase is 20 A and rotor slots are 55. Hence find the suitable size of the cage bars and end rings.*

Given:

$$p = 6$$
$$m = 3$$
$$S_s = 72$$
$$Z_{ss} = 15$$
$$I_s = 20\text{ A}$$
$$S_r = 55$$

To find:

(*i*) Rotor bar current (I_b)

(*ii*) End ring current (I_e)

(*iii*) Size or cross section area of each bar (a_b)

(*iv*) Size or cross section area of each end ring (a_e)

☺Solution:

(*i*) Rotor bar current (I_b)

Assume that, mmf in the rotor is approximately 85% of the mmf in the stator.

$$\therefore \quad \text{Rotor bar current, } I_b = 0.85\frac{6\,T_s\,I_s}{S_r}$$

Now, number of stato nductors, Z_s = Conductors/slot × stator slots

$$Z_s = Z_{ss} \times S_s$$

$$6\,T_s = Z_{ss}\,S_s$$

$(\because T_s = T_{ph})$

$\therefore$ Number of stator turns per phase, $T_s = T_{ph} = \dfrac{Z_{ss} \times S_s}{6}$

$$T_s = \frac{15 \times 72}{6} = 180$$

$$\therefore \quad I_b = 0.85 \times \frac{6\,T_s\,I_s}{S_r}$$

$$= 0.85 \times \frac{6 \times 180 \times 20}{55} = 333.8$$

$\therefore$ Rotor bar current, $\boxed{I_b = 333.8\text{ A}}$ **Ans.**

(*ii*) End ring current (I_e)

$$\text{End ring current } I_e = \frac{S_r\,I_b}{\pi\,p}$$

$$= \frac{55 \times 333.8}{\pi \times 6} = 973.9\text{ A}$$

$\boxed{I_e = 973.9\text{ A}}$ **Ans.**

(*iii*), (*iv*) Cross-section area of rotor bars and end rings (a_b, a_e)

Assuming a current density in the rotor bars and end rings are 5 A/mm²

$(\because \delta_e = \delta_b = 5\text{ A/mm}^2)$

Cross section area of each rotor bar, $a_b = \dfrac{I_b}{\delta_b}$

$$a_b = \frac{333.8}{5} = 66.76$$

$\boxed{a_b = 66.76\text{ mm}^2}$ **Ans.**

Cross section area of each end rings, $a_e = \dfrac{I_e}{\delta_e}$

$$= \frac{973.9}{5} = 194.78$$

$\boxed{a_e = 194.78\text{ mm}^2}$ **Ans.**

Result

(*i*) Rotor bar current, $I_b = 333.8$ A

(*ii*) End ring current, $I_e = 973.9$ A

(*iii*) Cross section of rotor-bars, $a_b = 66.76$ mm^2

(*iv*) Cross section of end rings, $I_e = 194.78$ mm^2

Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
https://www.youtube.com/watch?v=vz4a65ALLs0
https://swayam.gov.in/nd1_noc19_ee65/preview

Important Books/Journals for further learning including the page nos.: 622-623
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L58

LECTURE HANDOUTS

EEE | **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : IV-INDUCTION MOTORS **Date of Lecture:**

Topic of Lecture:

Design of wound rotor(Tutorial IV)

Introduction :

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Induction motors
2. Construction of induction machines
3. Torque and emf equations

Problem 4.14 *A 90 KW, 500 V, 50 Hz, three phase, 8 pole induction motor has a star connected stator winding accommodated in 63 slots with 6 conductors per slot. The slip ring voltage on open circuit should be 400 volts approximately. Design a suitable rotor winding and state (i) number of slots in rotor, (ii) number of conductors per slot, (iii) coil span, (iv) slip ring voltage on open circuit, (v) full load current per phase in rotor. Assume efficiency of 90 percent and power factor of 0.86.*

(Anna Univ, Nov/Dec 2006, April/May 2008, April/May 2011)

Given:

$$P = 90 \text{ KW}$$

$$V_L = 500 \text{ volts}$$

$$f = 50 \text{ Hz}$$

$$m = 3$$
$$p = 8$$
$$S_s = 63$$
$$Z_{ss} = 6$$
$$\text{Slip ring voltage} = 400 \text{ volts}$$
$$\eta = 90\% = 0.9$$
$$\text{Power factor, } \cos\phi = 0.86$$

To find:

(i) Number of slots in rotor (S_r)

(ii) Number of conductors per slot in rotors (Z_{rr})

(iii) Coil span

(iv) Slip ring voltage on open circuit

(v) Full load current per phase in rotor (I_r)

Solution:

(i) Number of slots in rotor (S_r)

$$S_r = \text{rotor slots per pole per phase} \times \text{poles} \times \text{number of phase}$$

$$S_r = q_r\, m\, p$$

Take rotor slots per pole per phase $q_r = 3$

$$\therefore \quad S_r = 3 \times 3 \times 8 = 72$$

$\therefore$ Number of rotor slots, $\boxed{S_r = 72}$ **Ans.**

(ii) Number of conductors per slot in rotors (Z_{rr})

$$\text{Rotor conductors/slot, } Z_{rr} = \frac{\text{Number of rotor conducttors}}{\text{Number of rotor slots}}$$

$$Z_{rr} = \frac{6\, T_r}{S_r}$$

Using turns ratio of induction motors,

$$\frac{E_s}{E_r} = \frac{K_{ws}\, T_s}{K_{wr}\, T_r}$$

$$\frac{E_s}{E_r} = \frac{T_s}{T_r}$$

($\because$ winding factor of stator is equal to rotor, $K_{ws} = K_{wr}$)

$$\text{Number of rotor turns, } T_r = T_s \times \frac{E_r}{E_s}$$

$$\text{Rotor emf per phase, } E_r = \frac{\text{slip ring voltage}}{\sqrt{3}} = \frac{400}{\sqrt{3}} = 230.9 \text{ volts}$$

$$\text{Stator emf per phase, } E_s = \frac{V_L}{\sqrt{3}} = \frac{500}{\sqrt{3}} = 288.6 \text{ volts}$$

($\because$ star connected induction motor)

The number of stator conductors, $Z_s = 6\,T_s = 6\,T_{ph}$

Stator conductors/slot × stator slots = $6\,T_s$

$\therefore Z_{ss} \times S_s = 6 T_s$

$\therefore T_s = \frac{Z_{ss} \times S_s}{6}$

$$= \frac{Z_{ss} \times S_s}{6} = \frac{6 \times 63}{6} = 63 \quad (\because Z_{ss} \times S_s = 6\,T_s)$$

$$\therefore \quad T_r = T_s \times \frac{E_r}{E_s} = 63 \times \frac{230.9}{288.6} \approx 50$$

$\because T_s = \frac{Z_{ss} \times S_s}{6}$

$$\therefore \quad Z_{rr} = \frac{6\,T_r}{S_r} = \frac{6 \times 50}{72} = 4.16 \approx 4$$

(Z_{rr} should be even)

$\therefore$ Conductors per slot in rotors, $\boxed{Z_{rr} = 4}$ **Ans.**

$\therefore$ Actual value of rotor conductors, Z_{rn} = rotor conductors per slot × number of rotor slots

$$Z_{rn} = Z_{rr} \times S_r$$

$$= 4 \times 72$$

$$Z_{rn} = 288$$

(*iii*) Coil span

$$\text{Coil span} = \frac{\text{Rotor slots}}{\text{Poles}} = \frac{S_r}{p} = \frac{72}{8} = 9 \text{ slots}$$

(*iv*) Slip ring voltage on open circuit

Actual value of voltage between slip rings = $\sqrt{3}$ × actual value of rotor emf

$$= \sqrt{3}\ E_{rn}$$

$$\frac{E_s}{E_{rn}} = \frac{T_s}{T_{rn}}$$

Actual value of rotor emf, $E_{rn} = E_s \times \frac{T_{rn}}{T_s}$

Actual value of rotor turns, $T_{rn} = \frac{Z_{rn}}{6} = \frac{288}{6} = 48$

$$E_{rn} = 288.6 \times \frac{48}{63}$$

$$E_{rn} = 219.88 \text{ volts}$$

∴ Actual value between slip rings $= \sqrt{3} \times 219.88$

$$= 381 \text{ volts}$$

(*v*) Full load current per phase in rotor (I_r)

Assume that, rotor mmf $= 0.85 \times$ stator mmf

Rotor current per phase, $I_r = 0.85 \times \frac{T_s I_s}{T_r}$

For star connected induction motor,

Stator current per phase, $I_s = I_{LS} = \frac{P \times 10^3}{\sqrt{3}\ V_L \eta \cos\phi}$

$$= \frac{90 \times 10^3}{\sqrt{3} \times 500 \times 0.9 \times 0.86}$$

$$I_s = 134.26 \text{ A}$$

∴ $$I_r = 0.85 \frac{T_s I_s}{T_r}$$

$$= 0.85 \frac{63 \times 134.26}{48} \qquad (\because T_r = T_{rn})$$

Rotor current per phase, $I_r \approx 150$ A **Ans.**

Result

(*i*) Number of slots in rotor, $S_r = 72$

(*ii*) Number of conductors per slot in rotors, $Z_{rr} = 4$

(*iii*) Coil span = 6 slots

(*iv*) Slip ring voltage on open circuit = 381 volts

(*v*) Full load current per phase in rotor, $I_r = 150$ A

Video Content / Details of website for further learning (if any): https://nptel.ac.in/courses/108104140/ https://www.youtube.com/watch?v=vz4a65ALLs0 https://swayam.gov.in/nd1_noc19_ee65/preview
Important Books/Journals for further learning including the page nos.: 622-623 Sawhney, A.K   A Course in Electrical Machine Design   Dhanpat Rai & Sons   2010

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L59

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : IV-INDUCTION MOTORS **Date of Lecture:**

Topic of Lecture:

Magnetizing current, Short circuit current(Tutorial V)

Introduction :

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Induction motors
2. Construction of induction machines
3. Torque and emf equations

Problem 4.19 *A 75 KW, 3300 V, 50 Hz, 8 pole, 3 phase delta connected induction motor has a magnetizing current which is 40 percent of the full load current. Calculate the value of stator turns per phase if the mmf required for the flux density at 30° from pole axis (60° from interpolar axis) is 600 A.*

Assuming winding factor = 0.95, full load efficiency and power factor 0.94 and 0.86 respectively.

Given:

$P = 75$ KW

$V_L = 3300$ V

$f = 50$ Hz

$p = 8$

$m = 3$

Magnetizing current, $I_m = 40\% \times$ full load current

$I_m = 0.4 \times I_s$

$AT_{60} = 600$ A

$K_{ws} = 0.95$

$\eta = 0.94$

Power factor, $\cos\phi = 0.86$

To find:

Number of stator turns per phase

☺***Solution:***

Magnetizing current per phase, $I_m = \dfrac{0.427 \times p\ AT_{60}}{K_{ws}\ T_s}$

Number of stator turns per phase, $T_s = T_{ph} = \frac{0.427 \times p\ AT_{60}}{K_{ws} I_m}$

Given as, magnetizing current per phase, $I_m = 0.4\ I_s$

Stator current per phase, $I_s = I_{ph} = \frac{I_{LS}}{\sqrt{3}}$ ($\because$ delta connected IM)

$$I_{LS} = \frac{P \times 10^3}{\sqrt{3}\ V_L\ \eta \cos\phi}$$

$$= \frac{75 \times 10^3}{\sqrt{3} \times 3300 \times 0.94 \times 0.86}$$

$$I_{LS} = 16.23\ A$$

$$\therefore \quad I_s = \frac{I_{LS}}{\sqrt{3}} = \frac{16.23}{\sqrt{3}} = 9.37\ A$$

$$\therefore \quad I_m = 0.4\ I_s = 0.4 \times 9.37 = 3.75\ A$$

$$\therefore \quad T_s = T_{ph} = \frac{0.427\ p\ AT_{60}}{K_{ws} I_m}$$

$$= \frac{0.427 \times 8 \times 600}{0.95 \times 3.75} \approx 575$$

$\therefore$ Number of turns per phase, $\boxed{T_s = T_{ph} = 575}$ **Ans.**

Result

The value of stator turns per phase, $T_s = T_{ph} = 575$.

Video Content / Details of website for further learning (if any):

https://nptel.ac.in/courses/108104140/

https://www.youtube.com/watch?v=vz4a65ALLs0

https://swayam.gov.in/nd1_noc19_ee65/preview

Important Books/Journals for further learning including the page nos.: 622-623

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MUTHAYAMMAL ENGINEERING COLLEGE

(An Autonomous Institution)

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Rasipuram - 637 408, Namakkal Dist., Tamil Nadu

L60

LECTURE HANDOUTS

EEE | **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : IV-INDUCTION MOTORS **Date of Lecture:**

Topic of Lecture:

Losses and Efficiency(Tutorial VI)

Introduction :

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Induction motors
2. Construction of induction machines
3. Torque and emf equations

Problem 4.18 *A 20 HP, 3 phase, 400 V, 50 Hz, 4 pole star connected induction motor has 3 slots/pole phase with short pitched coils of 160° span. Flux per pole is 0.009 Wb, gap area 180 cm², effective gap length is 0.55 mm. Estimate the component of magnetizing current for the air gap.* (Anna Univ, May/June 2007)

Given:

$$P = 20\text{ HP} = 20 \times 0.746 = 14.92\text{ KW}$$

$$m = 3$$

$$V_L = 400\text{ V}$$

$$f = 50\text{ Hz}$$

$$p = 4$$

Slots/pole/phase, $q_s = 3$

$$\phi = 0.009\text{ Wb}$$

Gap area, $A_g = 180\text{ cm}^2 = 180 \times 10^{-4}\text{ m}^2$

Effective gap length, $K_g\, l_g = 0.55\text{ mm} = 0.55 \times 10^{-3}\text{ m}$

To find:

Magnetizing current for the air gap (I_m)

☺***Solution:***

Magnetizing current per phase, $I_m = \dfrac{0.427\, p\, AT_{60}}{K_{ws}\, T_s}$

While considering only air gap, the magnetizing mmf per pole is given by

$$\text{Total mmf } AT_{60} = AT_g$$

$$= 800000\, B_{g60}\, K_g\, l_g$$

Flux density at 60° from interpolar axis,

$$B_{g60} = 1.36\, B_{av}$$

Specific magnetic loading, $B_{av} = \dfrac{p\,\phi}{\pi D L}$

We know that gap area per pole, $A_g = \dfrac{\pi DL}{p}$

$$DL = \frac{A_g \times p}{\pi}$$

$$= \frac{180 \times 10^{-4} \times 4}{\pi}$$

$$DL = 0.0229$$

$$B_{av} = \frac{p\,\phi}{\pi\,D\,L} = \frac{4 \times 0.009}{\pi \times 0.0229}$$

$$= 0.5 \text{ Wb/m}^2$$

$$B_{g60} = 1.36\,B_{av} = 1.36 \times 0.5 = 0.68 \text{ Wb/m}^2$$

mmf for air gap, $AT_{60} = AT_g = 800000 \times 0.68 \times 0.55 \times 10^{-3}$

$$AT_{60} = 299.2 \text{ AT}$$

Stator emf per phase, $E_s = E_{ph} = 4.44 f\,\phi\,K_{ws}\,T_{ph}$

Number of stator turns/phase, $T_s = T_{ph} = \frac{E_s}{4.44 f\,\phi\,K_{ws}}$

$$E_s = E_{ph} = \frac{V_L}{\sqrt{3}} \quad (\because \text{ star connected induction motor})$$

$$E_s = \frac{400}{\sqrt{3}} = 230.9 \text{ volts}$$

Winding factor, K_{ws} = pitch factor × distribution factor

$$K_{ws} = K_p \times K_d$$

Pitch factor, $K_p = \cos \alpha/2$

$$\alpha = 180° - 160° = 20°$$

$$K_p = \cos 20°/2 = \cos 10° = 0.9848$$

Distribution factor, $K_d = \frac{\sin (q_s\,\beta/2)}{q_s \sin (\beta/2)}$

$$\beta = \frac{180°}{\text{slots/pole}} = \frac{180°}{q_s \times \text{phase}} = \frac{180°}{3 \times 3} = 20°$$

$$K_d = \frac{\sin (20° \times 3/2)}{3 \sin (20°/2)} = 0.9597$$

$$K_{ws} = K_p \times K_d = 0.9848 \times 0.9597 = 0.9451$$

$$T_s = \frac{230.9}{4.44 \times 50 \times 0.009 \times 0.9451} \approx 122$$

$$T_s = 122$$

$$\therefore \quad I_m = \frac{0.427\,p\,AT_{60}}{K_{ws}\,T_s}$$

$$= \frac{0.427 \times 299.2}{0.9451 \times 122} = 4.432 \text{ A}$$

$\therefore$ Magnetizing current per phase, $I_m = 4.432$ A

Result

Magnetizing current per phase for the air gap, $I_m = 4.432$ A

Problem 4.19 *A 75 KW, 3300 V, 50 Hz, 8 pole, 3 phase delta con...*

Video Content / Details of website for further learning (if any): https://nptel.ac.in/courses/108104140/ https://www.youtube.com/watch?v=vz4a65ALLs0 https://swayam.gov.in/nd1_noc19_ee65/preview
Important Books/Journals for further learning including the page nos.: 638-656 Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010

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L61

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : V-SYNCHRONOUS MACHINES **Date of Lecture:**

Topic of Lecture: Output equations

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Synchronous motors
2. Construction of synchronous machines
3. Torque and emf equations

Detailed Content:

Output of the 3 phase synchronous generator is given by

Output of the machine Q = 3Vph Iph x 10^{-3} kVA

Assuming Induced emf Eph = Vph

Output of the machine Q = 3Eph Iph x 10^{-3} kVA

Induced emf Eph = 4.44 f φ TphKw

= 2.22 f φZphKw

Frequency of generated emf f = $PN_S/120$ = Pns/2,

Air gap flux per pole φ = BavφDL/p, and Specific electric loading q = 3Iph Zph/ φD

Output of the machine Q = 3 x (2.22 x $Pn_s/2$ x BavφDL/p x Zphx Kw) Iph x 10^{-3} kVA

Output Q = (1.11 x BavφDL x ns x Kw) (3 x IphZph) x 10^{-3} kVA

Substituting the expressions for Specific electric loadings

Output $Q = (1.11 \times Bav\varphi DL \times ns \times Kw)(\varphi D\, q) \times 10^{-3}$ kVA

$Q = (1.11\ \varphi^2\ D^2L\ Bav\ q\ Kw\ ns \times 10^{-3})$ kVA

$Q = (11\ Bav\ q\ Kw \times 10^{-3})\ D2L\ n^s$ kVA

Therefore Output $Q = Co\ D^2Ln_s$ kVA

or $D^2L = Q/ Cons\ m^3$

where $Co = (11\ Bav\ q\ Kw \times 10^{-3})$

Vph = phase voltage ; Iph = phase current Eph = induced EMF per phase

Zph = no of conductors/phase in stator

Tph = 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; Bav = Average flux density

kw = winding factor

From the output equation of the machine it can be seen that the volume of the machine is directly proportional to the output of the machine and inversely proportional to the speed of the machine. The machines having higher speed will have reduced size and cost. Larger values of specific loadings smaller will be the size of the machine.

Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
https://www.youtube.com/watch?v=vz4a65ALLs0
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Important Books/Journals for further learning including the page nos.: 344-360

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L62

LECTURE HANDOUTS

EEE | III/VI

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : V-SYNCHRONOUS MACHINES **Date of Lecture:**

Topic of Lecture: Choice Specific electric and magnetic loading

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Synchronous motors
2. Construction of synchronous machines
3. Torque and emf equations

Detailed Content:

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 D^2L 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 machines the diameter of the machine will be quite larger than the axial length.

Round Poles: The ratio of pole arc to pole pitch may be assumed varying between 0.6 to 0.7 and pole arc may be taken as approximately equal to axial length of the stator core. Hence Axial length of the core/ pole pitch = $L/\varphi p$ = 0.6 to 0.7 Rectangular poles: The ratio of axial length to pole pitch may be assumed varying between 0.8 to 3 and a suitable value may be assumed based on the design specifications.

Axial length of the core/ pole pitch = $L/\varphi p$ = 0.8 to 3 Using the above relations D and L can be separated. However once these values are obtained diameter of the machine must satisfy the limiting value of peripheral speed so that the rotor can withstand centrifugal forces produced. Limiting values of peripheral speeds are as follows:

Bolted pole construction = 45 m/s

Dove tail pole construction = 75 m/s

Normal design = 30 m/s

Choice 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.

Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
https://www.youtube.com/watch?v=vz4a65ALLs0
https://swayam.gov.in/nd1_noc19_ee65/preview

Important Books/Journals for further learning including the page nos.: 364-368

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010

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L63

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : V-SYNCHRONOUS MACHINES **Date of Lecture:**

Topic of Lecture: Design of salient pole machines

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Synchronous motors
2. Construction of synchronous machines
3. Torque and emf equations

Detailed Content:

Design of salient pole machines

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

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.

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

Round Poles: The ratio of pole arc to pole pitch may be assumed varying between 0.6 to 0.7 and pole arc may be taken as approximately equal to axial length of the stator core. Hence

Axial length of the core/ pole pitch = $L/\tau p$ = 0.6 to 0.7

Rectangular poles: The ratio of axial length to pole pitch may be assumed varying between 0.8 to 3 and a suitable value may be assumed based on the design specifications.

Axial length of the core/ pole pitch = $L/\tau p$ = 0.8 to 3

Using the above relations D and L can be separated. However once these values are obtained diameter of the machine must satisfy the limiting value of peripheral speed so that the rotor can withstand centrifugal forces produced. Limiting values of peripheral speeds are as follows:

Bolted pole construction = 45 m/s Dove tail pole construction = 75 m/s Normal design = 30 m/s

Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
https://www.youtube.com/watch?v=vz4a65ALLs0
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Important Books/Journals for further learning including the page nos.: 368-370

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L64

LECTURE HANDOUTS

EEE | **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : V-SYNCHRONOUS MACHINES **Date of Lecture:**

Topic of Lecture: Short circuit ratio

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.

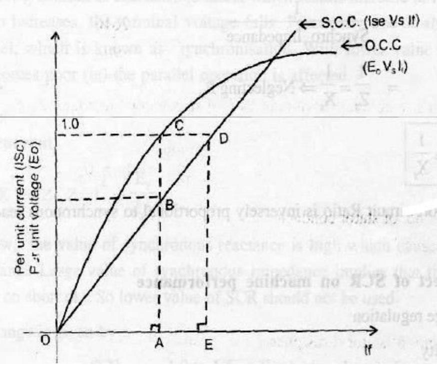
Prerequisite knowledge for Complete understanding and learning of Topic:

1. Synchronous motors
2. Construction of synchronous machines
3. Torque and emf equations

Detailed Content:

Short circuit ratio

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



Explanation

The fig shows open Circuit and short Circuit characteristics of an alternator.

According to definition,

$$\boxed{SCR = \frac{OA}{OE}}$$

Triangles OAB and OED are similar

Since $\angle OAB = \angle OED$

$\angle OBA = \angle ODE$

$\angle AOB = \angle EOD$

$$\text{Now, } \frac{OA}{OE} = \frac{AB}{ED} = \frac{OB}{OD}$$

$$\therefore SCR = \frac{AB}{ED}$$

$$= \frac{AB}{AC} \Rightarrow \frac{1}{\left(\frac{AC}{AB}\right)} \Rightarrow \frac{1}{\frac{\text{open ckt voltage}}{\text{short ckt. current}}}$$

$$= \frac{1}{\text{Synchro Impedance}}$$

$$= \frac{1}{Z_s} = \frac{1}{X_s} \Rightarrow \text{Neglecting } R_a$$

Effect of SCR on Machine performance

1. Voltage regulation
2. Stability
3. Parallel operation
4. Short circuit Current
5. Cost and size of the machine

1.Voltage Regulation

$$\overset{\downarrow}{SCR} = \frac{1}{X_S}, \overset{\uparrow}{E_0} \sqrt{(VCos\varphi + IR_a)^2 + (VSin\varphi \pm I\overset{\uparrow}{X_S})}$$

$$\overset{\uparrow}{R} = \frac{\overset{\uparrow}{E_0 - V}}{V}$$

2. Stability

$$\overset{\downarrow}{SCR} = \frac{1}{X_s\uparrow}, \overset{\downarrow}{P}_{Syn.\,Max} \Rightarrow \frac{EV}{X_s}\uparrow, \overset{\downarrow}{P}_{Syn.\,Max} \Rightarrow \overset{\downarrow}{\text{Stability}}$$

3 Parallel operation: SCR = 1/ Xs, as SCR↑ Xs ↓ IXs ↑ V ↓ P_{sync} ↓

4. Short circuit current

$$SCR\downarrow = \frac{1}{X_s\uparrow}, X_s\uparrow \Rightarrow Z_s\uparrow, Z_s\uparrow, I_{sc}\downarrow = \frac{E_s}{Z_s\downarrow}$$

5. Size and cost of the machine as SCR ↓ Xs ↑ Zs ↑ Isc ↓ and hence cost of control equipment reduces

For salient pole machines SCR value varies from 0.9 to 1.3

For turbo alternators SCR value varies from 0.7 to 1.1

Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
https://www.youtube.com/watch?v=vz4a65ALLs0
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Important Books/Journals for further learning including the page nos.: 371-374
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LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED095 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : V-SYNCHRONOUS MACHINES **Date of Lecture:**

Topic of Lecture: Armature design

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Synchronous motors
2. Construction of synchronous machines
3. Torque and emf equations

Detailed Content:

Armature design

Armature windings are rotating-field windings, into which the rotating-field-induced voltage required in energy conversion is induced. According to IEC 60050-411, the armature winding is a winding in a synchronous machine, which, in service, receives active power from or delivers active power to the external electrical system. This definition also applies to a synchronous compensator if the term ‘active power’ is replaced by ‘reactive power’. The air-gap flux component caused by the armature current linkage is called the armature reaction.

An armature winding determined under these conditions can transmit power between an electrical network and a mechanical system. Magnetizing windings create a magnetic field required in the energy conversion. All machines do not include a separate magnetizing winding; for instance, in asynchronous machines, the stator winding both magnetizes the machine and acts as a winding, where the operating voltage is induced. The stator winding of an asynchronous machine is similar to the armature of a synchronous machine; however, it is not defined as an armature in the IEC standard. In this material, the asynchronous machine stator is therefore referred to as a rotating-field stator winding, not an armature winding. Voltages are also induced in the rotor of an asynchronous machine, and currents that are significant in torque production are created. However, the rotor itself takes only a rotor's dissipation power (I^2R) from the air-gap power of the machine, this power being proportional to the slip;

Armature parameters

1. Number of Slots
2. Turns per phase
3. Single turn bar windings
4. Dimensions
5. Depth
6. Mean length

Turns per phase:

Turns per phase can be calculated from emf equation of the alternator.

- Induced emf Eph = 4.44 f φ TphKw
- Hence turns per phase Tph = Eph / 4.44 f φKw
- Eph = induced emf per phase
- Zph = no of conductors/phase in stator
- Tph = no of turns/phase
- kw = winding factor may assumed as 0.955

Conductor cross section: Area of cross section of stator conductors can be estimated from the stator current per phase and suitably assumed value of current density for the stator windings.

Sectional area of the stator conductor as = Is / δs where δs is the current density in stator windings

Is is stator current per phase A suitable value of current density has to be assumed considering the advantages and disadvantages.

Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
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Important Books/Journals for further learning including the page nos.: 399-403

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L66

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : V-SYNCHRONOUS MACHINES **Date of Lecture:**

Topic of Lecture: Length of the air gap

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Synchronous motors
2. Construction of synchronous machines
3. Torque and emf equations

Detailed Content:

Length of the air gap:

Length of the air gap is a very important parameter as it greatly affects the performance of the machine. Air gap in synchronous machine affects the value of SCR and hence it influences many other parameters. Hence, choice of air gap length is very critical in case of synchronous machines.

Following are the advantages and disadvantages of larger air gap.

Advantages:

(i) Stability: Higher value of stability limit

(ii) Regulation: Smaller value of inherent regulation

(iii) Synchronizing power: Higher value of synchronizing power

(iv) Cooling: Better cooling

(v) Noise: Reduction in noise

(vi) Magnetic pull: Smaller value of unbalanced magnetic pull

Disadvantages:

(i) Field MMF: Larger value of field MMF is required

(ii) Size: Larger diameter and hence larger size

(iii) Magnetic leakage: Increased magnetic leakage

(iv) Weight of copper: Higher weight of copper in the field winding

(v) Cost: Increase overall cost.

Hence length of the air gap must be selected considering the above factors.

Estimation of air gap length

Length of the air gap is usually estimated based on the ampere turns required for the air gap. Armature ampere turns per pole required ATa = 1.35 Tphkw /p

Where Tph = Turns per phase, Iph = Phase current, kw = winding factor, p = pairs of poles

No load field ampere turns per pole ATfo = SCR x Armature ampere turns per pole

ATfo = SCR x ATa

Suitable value of SCR must be assumed.

Ampere turns required for the air gap will be approximately equal to 70 to 75 % of the no load field ampere turns per pole.

ATg = (0.7 to 0.75) ATfo

Air gap ampere turns ATg = 796000 Bgkglg

Air gap coefficient or air gap contraction factor may be assumed varying from 1.12 to 1.18.

As a guide line, the approximate value of air gap length can be expressed in terms of pole pitch

For salient pole alternators: lg = (0.012 to 0.016) x pole pitch

For turbo alternators: lg = (0.02 to 0.026) x pole pitch

Synchronous machines are generally designed with larger air gap length compared to that of Induction motors.

Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
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Important Books/Journals for further learning including the page nos.: 403-406

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L67

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : V-SYNCHRONOUS MACHINES **Date of Lecture:**

Topic of Lecture: Design of rotor

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Synchronous motors
2. Construction of synchronous machines
3. Torque and emf equations

Detailed Content:

Design of rotor

There are two types of rotor construction. One is the squirrel cage rotor and the other is the slip ring rotor. Most of the induction motor are squirrel cage type. These are having the advantage of rugged and simple in construction and comparatively cheaper. However they have the disadvantage of lower starting torque. In this type, the rotor consists of bars of copper or aluminum accommodated in rotor slots. In case slip ring induction motors the rotor complex in construction and costlier with the advantage that they have the better starting torque. This type of rotor consists of star connected distributed three phase windings. Between stator and rotor is the air gap which is a very critical part. The performance parameters of the motor like magnetizing current, power factor, over load capacity, cooling and noise are affected by length of the air gap. Hence length of the air gap is selected considering the advantages and disadvantages of larger air gap length.

Advantages:

(i) Increased overload capacity

(ii) Increased cooling

(iii) Reduced unbalanced magnetic pull

(iv) Reduced in tooth pulsation

(v) Reduced noise

Disadvantages

(i) Increased Magnetising current

(ii) Reduced power factor

Dimensions of Rotor slot:

Width of the slot = slot pitch – tooth width

The flux density in the stator tooth should not exceed 1.8 to 2.0 Tesla. In salient pole alternators internal diameter is quite large and hence the flux density along the depth of the tooth does not vary appreciably. Hence width of the tooth may be estimated corresponding to the permissible flux density at the middle section of the tooth. The flux density should not exceed 1.8 Tesla. However in case of turbo alternators variation of flux density along the depth of the slot is appreciable and hence the width of the tooth may be estimated corresponding to the flux density at the top section of the tooth or the width of the tooth at the air gap. The flux density at this section should not exceed 1.8 Tesla.

For salient pole alternator:

Flux density at the middle section = Flux / pole /(width of the tooth at the middle section x iron length x number of teeth per pole arc)

Number of teeth per pole arc = pole arc/slot pitch

For turbo alternators:

Flux density at the top section = Flux / pole /(width of the tooth at the top section x iron length x number of teeth per pole pitch)

As the 2/3rd pole pitch is slotted the number of teeth per pole pitch = 2/3 x pole pitch/(slot pitch at top section)

Slot width = slot pitch at the top section – tooth width at the top section.

Once the width of the slot is estimated the insulation required width wise and the space available for conductor width wise can be estimated.

Slot insulation width wise:

(i) Conductor insulation

(ii) Mica slot liner

(iii) Binding tape over the coil

(iv) Tolerance or clearance

Space available for the conductor width wise = width of the slot – insulation width wise We have already calculated the area of cross section of the conductor. Using above data on space available for the conductor width wise depth of the conductor can be estimated. Now the depth of the slot may be estimated as follows.

Depth of the slot:

(i) Space occupied by the conductor = depth of each conductor x no. of conductor per slot

(ii) Conductor insulation

(iii) Mica slot liner

(iv) Mica or bituminous layers to separate the insulated conductors

(v) Coil separator between the layers

(vi) Wedge

(vii) Lip

(viii) Tolerance or clearance

Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
https://www.youtube.com/watch?v=vz4a65ALLs0
https://swayam.gov.in/nd1_noc19_ee65/preview

Important Books/Journals for further learning including the page nos.: 412-413

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L68

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : V-SYNCHRONOUS MACHINES **Date of Lecture:**

Topic of Lecture: Design of damper winding

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Synchronous motors
2. Construction of synchronous machines
3. Torque and emf equations

Detailed Content:

Design of damper winding

- Damper windings are provided in the pole faces of salient pole alternators. Damper windings are nothing but the copper or aluminum bars housed in the slots of the pole faces.
- The ends of the damper bars are short circuited at the ends by short circuiting rings similar to end rings as in the case of squirrel cage rotors.
- These damper windings are serving the function of providing mechanical balance; provide damping effect, reduce the effect of over voltages and damp out hunting in case of alternators.
- In case of synchronous motors they act as rotor bars and help in self starting of the motor.

Determination of full load field MMF

Full load field mmf can be taken as twice the armature mmf.

$$AT_{fl} = 2 \times AT_a = 2 \times 1.35 \times I_{ph} \times T_{ph} \times k_w / p$$

Design of field winding

Stator winding is made up of former wound coils of high conductivity copper of diamond shape. These windings must be properly arranged such that the induced emf in all the phases of the coils must have the same magnitude and frequency. These emfs must have same wave shape and be displaced by 1200 to each other. Single or double layer windings may be used depending on the requirement. The three phase windings of the synchronous machines are always connected in star with neutral earthed. Star connection of windings eliminates the 3rd harmonics from the line emf. Double layer winding: Stator windings of alternators are generally double layer lap windings either integral slot or fractional slot windings. Full pitched or short chorded windings may be employed. Following are the advantages and disadvantages of double layer windings.

Advantages:

(i) Better waveform: by using short pitched coil

(ii) Saving in copper: Length of the overhang is reduced by using short pitched coils

(iii) Lower cost of coils: saving in copper leads to reduction in cost

(iv) Fractional slot windings: Only in double layer winding, leads to improvement in waveform

Disadvantages:

(i) Difficulty in repair: difficult to repair lower layer coils

(ii) Difficulty in inserting the last coil: Difficulty in inserting the last coil of the windings

(iii) Higher Insulation: More insulation is required for double layer winding

(iv) Wider slot opening: increased air gap reluctance and noise

Number of Slots:

The number of slots are to be properly selected because the number of slots affect the cost and performance of the machine. There are no rules for selecting the number of slots. But looking into the advantages and disadvantages of higher number of slots, suitable number of slots per pole per phase is selected. However the following points are to be considered for the selection of number of slots.

Advantages:

(i) Reduced leakage reactance

(ii) Better cooling

(iii) Decreased tooth ripples

Disadvantages:

(i) Higher cost

(ii) Teeth becomes mechanically weak

(iii) Higher flux density in teeth

(b) Slot loading must be less than 1500 ac/slot

(c) Slot pitch must be with in the following limitations

(i) Low voltage machines $\leq$3.5 cm

(ii) Medium voltage machines up to 6kV $\leq$ 5.5 cm

(iv) High voltage machines up to 15 kV $\leq$ 7.5 cm

Considering all the above points number of slots per pole phase for salient pole machines may be taken as 3 to 4 and for turbo alternators it may be selected as much higher of the order of 7 to 9slots per pole per phase In case of fractional slot windings number of slots per pole per phase may be selected as fraction 3.5.

Turns per phase:

Turns per phase can be calculated from emf equation of the alternator.

- Induced emf Eph = 4.44 f φ TphKw
- Hence turns per phase Tph = Eph / 4.44 f φKw
- Eph = induced emf per phase
- Zph = no of conductors/phase in stator
- Tph = no of turns/phase
- kw = winding factor may assumed as 0.955

Conductor cross section: Area of cross section of stator conductors can be estimated from the stator current per phase and suitably assumed value of current density for the stator windings.

Sectional area of the stator conductor as = Is / δs where δs is the current density in stator windings

Is is stator current per phase A suitable value of current density has to be assumed considering the advantages and disadvantages.

Advantages of higher value of current density:

(i) reduction in cross section

(ii) reduction in weight

(iii) reduction in cost

Disadvantages of higher value of current density

(i) increase in resistance

(ii) increase in cu loss

(iii) increase in temperature rise

(iv) reduction in efficiency

Hence higher value is assumed for low voltage machines and small machines. Usual value of current density for stator windings is 3 to 5 amps/mm2.

Video Content / Details of website for further learning (if any): https://nptel.ac.in/courses/108104140/ https://www.youtube.com/watch?v=vz4a65ALLs0 https://swayam.gov.in/nd1_noc19_ee65/preview
Important Books/Journals for further learning including the page nos.: 201-210 Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010

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L69

EEE

III/VI

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : V-SYNCHRONOUS MACHINES **Date of Lecture:**

Topic of Lecture: Design of damper winding

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Synchronous motors
2. Construction of synchronous machines
3. Torque and emf equations

Detailed Content:

Design of damper winding

- Damper windings are provided in the pole faces of salient pole alternators. Damper windings are nothing but the copper or aluminum bars housed in the slots of the pole faces.
- The ends of the damper bars are short circuited at the ends by short circuiting rings similar to end rings as in the case of squirrel cage rotors.
- These damper windings are serving the function of providing mechanical balance; provide damping effect, reduce the effect of over voltages and damp out hunting in case of alternators.
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Design of field winding

Stator winding is made up of former wound coils of high conductivity copper of diamond shape. These windings must be properly arranged such that the induced emf in all the phases of the coils must have the same magnitude and frequency. These emfs must have same wave shape and be displaced by 1200 to each other. Single or double layer windings may be used depending on the requirement. The three phase windings of the synchronous machines are always connected in star with neutral earthed. Star connection of windings eliminates the 3rd harmonics from the line emf. Double layer winding: Stator windings of alternators are generally double layer lap windings either integral slot or fractional slot windings. Full pitched or short chorded windings may be employed. Following are the advantages and disadvantages of double layer windings.

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(iii) Lower cost of coils: saving in copper leads to reduction in cost

(iv) Fractional slot windings: Only in double layer winding, leads to improvement in waveform

Disadvantages:

(i) Difficulty in repair: difficult to repair lower layer coils

(ii) Difficulty in inserting the last coil: Difficulty in inserting the last coil of the windings

(iii) Higher Insulation: More insulation is required for double layer winding

(iv) Wider slot opening: increased air gap reluctance and noise

Number of Slots:

The number of slots are to be properly selected because the number of slots affect the cost and performance of the machine. There are no rules for selecting the number of slots. But looking into the advantages and disadvantages of higher number of slots, suitable number of slots per pole per phase is selected. However the following points are to be considered for the selection of number of slots.

Advantages:

(i) Reduced leakage reactance

(ii) Better cooling

(iii) Decreased tooth ripples

Disadvantages:

(i) Higher cost

(ii) Teeth becomes mechanically weak

(iii) Higher flux density in teeth

(b) Slot loading must be less than 1500 ac/slot

(c) Slot pitch must be with in the following limitations

(i) Low voltage machines $\leq$ 3.5 cm

(ii) Medium voltage machines up to 6kV $\leq$ 5.5 cm

(iv) High voltage machines up to 15 kV $\leq$ 7.5 cm

Considering all the above points number of slots per pole phase for salient pole machines may be taken as 3 to 4 and for turbo alternators it may be selected as much higher of the order of 7 to 9slots per pole per phase In case of fractional slot windings number of slots per pole per phase may be selected as fraction 3.5.

Turns per phase:

Turns per phase can be calculated from emf equation of the alternator.

- Induced emf Eph = 4.44 f φ TphKw
- Hence turns per phase Tph = Eph / 4.44 f φKw
- Eph = induced emf per phase
- Zph = no of conductors/phase in stator
- Tph = no of turns/phase
- kw = winding factor may assumed as 0.955

Conductor cross section: Area of cross section of stator conductors can be estimated from the stator current per phase and suitably assumed value of current density for the stator windings.

Sectional area of the stator conductor as = Is / δs where δs is the current density in stator windings

Is is stator current per phase A suitable value of current density has to be assumed considering the advantages and disadvantages.

Advantages of higher value of current density:

(i) reduction in cross section

(ii) reduction in weight

(iii) reduction in cost

Disadvantages of higher value of current density

(i) increase in resistance

(ii) increase in cu loss

(iii) increase in temperature rise

(iv) reduction in efficiency

Hence higher value is assumed for low voltage machines and small machines. Usual value of current density for stator windings is 3 to 5 amps/mm2.

Video Content / Details of website for further learning (if any): https://nptel.ac.in/courses/108104140/ https://www.youtube.com/watch?v=vz4a65ALLs0 https://swayam.gov.in/nd1_noc19_ee65/preview
Important Books/Journals for further learning including the page nos.: 201-210 Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010

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L70

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : V-SYNCHRONOUS MACHINES **Date of Lecture:**

Topic of Lecture: Output equations (Tutorial I)

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Synchronous motors
2. Construction of synchronous machines
3. Torque and emf equations

Detailed Content:

Problem 5.1 *Compute the main dimensions of a 1000 KVA, 50 Hz, 3 phase, 375 rpm alternator. The average air gap density is 0.55 Wb/m² and the ampere conductors per metre are 28000. Use rectangular poles. Assume the ratio of core length to pole pitch equal to 2. Maximum permissible peripheral speed is 50 m/sec. The runaway speed is 1.8 times the synchronous speed.*

(Anna Univ, Nov/Dec 2007, Nov/Dec 2004, Nov/Dec 2005)

Given:

$$Q = 1000 \text{ kVA}$$
$$f = 50 \text{ Hz}$$
$$m = 3$$
$$N_s = N = 375 \text{ rpm}$$
$$B_{av} = 0.55 \text{ Wb/m}^2$$
$$ac = 28000 \text{ amp.cond/m}$$
$$L/\tau = 2$$
$$V_a \leq 50 \text{ m/sec, Take} = K_{ws} = 0.955$$

Runaway peripheral speed = 1.8 peripheral speed

To find:

Main Dimensions

(i) Stator bore (D)

(ii) Stator core length (L)

Solution:

The output equation of synchronous machine

$$Q = C_O D^2 L n_s \quad \text{in KVA}$$

$$\text{Output coefficient, } C_O = 1.11\,\pi^2 B_{av}\, ac\, K_{ws} \times 10^{-3}$$
$$= 1.11\,\pi^2 \times 0.55 \times 28000 \times 0.955 \times 10^{-3}$$
$$C_O = 161.12$$

$$\text{Synchronous speed in rps, } n_s = \frac{N_s}{60} \text{ (or) } n_s = \frac{2f}{p}$$
$$n_s = \frac{375}{60} = 6.25 \text{ rps}$$
$$1000 = 161.12\, D^2 L \times 6.25$$
$$D^2 L = 0.993$$

Given as, rectangular pole with $L/\tau = 2$

$$L = 2\tau \qquad \left[\because N_s = \frac{120 f}{p}\right.$$
$$= 2\frac{\pi D}{p} \qquad p = \frac{120 f}{N_s} = \frac{120 \times 50}{375}$$

$$L = \frac{2\pi \times D}{16}$$

$$L = 0.3926\ D$$

Substitute L = 0.3926 D in $D^2L = 0.993$

$$D^2 (0.3926\ D) = 0.993$$

$$D^3 = 2.5292$$

$$\boxed{D = 1.362\ m}$$ **Ans.**

Substitute D = 1.362 m in L = 0.3926 D

$$L = 0.3926 \times 1.362$$

$$\boxed{L = 0.534\ m}$$ **Ans.**

Checking peripheral speed and runaway peripheral speed,

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

$$= \pi \times 1.362 \times 6.25$$

$$V_a = 26.74\ m/s$$

$$\text{Runaway peripheral speed} = 1.8 \times \text{peripheral speed}$$ (∵ give

$$= 1.8 \times 26.74$$

$$= 48.132\ m/s$$

Both speed is below 50 m/sec. Therefore bolted on pole construction used rectangular poles.

Result

Main dimensions

(*i*) Stator bore, D = 1.362 m

(*ii*) Stator core length, L = 0.534 m

Video Content / Details of website for further learning (if any):

https://nptel.ac.in/courses/108104140/

https://www.youtube.com/watch?v=vz4a65ALLs0

https://swayam.gov.in/nd1_noc19_ee65/preview

Important Books/Journals for further learning including the page nos.: 344-360

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(Approved by AICTE, New Delhi, Accredited by NAAC & Affiliated to Anna University)
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L71

LECTURE HANDOUTS

EEE

III/VI

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : V-SYNCHRONOUS MACHINES **Date of Lecture:**

Topic of Lecture: Design of salient pole machines (Tutorial II)

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Synchronous motors
2. Construction of synchronous machines
3. Torque and emf equations

Problem 5.7 *Find main dimensions of 100 MVA, 11 KV, 50 Hz, 150 rpm, three phase water wheel generator. The average gap density = 0.65 Wb/m² and ampere conductors per metre 40000. The peripheral speed should not exceed 65 m/s at normal running speed in order to limit runaway peripheral speed.*

(Anna Univ, April/May 2011, April/May 2010, Nov/Dec 2006, Nov/Dec 2009)

Given:

$$Q = 100\ MVA = 100 \times 10^3\ KVA$$
$$= 100000\ KVA$$
$$V_L = 11\ KV$$
$$f = 50\ Hz$$
$$N_s = N = 150\ rpm$$
$$B_{av} = 0.65\ Wb/m^2$$
$$ac = 40000\ amp.cond/m$$
$$V_a \leq 65\ m/s,\ \text{Take } K_{ws} = 0.955$$

To find:

Main Dimensions

(i) Stator bore (or) stator diameter (D)

(ii) Stator core length (L)

Solution:

The output equation of synchronous machine

$$Q = C_O D^2 L n_s \quad \text{in KVA}$$

Output coefficient, $C_O = 1.11\ \pi^2 B_{av}\ ac\ K_{ws} \times 10^{-3}$

$$= 1.11\ \pi^2 \times 0.65 \times 40000 \times 0.955 \times 10^{-3}$$
$$C_O = 272$$

Synchronous speed in rps, $n_s = \dfrac{N_s}{60} = \dfrac{150}{60} = 2.5$ rps

$$100000 = 272\ D^2 L \times 2.5$$
$$D^2 L = 147$$

For circular poles, $\dfrac{L}{\tau} = 0.6$ to 0.7

If $L/\tau = 0.6 \Rightarrow$

$$L = 0.6\ \tau$$
$$= 0.6 \frac{\pi D}{p} \qquad \left[\because N_s = \frac{120 f}{p}\right.$$
$$= \frac{0.6\ \pi \times D}{40} \qquad p = \frac{120 f}{N_s} = \frac{120 \times 50}{150}$$

$$L = 0.0471\ D$$

Substitute L = 0.0471 D in $D^2L = 147$ $p = 40$

$$D^2\ (0.0471\ D) = 147$$

$$D = 14.61\ m$$

Checking peripheral speed, $V_a = \pi\ D\ n_s$

$$V_a = \pi \times 14.61 \times 2.5$$

$$V_a = 114.74\ m/s \quad \text{(not satisfied)}$$

If $L/\tau = 0.7 \Rightarrow L = 0.7\ \tau$

$$L = 0.7\frac{\pi D}{p}$$

$$= 0.7\frac{\pi D}{40}$$

$$L = 0.0549\ D$$

Substitute L = 0.0549 D in $D^2L = 147$

$$D^2\ (0.0549\ D) = 147$$

$$D = 13.88\ m$$

Checking peripheral speed, $V_a = \pi\ D\ n_s$

$$= \pi \times 13.88 \times 2.5$$

$$= 109\ m/s \quad \text{(not satisfied)}$$

For rectangular poles, L/τ = 1 to 5

Take $L/\tau = 3$ ($\because$ economical design)

$$L = 3\ \tau$$

$$= 3\frac{\pi D}{p} = \frac{3\ \pi D}{40}$$

$$L = 0.2356\ D$$

Substitute L = 0.2356 D in $D^2\ L = 147$

$$D^2\ (0.2356\ D) = 147$$

$$D = 8.545\ m$$

Checking peripheral speed, $V_a = \pi D n_s$

$= \pi \times 8.545 \times 2.5$

$= 67.11$ m/s (not satisfied)

Now, take $L/\tau = 4$

$$L = 4\tau = \frac{4\pi D}{p}$$

$$= \frac{4\pi D}{40}$$

$$L = 0.1\pi D$$

Substitute $L = 0.1\pi D$ in $D^2 L = 147$

$$D^2(0.1\pi D) = 147$$

$$D^3 = 467.9$$

$$\boxed{D = 7.763 \text{ m}}$$ **Ans.**

Checking peripheral speed, $V_a = \pi D n_s$

$= \pi \times 7.763 \times 2.5$

$= 60.9$ m/s (satisfied)

Now substitute $D = 7.763$ m in $L = 0.1\pi D$

$= 0.1\pi \times 7.763$

$$\boxed{L = 2.438 \text{ m}}$$ **Ans.**

Pole type: Rectangular pole with dove tail construction, $V_a \leq 80$ m/s

Result

Main dimensions

(*i*) Stator bore or stator diameter, $D = 7.763$ m

(*ii*) Stator core length, $L = 2.438$ m

Video Content / Details of website for further learning (if any):
https://nptel.ac.in/courses/108104140/
https://www.youtube.com/watch?v=vz4a65ALLs0
https://swayam.gov.in/nd1_noc19_ee65/preview

Important Books/Journals for further learning including the page nos.: 368-370
Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010

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L72

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : V-SYNCHRONOUS MACHINES **Date of Lecture:**

Topic of Lecture: Short circuit ratio(Tutorial III)
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.
Prerequisite knowledge for Complete understanding and learning of Topic: 1. Synchronous motors 2. Construction of synchronous machines 3. Torque and emf equations

Problem 5.10 *A 500 KVA, 33 KV, 50 Hz, 600 rpm, 3 phase salient pole ternator has 180 turns per phase. Estimate the length of air gap if the average flux ensity is 0.54 Wb/m², the ratio of pole arc to pole pitch = 0.65, short circuit ratio = 1.2, gap contraction factor = 1.15 and the winding factor = 0.955. The mmf required r gap is 80 percent of no load field mmf.* *(Anna Univ, Nov/Dec 2005)*

Given:

$$Q = 500 \text{ KVA}$$

$$V_L = 33 \text{ KV}$$

$$f = 50 \text{ Hz}$$

$$N_s = N = 600 \text{ rpm}$$

$$m = 3$$

$$T_{ph} = T_s = 180$$

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

$$K_f = \Psi = b/\tau = 0.65$$

$$SCR = 1.2$$

$K_g = 1.15$

$K_{ws} = 0.955$

$AT_g = 80\%$ of AT_{fo}

$AT_g = 0.8\ AT_{fo}$

To find:

The length of air gap (l_g)

Solution:

The length of air gap, $l_g = \dfrac{0.8\ AT_{fo}}{800000\ B_g K_g}$

The no load field mmf, $AT_{fo} = AT_a \times SCR$

$$AT_{fo} = 2.7 \times \frac{I_{ph}\, T_{ph}\, K_{ws}}{p} \times SCR$$

Current per phase, $I_{ph} = I_{LS}$ ($\because$ assume that star connected stator)

$$I_{ph} = I_{LS} = \frac{P \times 10^3}{\sqrt{3}\ V_L\, \eta \cos\phi}$$

$$I_{ph} = \frac{Q \times 10^3}{\sqrt{3}\ V_L} = \frac{500 \times 10^3}{\sqrt{3} \times 33 \times 10^3} = 8.74\ \text{A}$$

$$N_s = \frac{120 f}{p} = 600 \Rightarrow p = \frac{120 \times 50}{600} = 10$$

$$\therefore \quad AT_{fo} = \frac{2.7 \times 8.74 \times 180 \times 0.955 \times 1.2}{10}$$

$$= 486.78\ \text{AT}$$

Form factor, $K_f = \Psi = \dfrac{b}{\tau} = \dfrac{B_{av}}{B_g} = 0.65$

$$B_g = \frac{B_{av}}{\Psi} = \frac{0.54}{0.65}$$

$$B_g = 0.8307\ \text{Wb/m}^2$$

$$\therefore \quad l_g = \frac{0.8 \times 486.78}{800000 \times 0.8307 \times 1.15}$$

$$= 5.095 \times 10^{-4}\ \text{m}$$

$$l_g = 0.5095 \times 10^{-3}\ \text{m}$$

Length of air gap, $\boxed{l_g = 0.5095\ \text{mm}}$ **Ans.**

Result

The length of air gap, $l_g = 0.5095$ mm

Video Content / Details of website for further learning (if any): https://nptel.ac.in/courses/108104140/ https://www.youtube.com/watch?v=vz4a65ALLs0 https://swayam.gov.in/nd1_noc19_ee65/preview
Important Books/Journals for further learning including the page nos.: 371-374 Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010

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L73

LECTURE HANDOUTS

EEE | **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : V-SYNCHRONOUS MACHINES **Date of Lecture:**

Topic of Lecture: Design of rotor(Tutorial IV)

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Synchronous motors
2. Construction of synchronous machines
3. Torque and emf equations

Problem 5.14 *A 1250 KVA, 3 phase, 6600 V salient pole alternator has the following data:*

Air gap diameter = 1.6 m, length of core = 0.45 m, number of poles = 20, armature ampere conductors per metre = 28000, ratio of pole arc to pole pitch =0.68, stator slot pitch = 28 mm, current density in damper bars = 3 A/mm². Design a suitable damper winding for the machine.

(Anna Univ, April/May 2004, May/June 2012)

Given:

$$Q = 1250 \text{ KVA}$$
$$m = 3$$
$$V_L = 6600 \text{ volts}$$
$$D = 1.6 \text{ m}$$
$$L = 0.45 \text{ m}$$
$$p = 20$$
$$ac = 28000 \text{ amp.cond/m}$$
$$\Psi = \frac{b}{\tau} = 0.68$$
$$y_{ss} = 28 \text{ mm} = 28 \times 10^{-3} \text{ m}$$
$$\delta_d = 3 \text{ A/mm}^2$$

To find:

Design of damper winding

(*a*) Total area of damper bars per pole (A_d)

(*b*) Number of damper bars per pole (N_d)

(*c*) Area of each damper bar (a_d)

(*d*) Diameter of each bar (d_d)

(*e*) Length of each bar (L_d)

Solution:

(*a*) Total area of damper bars per pole

$$A_d = \frac{0.2 \text{ ac } \tau}{\delta_d}$$

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

$$= \frac{\pi \times 1.6}{20} = 0.251 \text{ m}$$

$$\therefore A_d = \frac{0.2 \times 28000 \times 0.251}{3} = 468.53 \text{ mm}^2$$

Total area of damper bars per pole, $\boxed{A_d = 468.53 \text{ mm}^2}$ **Ans.**

(*b*) Number of damper bars per pole

$$\text{Pole arc, } b = N_d \times y_{ss} \times 0.8$$

$$N_d = \frac{b}{0.8\, y_{ss}}$$

$$= \frac{0.68\,\tau}{0.8\, y_{ss}} \qquad (\because b/\tau = 0.68)$$

$$= \frac{0.68 \times 0.251}{0.8 \times 28 \times 10^{-3}}$$

$$N_d = 7.619 \approx 8$$

$\therefore$ Number of damper bars per pole, $\boxed{N_d = 8}$ **Ans.**

(*c*) Area of each damper bar

$$a_d = \frac{\text{Total area of damper bars per pole}}{\text{Number of damper bars per pole}}$$

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

$$a_d = \frac{468.53}{8} = 58.566 \text{ mm}^2$$

Area of each damper bar, $\boxed{a_d = 58.566 \text{ mm}^2}$ **Ans.**

(*d*) Diameter of each bar, $d_d = \sqrt{\frac{4\,a_d}{\pi}}$

$$= \sqrt{\frac{4 \times 58.566}{\pi}}$$

$$\boxed{d_d = 8.63 \text{ mm}}$$ **Ans.**

(*e*) Length of each bar, $L_d = 1.1\,L$

$$= 1.1 \times 0.45$$

$$\boxed{L_d = 0.495 \text{ m}}$$ **Ans.**

Result

Design of damper winding

(*a*) Total area of damper bars per pole, $A_d = 468.53 \text{ mm}^2$

(*b*) Number of damper bars per pole, $N_d = 8$

(*c*) Area of each damper bar, $a_d = 58.566 \text{ mm}^2$

(*d*) Diameter of each bar, $d_d = 8.63$ mm

(*e*) Length of each bar, $L_d = 0.495$ m

Video Content / Details of website for further learning (if any):

https://nptel.ac.in/courses/108104140/

https://www.youtube.com/watch?v=vz4a65ALLs0

https://swayam.gov.in/nd1_noc19_ee65/preview

Important Books/Journals for further learning including the page nos.: 412-413

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L74

LECTURE HANDOUTS

EEE **III/VI**

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : V-SYNCHRONOUS MACHINES **Date of Lecture:**

Topic of Lecture: Design of damper winding(Tutorial V)

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.

Prerequisite knowledge for Complete understanding and learning of Topic:

1. Synchronous motors
2. Construction of synchronous machines
3. Torque and emf equations

...(5.2...

Problem 5.6 *Determine the main dimensions of a 75000 KVA, 13.8 KV, 50 Hz, 62.5 rpm, 3 phase, star connected alternator. The peripheral speed should be about 40 m/s. Assume, average gap density = 0.65 Wb/m², ampere conductors per metre 40000 and current density = 4 A/mm². Also find the number of stator slots, conductors per slot and conductor area.* *(Anna Univ, May/June 200...)*

Given:

$$Q = 75000 \text{ KVA}$$
$$V_L = 13.8 \text{ KV}$$
$$f = 50 \text{ Hz}$$
$$N_s = N = 62.5 \text{ rpm}$$
$$m = 3$$
$$V_a = 40 \text{ m/s}$$
$$B_{av} = 0.65 \text{ Wb/m}^2$$
$$ac = 40000 \text{ amp.cond/m}$$
$$\delta = 4 \text{ A/mm}^2; \text{ Take } K_{ws} = 0.955$$

To find:

(*i*) Main dimensions

(*a*) Stator bore (or) stator diameter (D)

(*b*) Stator core length (L)

(*ii*) Number of stator slots (S_s)

(*iii*) Conductors per slot (Z_{ss})

☺***Solution:***

(*i*) Main dimensions (D and L)

The output equation of synchronous machine

$$Q = C_O D^2 L n_s \quad \text{in KVA}$$

$$\text{Output coefficient, } C_O = 1.11 \pi^2 B_{av} \, ac \, K_{ws} \times 10^{-3}$$

$$= 1.11 \pi^2 \times 0.65 \times 40000 \times 0.955 \times 10^{-3}$$

$$C_O = 272$$

Synchronous speed in rps, $n_s = \frac{N_s}{60} = \frac{62.5}{60} = 1.0417$ rps

$$75000 = 272\, D^2 L \times 1.0417$$

$$D^2 L = 264.69$$

Given as, peripheral speed, $V_a = 40$ m/s

$$\pi D n_s = 40$$

$$\pi D \times 1.0417 = 40$$

$$\boxed{D = 12.22 \text{ m}}$$ **Ans.**

Substitute D = 12.22 m in $D^2 L = 264.69$

$$(12.22)^2 L = 264.69$$

$$\boxed{L = 1.77 \text{ m}}$$ **Ans.**

(iii) Number of stator slots (S_s)

For given voltage rating 13.8 KV, the stator slot pitch should be less than or equal 60 mm.

$$y_{ss} \leq 60 \text{ mm}$$

Stator slot pitch, $y_{ss} = \frac{\pi D}{S_s} = \frac{\pi \times 12.22}{S_s}$

Number of stator slots, S_s = slots/pole/phase × phase × poles

$$= 3 \times p\, q_s$$

Synchronous speed, $N_s = \frac{120 f}{p}$

$$62.5 = \frac{120 \times 50}{p}$$

$$p = 96$$

∴ $S_s = 3 \times 96\, q_s = 288\, q_s$

If $q_s = 2$, $S_s = 288 \times 2 = 576$, $y_{ss} = \frac{\pi \times 12.22}{576} = 0.0666 \approx 66.6$ mm (not satisfied)

If $q_s = 3$, $S_s = 288 \times 3 = 864$, $y_{ss} = \frac{\pi \times 12.22}{864} = 0.0444 \approx 44.4$ mm (satisfied)

$\therefore$ Number of stator slots, $S_s = 864$ **Ans.**

(*iii*) Conductors per slot (Z_{ss})

$$\text{Conductors per slot, } Z_{ss} = \frac{\text{Number of stator conductors}}{\text{Number of stator slots}}$$

$$Z_{ss} = \frac{Z_s}{S_s}$$

$$\text{Number of stator conductors, } Z_s = 6\,T_{ph}$$

$$\text{Number of turns per phase, } T_{ph} = \frac{E_s}{4.44 f \phi_m K_{ws}}$$

$$\text{Specific magnetic loading, } B_{av} = \frac{p\,\phi_m}{\pi D L}$$

$$\text{Flux per pole, } \phi_m = \frac{B_{av}\,\pi DL}{p}$$

$$= \frac{0.65 \times \pi \times 12.22 \times 1.77}{96}$$

$$\phi_m = 0.46 \text{ Wb}$$

For star connected alternator, $E_s = \frac{V_L}{\sqrt{3}}$

$$= \frac{13.8 \times 10^3}{\sqrt{3}}$$

$$E_s = 7967.43 \text{ V}$$

$$\therefore \quad T_{ph} = \frac{7967.43}{4.44 \times 50 \times 0.46 \times 0.955} = 81.69$$

$$\text{Number of turns per phase, } T_{ph} = 82$$

$$\therefore \quad Z_s = 6\,T_{ph} = 6 \times 82 = 492$$

$$\therefore \quad Z_{ss} = \frac{Z_s}{S_s} = \frac{492}{864} = 0.569$$

For a double layer winding, the conductor per slot is not fraction and it should be even number. Therefore, the number of parallel paths or circuits is assumed to be make a symmetrical.

Let number of parallel paths per phase, $a = 8$

∴ Number of conductors for 'a' parallel path circuits per phase

$$Z_s = 6\,a\,T_{ph}$$

$$Z_s = 6 \times 8 \times 82 = 3936$$

∴ New value of conductors per slot, $Z_{ss} = \frac{Z_s}{S_s} = \frac{3936}{864} \approx 4$

$$\boxed{Z_{ss} = 4}$$ **Ans.**

∴ New value of conductors, $Z_s = Z_{ss} \times S_s$

$$= 4 \times 864$$

$$Z_s = 3456$$

Result

(*i*) Main dimensions

(*a*) Stator bore (or) stator diameter, D = 12.22 m

(*b*) Stator core length, L = 1.77 m

(*ii*) Number of stator slots, $S_s = 864$

(*iii*) Conductors per slot, $Z_{ss} = 4$

Video Content / Details of website for further learning (if any):

https://nptel.ac.in/courses/108104140/

https://www.youtube.com/watch?v=vz4a65ALLs0

https://swayam.gov.in/nd1_noc19_ee65/preview

Important Books/Journals for further learning including the page nos.: 201-210

Sawhney, A.K A Course in Electrical Machine Design Dhanpat Rai & Sons 2010

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LECTURE HANDOUTS

L75

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III/VI

Course Name with Code : 19EED05 & DESIGN OF ELECTRICAL APPARATUS

Course Faculty : Mr. C. Ram Kumar

Unit : V-SYNCHRONOUS MACHINES **Date of Lecture:**

Topic of Lecture: Length of the air gap(Tutorial VI)
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.
Prerequisite knowledge for Complete understanding and learning of Topic: 1. Synchronous motors 2. Construction of synchronous machines 3. Torque and emf equations

... (5.2...)

Problem 5.6 *Determine the main dimensions of a 75000 KVA, 13.8 KV, 50 Hz, 62.5 rpm, 3 phase, star connected alternator. The peripheral speed should be about 40 m/s. Assume, average gap density = 0.65 Wb/m², ampere conductors per metre = 40000 and current density = 4 A/mm². Also find the number of stator slots, conductors per slot and conductor area.* *(Anna Univ, May/June 20..)*

Given:

$$Q = 75000 \text{ KVA}$$
$$V_L = 13.8 \text{ KV}$$
$$f = 50 \text{ Hz}$$
$$N_s = N = 62.5 \text{ rpm}$$
$$m = 3$$
$$V_a = 40 \text{ m/s}$$
$$B_{av} = 0.65 \text{ Wb/m}^2$$
$$ac = 40000 \text{ amp.cond/m}$$
$$\delta = 4 \text{ A/mm}^2; \text{ Take } K_{ws} = 0.955$$

To find:

(*i*) Main dimensions

(*a*) Stator bore (or) stator diameter (D)

(*b*) Stator core length (L)

(*ii*) Number of stator slots (S_s)

(*iii*) Conductors per slot (Z_{ss})

☺***Solution:***

(*i*) Main dimensions (D and L)

The output equation of synchronous machine

$$Q = C_O D^2 L n_s \quad \text{in KVA}$$

$$\text{Output coefficient, } C_O = 1.11\, \pi^2 B_{av}\, ac\, K_{ws} \times 10^{-3}$$
$$= 1.11\, \pi^2 \times 0.65 \times 40000 \times 0.955 \times 10^{-3}$$

$$C_O = 272$$

Synchronous speed in rps, $n_s = \frac{N_s}{60} = \frac{62.5}{60} = 1.0417$ rps

$$75000 = 272\ D^2\ L \times 1.0417$$

$$D^2\ L = 264.69$$

...iven as, peripheral speed, $V_a = 40$ m/s

$$\pi\ D\ n_s = 40$$

$$\pi\ D \times 1.0417 = 40$$

$$\boxed{D = 12.22\ m}$$ **Ans.**

Substitute D = 12.22 m in $D^2\ L = 264.69$

$$(12.22)^2\ L = 264.69$$

$$\boxed{L = 1.77\ m}$$ **Ans.**

(ii) Number of stator slots (S_s)

For given voltage rating 13.8 KV, the stator slot pitch should be less than or equal 60 mm.

$$y_{ss} \leq 60\ mm$$

Stator slot pitch, $y_{ss} = \frac{\pi\ D}{S_s} = \frac{\pi \times 12.22}{S_s}$

Number of stator slots, S_s = slots/pole/phase × phase × poles

$$= 3 \times p\ q_s$$

Synchronous speed, $N_s = \frac{120\ f}{p}$

$$62.5 = \frac{120 \times 50}{p}$$

$$p = 96$$

$$\therefore \quad S_s = 3 \times 96\ q_s = 288\ q_s$$

If $q_s = 2$, $S_s = 288 \times 2 = 576$, $\quad y_{ss} = \frac{\pi \times 12.22}{576} = 0.0666 \approx 66.6$ mm (not satisfied)

If $q_s = 3$, $S_s = 288 \times 3 = 864$, $y_{ss} = \frac{\pi \times 12.22}{864} = 0.0444 \approx 44.4$ mm (satisfied)

$\therefore$ Number of stator slots, $\boxed{S_s = 864}$ **Ans.**

(*iii*) Conductors per slot (Z_{ss})

$$\text{Conductors per slot, } Z_{ss} = \frac{\text{Number of stator conductors}}{\text{Number of stator slots}}$$

$$Z_{ss} = \frac{Z_s}{S_s}$$

$$\text{Number of stator conductors, } Z_s = 6\,T_{ph}$$

$$\text{Number of turns per phase, } T_{ph} = \frac{E_s}{4.44\, f\, \phi_m\, K_{ws}}$$

$$\text{Specific magnetic loading, } B_{av} = \frac{p\,\phi_m}{\pi D L}$$

$$\text{Flux per pole, } \phi_m = \frac{B_{av}\,\pi DL}{p}$$

$$= \frac{0.65 \times \pi \times 12.22 \times 1.77}{96}$$

$$\phi_m = 0.46 \text{ Wb}$$

$$\text{For star connected alternator, } E_s = \frac{V_L}{\sqrt{3}}$$

$$= \frac{13.8 \times 10^3}{\sqrt{3}}$$

$$E_s = 7967.43 \text{ V}$$

$$\therefore T_{ph} = \frac{7967.43}{4.44 \times 50 \times 0.46 \times 0.955} = 81.69$$

$$\text{Number of turns per phase, } T_{ph} = 82$$

$$\therefore Z_s = 6\,T_{ph} = 6 \times 82 = 492$$

$$\therefore Z_{ss} = \frac{Z_s}{S_s} = \frac{492}{864} = 0.569$$

For a double layer winding, the conductor per slot is not fraction and it should be even number. Therefore, the number of parallel paths or circuits is assumed to be make a symmetrical.

Let number of parallel paths per phase, $a = 8$

∴ Number of conductors for 'a' parallel path circuits per phase

$$Z_s = 6\,a\,T_{ph}$$

$$Z_s = 6 \times 8 \times 82 = 3936$$

∴ New value of conductors per slot, $Z_{ss} = \frac{Z_s}{S_s} = \frac{3936}{864} \approx 4$

$$\boxed{Z_{ss} = 4}$$ **Ans.**

∴ New value of conductors, $Z_s = Z_{ss} \times S_s$

$$= 4 \times 864$$

$$Z_s = 3456$$

Result

(*i*) Main dimensions

(*a*) Stator bore (or) stator diameter, D = 12.22 m

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